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Technical Greenhouse-Gas Mitigation Potentials of Biochar Soil Incorporation in Germany¹

Isabel Teichmann²

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Abstract

Biochar is a carbon-rich solid obtained from the heating of biomass in the (near) absence of oxygen in a process called pyrolysis. Its deployment in soils is increasingly discussed as a promising means to sequester carbon in soils and, thus, to help mitigate climate change. For a wide range of feedstocks and scenarios and against the baseline of conventional feedstock management, we calculate the technical greenhouse-gas mitigation potentials of slow-pyrolysis biochar in 2015, 2030 and 2050 when the biochar is incorporated into agricultural soils in Germany and when the by-products from biochar production – pyrolysis oils and gases – are used as renewable sources of energy. Covering the greenhouse gases carbon dioxide, methane and nitrous oxide, our analysis reveals that biochar allows for an annual technical greenhouse-gas mitigation potential in Germany in the range of 2.8-10.2 million tonnes of carbon-dioxide equivalents by 2030 and 2.9-10.6 million tonnes of carbon-dioxide equivalents by 2050. This corresponds to approximately 0.4-1.5% and 0.3-1.1% of the respective German greenhouse-gas reduction targets in 2030 and 2050.

JEL Classification: Q15; Q24; Q54

Keywords: Biochar, agriculture, Germany, climate change, soil carbon sequestration

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1) Introduction

The greenhouse-gas (GHG) concentrations of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) in the atmosphere have risen strongly since pre-industrial times.³ The driver of these concentrations is an increase in human-induced GHG emissions (Ciais et al. 2013). Currently, the global anthropogenic emissions of CO₂, CH₄ and N₂O account for about 50.1 petagrams (Pg) of carbon-dioxide equivalents (CO₂e) per year.⁴ Furthermore, Germany's total GHG emissions in 2011 amounted to 0.917 Pg CO₂e (i.e. 0.917 gigatonnes (Gt) CO₂e or 917 million tonnes (Mt) CO₂e) (UBA 2013: Table 1).⁵ As the main cause for the rise in the global mean surface temperature (Bindoff et al. 2013), it is widely recognized that the anthropogenic GHG concentrations need to be reduced drastically to combat climate change. Germany, for example, aims to cut its annual GHG emissions by 40% by 2020, 55% by 2030, 70% by 2040 and 80-95% by 2050 below the 1990 level (BMW and BMU 2010). Based on its total 1990 GHG emissions of about 1,251 Mt CO₂e (UBA 2013: Table 1), this would amount to an annual reduction of 688 Mt CO₂e by 2030 and at least 1,001 Mt CO₂e by 2050.

Basically, there are two ways to decrease atmospheric GHG concentrations – either by reducing GHG emissions into the atmosphere (climate-change mitigation) or by removing GHGs from the atmosphere (carbon-dioxide removal or carbon sequestration) (Rickels et al. 2011; Royal Society 2009; UNFCCC 1998).^{6, 7} Measures to reduce atmospheric GHG emissions range from energy efficiency and the replacement of fossil fuels by renewable energies to the capture of GHG emissions from industrial sites or power plants and their subsequent storage in the deep ocean or in geological formations – so-called carbon capture and storage (CCS) (Keith 2000). In turn, potential measures to actively remove GHGs from the atmosphere include, for example, afforestation, ocean iron fertilization or enhanced weathering (Rickels et al. 2011; Royal Society 2009). Likewise, the restoration of wetlands or the adoption of recommended agricultural practices, such as no-till farming, cover crops and crop rotation, are further measures to enhance carbon sequestration in natural sinks (Lal 2008). In addition, the incorporation of biochar into agricultural soils is increasingly discussed as an alternative and promising strategy for carbon-dioxide removal – a strategy that not only sequesters carbon in soils but at the same time might improve soil quality (Lehmann et al. 2006; Lehmann 2007a; Sohi 2012).

³ Ciais et al. (2013) report a 40% increase in atmospheric CO₂ concentrations from 1750 to 2011, with corresponding increases in CH₄ and N₂O by 150% and 20%, respectively.

⁴ This value equals 13.7 Pg carbon (C) equivalents per year (1 tonne of C = 3.667 tonnes of CO₂) and has been derived from the annual anthropogenic emissions reported in Ciais et al. (2013): carbon emissions from fossil-fuel combustion and cement production of 9.5 Pg C (2011), net CO₂ emissions from land-use change of 0.9 Pg C (2000-2010), CH₄ emissions of 0.354 Pg CH₄ (2011), and N₂O emissions of 0.0067 Pg N₂O-N (2011). N₂O = N₂O-N · 44/28 (De Klein et al. 2006). CH₄ (N₂O) emissions were transformed into CO₂e by multiplying them by their respective 100-year global warming potentials (GWPs) of 25 (298) given in Forster et al. (2007).

⁵ Excluding net CO₂ emissions from land use, land-use change and forestry (LULUCF). The share of CO₂ in the total GHG emissions was 87.1%, while N₂O and CH₄ contributed 6.2% and 5.3%, respectively (UBA 2013: Table 2). Note that UBA (2013) uses the 100-year GWPs of 21 for CH₄ and 310 for N₂O. Moreover, 1 Pg = 1 Gt = 1,000 Mt.

⁶ A further option to address climate change is radiation management, which is directly targeted at changing the global mean surface temperature by altering the incoming solar radiation or the outgoing thermal radiation (Rickels et al. 2011; Royal Society 2009). Leaving the atmospheric GHG concentration largely unaffected, it cures the symptoms of climate change (global warming), but not its cause (Rickels et al. 2011; Royal Society 2009). Together with (large-scale) carbon-dioxide removal, it belongs to so-called geo- or climate engineering.

⁷ The usage of 'climate-change mitigation' is not unambiguous. While it is often narrowly defined to refer to emissions reduction (e.g., Royal Society 2009), it could also be used more generally and include carbon sequestration (e.g., UNFCCC 1998). Unless otherwise indicated, we will follow its more general definition.

In light of the debate about biochar's role in fighting global warming, the aim of this paper is to assess the contribution biochar could make to achieve Germany's ambitious GHG reduction targets. Covering the GHGs CO₂, CH₄ and N₂O and considering slow-pyrolysis biochars from a wide variety of feedstocks, we provide estimates of the technical GHG mitigation potentials of biochar soil incorporation in Germany for a range of different scenarios in 2015, 2030 and 2050 as measured against conventional feedstock management.⁸

Biochar refers to carbonized biomass. It can be obtained from any feedstock, like wood, straw, other crop residues, green waste, sewage sludge, animal manure or digestates. More precisely, biochar is a carbon-rich solid produced by the thermochemical conversion of biomass, most commonly in a process known as pyrolysis. During pyrolysis, the biomass is heated in the (near) absence of oxygen. In this way, the organic material is incompletely combusted and decomposed into gaseous, liquid and solid substances, a unit of the solid – biochar – having a higher content of carbon than a unit of the original feedstock (Libra et al. 2011).⁹ Pyrolysis can be carried out at different reaction times and temperatures (e.g., slow and fast pyrolysis) and with the help of a variety of production technologies.¹⁰ In a broad sense, biochar refers to any type of carbonized biomass. A well-known example includes charcoal produced from wood and used for cooking and heating or for industrial processes. Under a more narrow definition, however, the term biochar is only applied when the carbonized biomass is used as a soil amendment intended to store carbon and improve soil quality (Lehmann and Joseph 2009).¹¹

Biochar is characterized by favorable properties, most notably by high carbon stability and a high nutrient-retention capacity (Lehmann 2007a).¹² That is, biochar carbon is more resistant to chemical and biological decay and, thus, degradation into CO₂ than the carbon in other organic matter, such as the original biomass (e.g., Lehmann et al. 2009; Baldock and Smernik 2002). Likewise, the capacity of biochar to hold nutrients, such as nitrogen (N), phosphorus (P) and potassium (K), also exceeds that of other soil organic matter (Lehmann 2007a). The combination of these properties renders biochar a candidate option for both carbon sequestration and soil improvement (e.g., Lehmann 2007a).¹³

Biochar's potential use for soil improvement is highlighted by a prominent example. It has been found that biochar was a key ingredient to the formation of the fertile dark earths located in small spots throughout the Amazon Basin, the so-called *Terra Preta (do Indio)* or Amazonian Dark Earth. While the *Terra Preta* soils date back to human activity in pre-Columbian times, today they are still characterized by a higher amount of soil organic carbon (SOC), higher nutrient levels and a better nutrient-retention capacity than the surrounding soils (oxisols) (e.g., Glaser et al. 2001). In addition to human and animal excrement, human and mammal bones, fish bones and turtle backs, *Terra Preta* contains a high share of biochar,

⁸ The GHG mitigation potentials will serve as the basis for an economic assessment of biochar to be provided in a subsequent study, leading to so-called marginal abatement cost curves for biochar.

⁹ (Bio-)Char is a form of black or elemental carbon (Hammes et al. 2007). As a residue of vegetation fires (under oxygen-limited conditions), black carbon is wide-spread. For example, it can be found in significant amounts in soils and sediments (e.g., Schmidt and Noack 2000; Masiello and Druffel 1998) and plays an important role in the global carbon cycle (Kuhlbusch 1998). Usually, however, 'biochar' does not refer to the carbonized residues from natural or anthropogenic fires, but to biomass that is intentionally pyrolyzed (Schmidt et al. 2011).

¹⁰ Production technologies range from small-scale traditional kilns (e.g., pit kilns or mound kilns) to advanced large-scale pyrolysis units (e.g., drum and screw pyrolysers or rotary kilns) (Brown 2009).

¹¹ In this paper, the term biochar is used in its most general meaning to allow for a sufficient degree of flexibility.

¹² Biochar might also improve the water-holding capacity of soils (e.g., Basso et al. 2013; Novak et al. 2009).

¹³ In addition to its potential use in agriculture as a soil amendment and carbon sink, biochar can also serve as a feed supplement in livestock breeding or be applied in a variety of industrial processes, for example, as reducing agent in metallurgy, insulating material for house building, and raw material for carbon fibre and plastic. Most importantly, biochar can also be used as an energy source, for example, co-firing it in conventional power plants.

and it is the biochar that is primarily associated with the high stability and long-term fertility of the *Terra Preta* soils (Glaser et al. 2001).¹⁴

Ameliorating soil quality in such a sustainable way, biochar might also play a central role for increasing agricultural productivity in the future. This is of particular importance since the agricultural sector faces numerous challenges that threaten global food security, such as a rising demand for food from a growing world population and changing diets in emerging countries, the expansion of energy crops, as well as climate change. Thereby, soil quality is becoming an ever greater constraint. In Europe, for example, challenges include soil sealing, contamination, erosion and organic-carbon loss (Jones et al. 2012).

Beyond its agricultural role, the stability of biochar makes it a promising carbon sink. That is, when adding biochar to soils, it might be a means to sequester atmospheric carbon for the medium- to long-term and, thus, help to mitigate climate change (Lehmann 2007a, 2007b).¹⁵ Very generally, the typical share of biomass carbon that can be recovered in biochar from slow pyrolysis is about 50% (Lehmann et al. 2006). Thereof, up to 80% might be stable in the long-term when applied to soils (Lehmann 2007b). Thus, when compared to the raw biomass – where the carbon taken up via photosynthesis would be released during the lifetime of a plant, either due to decay or combustion –, Lehmann (2007b) calculates that up to 20% of the biomass carbon could be possibly removed from the atmosphere if the biomass is instead turned into biochar.¹⁶

In addition to the direct carbon sequestration by stabilizing the biomass carbon in biochar and storing it in soils, biochar might also involve further indirect channels of carbon sequestration and aspects of climate-change mitigation. In particular, the favorable nutrient-holding capacity of biochar and complex interactions taking place in biochar-amended soils might result in increased carbon sequestration due to better plant growth and increases in non-biochar SOC as well as potential reductions in N₂O and CH₄ emissions from soils (e.g., Gaunt and Cowie 2009). Furthermore, reductions in emissions of N₂O and CH₄ could also result from potential fertilizer savings following biochar additions to soil (e.g., Gaunt and Cowie 2009). Moreover, the gases and liquids from pyrolysis obtained as by-products of biochar formation can be used as renewable energy sources and, thus, offset emissions from fossil fuels (e.g., Lehmann 2007a).¹⁷

Despite the emerging knowledge about biochar carbon sequestration and its potential role in fighting climate change, however, assessments of the GHG mitigation potentials of biochar are still rare. A prominent study for the global mitigation potential of biochar has been provided by Woolf et al. (2010a). Including both direct and indirect channels of carbon sequestration due to biochar soil incorporation as well as emissions reductions through the substitution of fossil fuels by the pyrolysis by-products, they arrive at an annual global net GHG sequestration-mitigation potential of 1.0-1.8 Pg C equivalents (equal to 3.7-6.6 Pg CO₂e) by 2050.¹⁸ Evaluated against the current global GHG emissions of 13.7 Pg C equivalents per year, as stated above, the contribution of biochar towards climate-change mitigation would be considerable, amounting to 7-13%. What needs to be taken into account, however, is that these values reflect a range of technical biomass potentials for biochar and do

¹⁴ The nutrients seem to have been introduced mainly by the just-mentioned organic wastes (Glaser 2007).

¹⁵ For a discussion about the time scales over which biochar is considered stable, see Section 4.1.

¹⁶ Note that this calculation takes into account that half of the carbon initially taken up via photosynthesis is released via respiration, leaving the remaining half of carbon captured in the biomass as the basis for the further computations (see Lehmann 2007b).

¹⁷ However, biochar will also lead to additional GHG emissions from biochar production, biomass and biochar transportation or biochar soil addition (Woolf et al. 2010a). These have to be balanced against any emissions savings or GHG removals.

¹⁸ Note that Woolf et al. (2010a) work with 100-year GWPs of 23 for CH₄ and 296 for N₂O.

not consider any social or economic obstacles towards implementing the biochar strategy (see Woolf et al. 2010a).

GHG mitigation potentials are, furthermore, touched upon in the economic assessments of biochar provided by Pratt and Moran (2010) – also with a global focus – and Shackley et al. (2011) for the United Kingdom (UK). Covering residue biomass from agriculture and forestry transformed in large-scale slow- and fast-pyrolysis plants in developed regions and biomass resources collected for stoves in rural areas transformed in small-scale slow-pyrolysis projects in developing regions, Pratt and Moran (2010) find that biochar stove and kiln projects in developing regions tend to abate more GHGs than pyrolysis-plant scenarios in developed regions. Shackley et al. (2011), in turn, focus on a variety of slow-pyrolysis biochar scenarios in the UK. Including the provision of renewable energy by the pyrolysis by-products, but abstracting from agricultural benefits of biochar soil incorporation, they find that an annual abatement of 6 Mt CO_{2e} could be economically viable.

Other studies (e.g., Hammond et al. 2011; Roberts et al. 2010; Gaunt and Cowie 2009) analyze the GHG emissions that can be avoided per tonne (t) of biomass turned into biochar, however, without providing an estimate of the biomass potentials that could be available for biochar production. For slow-pyrolysis biochar from a variety of woody and straw feedstocks and *miscanthus*, Hammond et al. (2011) have calculated net avoided GHG emissions due to biochar soil incorporation (including agricultural benefits) and energy generation from the pyrolysis by-products in the UK in the range of 0.7-1.3 t CO_{2e} per oven-dry tonne of feedstock. A similar study by Roberts et al. (2010) has focused on slow-pyrolysis biochar from corn stover, switchgrass and yard waste in the United States (US). For yard waste diverted from composting, for example, they have derived net avoided GHG emissions of 0.885 t CO_{2e} per dry tonne of feedstock. Likewise for slow-pyrolysis biochar in the US (without agricultural benefits), Gaunt and Cowie (2009) have found that 0.9-1.06 t CO_{2e} can be avoided per dry tonne of wheat straw that would otherwise decompose in the field, 1.04-1.13 t CO_{2e} per dry tonne of cattle manure usually stored and spread on land, and 1.09-3.80 t CO_{2e} per dry tonne of green waste normally composted or disposed of in landfill.

The limited amount of studies evaluating the GHG mitigation potentials of biochar combined with the promising global mitigation potential of biochar calculated by Woolf et al. (2010a) call for further, spatially disaggregated assessments. While estimates of the global GHG mitigation potentials of biochar provide important information about the possible climate impact of biochar when implemented on a large scale, they necessarily rely on very general assumptions and abstract from regional peculiarities. In contrast, being better able to reflect location-specific characteristics, more detailed studies on the regional or country level will provide more precision and, thus, greatly improve our understanding of the possible magnitudes of GHG mitigation with biochar.

To the best of our knowledge, we are the first to provide a comprehensive analysis of the GHG mitigation potentials of biochar soil deployment in Germany. Having a special focus on the current and likely future conditions prevailing in the country, not least concerning the availability of biomass for biochar production, we develop a wide range of slow-pyrolysis biochar options and scenarios for 2015, 2030 and 2050. Thereby, the biochar options are differentiated by the type of feedstocks considered relevant for biochar production in Germany – largely biomass residues, including, for example, cereal straw, forestry residues, certain types of wood and green waste, sewage sludge, animal manures, digestates, as well as sugar-beet leaf and potato haulm. Moreover, they account for feedstock-specific biochar yields, carbon contents and other biochar properties from an extensive literature survey. Different biochar scenarios, in turn, are constructed for the biomass potentials for each feedstock available for biochar or the scales of the production technology. For each scenario, we calculate the technical GHG mitigation potentials of the various biochar options, i.e. the

amount of GHG emissions that can be removed or avoided compared to a business-as-usual scenario. Thereby, the paper not only takes into account carbon sequestration through biochar soil incorporation, but also focuses on aspects of climate-change mitigation, in particular on emissions reductions associated with the provision of renewable energy by the pyrolysis by-products. Due to the greater uncertainties behind the effects of biochar on plant growth, non-biochar SOC and other soil processes, however, we abstract from any agricultural benefits and the associated changes in emissions.

Our analysis reveals that biochar soil incorporation combined with energy provision from the pyrolysis by-products allows for an annual technical GHG mitigation potential in Germany in the range of 2.8-10.2 Mt CO₂e by 2030 and 2.9-10.6 Mt CO₂e by 2050, where the wide range is mainly due to differing assumptions about the amount of biomass potentially available for biochar. This corresponds to approximately 0.4-1.5% and 0.3-1.1% of the respective German GHG reduction targets in 2030 and 2050. Thereby, forestry residues are associated with the greatest GHG mitigation potentials of biochar, followed by cereal straw, green waste from extensive grassland, solid cattle manure and some other solid biomass residues. In terms of the net GHG emissions that can be avoided per tonne of feedstock, on a dry-mass (DM) base, biochar from biomass with a low water content (e.g., cereal straw) appears superior to biochar from wet feedstocks (e.g., solid cattle manure). Some feedstocks with very high water contents – liquid cattle and swine manure, sugar-beet leaf and potato haulm, sewage sludge, and digestates – are even associated with a negative GHG mitigation balance due to the high amount of energy required to dry the feedstocks and are, thus, considered unsuitable for slow-pyrolysis-biochar carbon sequestration. In many cases, a negative GHG mitigation balance is also obtained for industrial wood waste and short-rotation coppice, the feedstocks that are assumed to be directly combusted in the baseline scenario. Besides the type of biomass and the choice of the baseline scenario, the net avoided GHG emissions are strongly influenced by the type of fossil fuel considered and by whether process heat is recovered during pyrolysis. In contrast, the size of the pyrolysis plants and, thus, the transport distances for biomass and biochar play only a minor role.

The remainder of the paper is organized as follows: In Section 2, we present our methodology. Section 3 contains a collection of general assumptions used in the analysis, while Section 4 provides the detailed calculations concerning the net GHG emissions that can be avoided per tonne of dry-matter feedstock turned into biochar. Section 5 repeats the analysis for a revised set of feedstocks and assumptions. The associated technical GHG mitigation potentials of biochar can be found in Section 6. Finally, we conclude.

2) Methodology

The technical GHG mitigation potentials of biochar deployment in soils in Germany are derived for a variety of biochar options and scenarios for the years 2015, 2030 and 2050, covering the GHGs CO₂, CH₄ and N₂O. Thereby, the term *technical* refers to the GHG mitigation potentials that are obtained when certain technological restrictions are applied to the maximally possible – *theoretical* – potentials (i.e. those that are only limited by laws of nature), without taking into account any economic considerations – which, in turn, would lead to the so-called *economic* potentials (cp. Slade et al. 2011).

The biochar options are differentiated by the types of feedstock the biochar is made from, e.g., cereal straw, forestry residues, solid cattle manure. For each biochar option, the technical GHG mitigation potential is derived against the business-as-usual or baseline scenario of no biochar production and soil addition, referring to the respective conventional feedstock management, i.e. the assumed use of the given feedstock would it not be turned into

biochar. Thus, the GHG mitigation potential of a biochar option in a specific year refers to the difference in the GHG emissions associated with the biochar option and those from conventional feedstock management (cp. Gaunt and Cowie 2009).

In addition to the type of feedstock and the baseline scenario, the technical GHG mitigation potential of biochar crucially hinges on a wide set of assumptions, such as concerning the availability of biomass for biochar conversion, the biochar carbon stability or the energy recovery from the pyrolysis by-products. Thereby, the choice of assumptions has been guided by our focus on biochar carbon sequestration in soils. An overview of the underlying framework is given in Figure 1.¹⁹

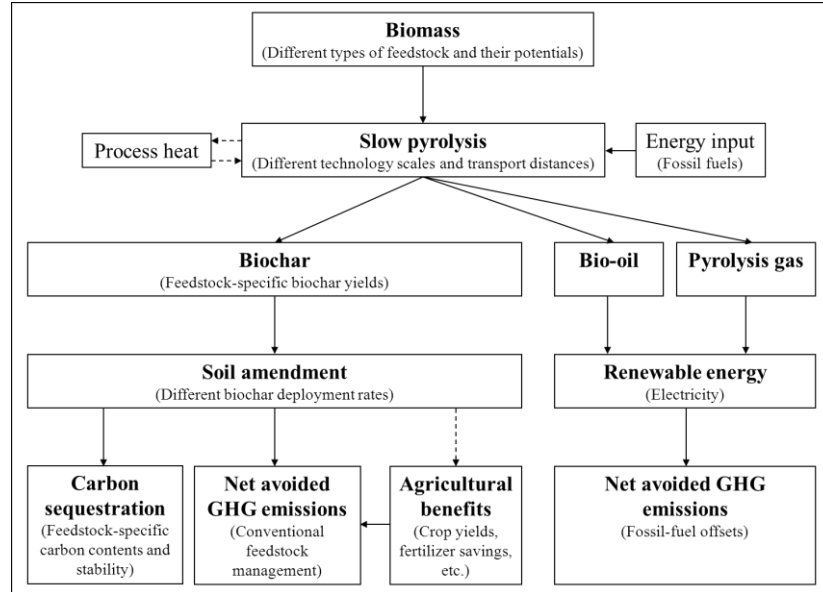


Figure 1: Framework of the analysis

Starting on top of Figure 1, the amount of biomass that could be available for biochar production in Germany is not known. For this reason, we construct six different biomass scenarios, largely focusing on biomass residues and abstracting from any biomass imports, where the biomass scenarios are derived from technical biomass potentials for bioenergy generation obtained from the literature. To maximize the yields of stable biochar carbon, the biomass is transformed into biochar using the slow-pyrolysis process (cp. Section 3.2). We base our calculations on modern pyrolysis plants at three different technology scales, i.e. different annual capacities of the pyrolysis plants. The technology scales, in turn, translate into different transport distances for biomass and biochar. Since biochar production creates new demand for energy, the energy inputs required to dry the feedstocks and to run the pyrolysis process are obtained from fossil fuels. During pyrolysis, process heat is recovered or not. The liquid (in particular, bio-oil) and gaseous by-products from biochar production are recovered and used energetically. To simplify the analysis, we aggregate the bio-oils and pyrolysis gases into a single product and assume that it is used for electricity generation.²⁰ In

¹⁹ Note that we do not provide a full life-cycle assessment, but focus on GHG emissions considered most relevant to the analysis. For the details, see Section 4.

²⁰ In addition to electricity generation, the bio-oils could be used as a source for heat or – after upgrading to bio-diesel – as a transport fuel (Slade et al. 2011). Depending on the conversion process used, the pyrolysis gases mainly consist of carbon monoxide (CO), CH₄, CO₂, hydrogen (H₂) and hydrocarbons (C_xH_y). In particular, the

this way, the by-products substitute for lignite, hard coal, or natural gas and offset the corresponding GHG emissions from fossil-fuel use.²¹ The biochar is incorporated into agricultural soils as a one-time supplement at three different deployment rates. Thereby, the role of biochar as a carbon sink depends on assumptions about its carbon content and stability. In addition to changes in GHG emissions from conventional feedstock management, biochar could also lead to agricultural benefits, such as improved crop yields or fertilizer savings (e.g., Gaunt and Cowie 2009). To date, however, the agricultural benefits of biochar and, thus, the related changes in GHG emissions remain highly uncertain, in particular in the long-term. For this reason, they are not included in our analysis.

Further assumptions refer to the way in which biomass and biochar are transported, stored, and otherwise handled as well as the means by which biochar is incorporated into soils. Throughout the analysis, we consider feedstock-specific characteristics, in particular concerning biochar yields as well as biochar and feedstock carbon, ash and water contents. Moreover, we assume that full-scale biochar production starts in 2015. Biochar is incorporated into soil in the year of its production. No biochar exports take place.²²

Abstracting from agricultural benefits of biochar addition to soils allows us to work with an average soil quality before biochar is applied. This means that the biochar options are independent of each other. Thus, we calculate so-called stand-alone mitigation measures, where the effectiveness of one biochar option is not influenced by interactions with other biochar measures (cp. Moran et al. 2011).²³

3) General Assumptions

In this section, we derive the biomass potentials that could be available for biochar production in Germany over the 2015-2050 period. Moreover, we present the feedstock-specific biochar yields and properties used in our analysis, the possible scales and corresponding number of slow-pyrolysis plants necessary to convert the potentially available biomass into biochar, the acreage for biochar soil application and the biochar deployment rates, as well as the feedstock-specific baseline scenarios.

3.1) Biomass Potentials

The biomass potentials that could be available for wide-spread biochar production in Germany over the next decades have not yet been established. Following the procedure applied by Shackley et al. (2011), we derive the type and amount of feedstocks that could be

valuable synthesis gas (or syngas), a mixture of CO and H₂, can be used for heat and power generation or be transformed into transport fuels (Slade et al. 2011). In practice, the precise application is dependent on the quality of the pyrolysis by-product (Mahinpey et al. 2009).

²¹ An alternative pathway to climate-change mitigation not analyzed in this study would be to focus on the production of bio-oil and pyrolysis gas for renewable energy generation, where biochar would be a by-product that could be used for soil carbon sequestration or as an additional source of energy.

²² The analysis abstracts from any other environmental impacts, such as direct and indirect effects of biochar on (reduced) water pollution. Likewise, changes in the longer-term mitigation potential of biochar due to the possible impact of climate change itself are beyond the scope of this study.

²³ Accounting for different pre-biochar soil qualities and given that both the type of crop grown on a certain land and its growth performance depend on soil quality, the agricultural impact of a given biochar would depend on the type of soil it is applied to and, thus, on the previously implemented biochar options – if it is assumed that biochar is added to the lowest-quality soils first and then successively to better soils.

used for biochar production from the biomass potentials for bioenergy production. That is, in a first step, the German biomass potentials for bioenergy production are obtained. They refer to the so-called technical potentials, which are the biomass potentials that are available after accounting for ecological, land-area, agro-technological or topographic constraints, i.e. after deducting land for food, housing or environmental purposes (Slade et al. 2011). In a second step, the biomass potentials for biochar production are derived as shares of the technical biomass potentials for bioenergy. To deal with possible rivalries between the energetic use of biomass and biochar production, a number of scenarios are derived for the technical biomass potentials for biochar production.²⁴

Biomass potentials for bioenergy production. Regarding the technical biomass potentials for bioenergy production, this paper largely focuses on biomass residues. It includes both biomass residues that can be used as a solid fuel (particularly, cereal straw, forestry residues, open-country biomass residues, industrial wood waste, wood in municipal solid waste, certain types of green waste, and short-rotation coppice)²⁵ and those that can be anaerobically digested (in particular, sewage sludge, solid cattle, swine and poultry manure, liquid cattle and swine manure, sugar-beet leaf and potato haulm, commercial and industrial waste, and organic municipal solid waste). For digestable feedstocks, the biomass potentials are given for both the initial feedstocks and the corresponding digestates. The inclusion of digestates allows us to construct scenarios where biochar production redirects less biomass from bioenergy production than will be the case if the initial feedstocks are used for biochar. As far as energy crops are concerned, we restrict our attention to the digestates obtained from the crops used for biogas production. The reason is that we assume that energy crops are cultivated with the primary purpose of energy production.²⁶

Biomass residues. The technical potential for bioenergy production from biomass residues has been mainly taken from Nitsch et al. (2004), in the version of their “*NaturschutzPlus*” (*nature conservation plus*) potential, with some updates for current developments. This biomass potential respects diverse environmental aspects, such as the expansion of organic farming, nature conservation, and water and soil protection (Nitsch et al. 2004). It is used for this study because it covers a wide range of feedstocks and spans until 2050. Moreover, it has been established as one of the bases for the German long-term scenarios for renewable energies (see Nitsch et al. 2012).²⁷ The study by Nitsch et al. (2004), in turn, is an extended version of the “*Umwelt*” (*environment*) scenario of Fritsche et al. (2004a). In other words, the biomass potentials obtained by Fritsche et al. (2004a, “*Umwelt*” scenario) form part of Nitsch et al. (2004, “*NaturschutzPlus*” scenario). While Fritsche et al. (2004a) focus on the time period up to 2030, Nitsch et al. (2004) prolong the potentials until 2050. Moreover, Nitsch et al. (2004, “*NaturschutzPlus*” scenario) consider future environmental requirements in greater detail. Both studies give priority to the material use of biomass residues and the use of land for food production. Furthermore, they cover quantitatively important feedstocks only.

²⁴ Note that, by definition, possible competition for land used for food and feed and the production of biomass for material use has already been accounted for in the biomass potentials for bioenergy.

²⁵ Short-rotation coppice – cultivated on some dedicated land area (see below) – is the only energy crop we consider. For the ease of exposition, it is included under solid biomass residues.

²⁶ Although biomass for energy use is currently imported and is likely to be imported in the future (BMELV and BMU 2010), we focus exclusively on the biomass potentials within German borders to simplify the analysis. Moreover, as Nitsch et al. (2012) put it, extended contributions of imported biomass seem unlikely in the long-term given the limited global sustainable biomass potential and the likely increase in the world-wide biomass use to combat climate change.

²⁷ The long-term scenarios are among the studies that form the data base for the German government’s energy reform. The recent version of the long-term scenarios is provided by Nitsch et al. (2012).

Table 1: Potential of Biomass Residues for Bioenergy, Germany, 2015-2050

Feedstocks	Dry mass**				
	2015*	2020	2030	2040	2050
	kt _{DM} /a				
Cereal straw ¹	3,035	3,151	2,971	3,081	3,081
Forestry residues ²	8,450	8,913	9,534	9,902	10,300
Open-country biomass residues ¹	1,264	1,264	1,264	1,264	1,264
Industrial wood waste ¹	3,098	3,098	3,098	3,098	3,098
Wood in municipal solid waste ¹	1,294	1,269	1,225	1,250	1,250
Green waste: Compensation areas ¹	0	570	570	570	570
Biomass: Habitat-connectivity areas ¹	0	459	1,100	1,100	1,100
Green waste: Extensive grassland ¹	0	710	1,630	1,630	1,630
Short-rotation coppice: Erosion areas ¹	0	0	5,500	5,500	5,500
Solid biomass residues	17,141	19,434	26,892	27,395	27,793
Sewage sludge ³	819	921	965	965	965
Solid cattle manure ³	4,776	4,845	4,753	4,837	4,837
Solid swine manure ³	1,322	1,329	1,276	1,296	1,296
Solid poultry manure ³	685	757	814	814	814
Liquid cattle and swine manure ³	9,059	9,175	8,967	9,123	9,123
Sugar-beet leaf and potato haulm ³	902	902	884	884	884
Commercial and industrial waste ³	595	595	595	595	595
Organic municipal solid waste ³	1,913	2,197	2,296	2,469	2,592
Digestible biomass residues	20,071	20,721	20,550	20,983	21,106
TOTAL	37,212	40,155	47,442	48,378	48,899

Sources: See Tables A.1 and A.2 in Teichmann (2014).

Notes: DM = dry mass. a = year. kt = kiloton. * = Values originally referring to 2010. ** = Except for some modifications in 2015 and 2020 to account for current developments (see comment (*) in Table A.1), the patterns in the time series derive entirely from Fritsche et al. (2004a, "Umwelt" scenario) and Nitsch et al. (2004, "NaturschutzPlus" scenario). For cereal straw, for example, the pattern originates from the underlying values in petajoule per annum (PJ/a) used to derive the dry-mass values (see Table A.1). While the entire 2010-2050 time series for cereal straw (in PJ/a) is used in Nitsch et al. (2004), the 2010-2030 data have been contributed by Fritsche et al. (2004a, "Umwelt" scenario) and the 2040-2050 values refer to an extension of these data by Nitsch et al. (2004, "NaturschutzPlus" scenario). In particular, the 2010-2030 potentials of cereal straw are derived from the so-called HEKTOR model (see Fritsche et al. 2004a). Among others, Fritsche et al. (2004a, "Umwelt" scenario) assume that the share of organic farming rises until 2030 and, thus, leads to a greater demand for straw in animal husbandry and a correspondingly lower availability of cereal straw for energy generation. Nitsch et al. (2004), however, do not provide an explanation for the particular choice of the 2040-2050 potentials for cereal straw. For an explanation of the time-series patterns of the biomass potentials of the other feedstocks, refer to Fritsche et al. (2004a, "Umwelt" scenario) and Nitsch et al. (2004, "NaturschutzPlus" scenario). For a general discussion of the biomass potentials obtained by Fritsche et al. (2004a, "Umwelt" scenario) and Nitsch et al. (2004, "NaturschutzPlus" scenario), see Section A.2 in Teichmann (2014).

- 1) Cereal straw = straw from wheat, rye and other cereals. Open-country biomass residues = woody biomass and green waste from trimming of shrubberies and reeds. Industrial wood waste = wood waste from sawmills, the wood material industry and the forest and furniture industry. Wood in municipal solid waste = woody components of municipal garden and park waste. Green waste from compensation areas = herbaceous biomass. Biomass from habitat-connectivity areas = woody and herbaceous biomass. Green waste from extensive grassland = woody and herbaceous biomass. Short-rotation coppice = poplar and willow. For the detailed feedstock descriptions, see Table A.1.
- 2) Forestry residues = forestry residues (i.e. logging residues and smallwood from oak, beech, spruce and pine) and additional forestry residues from historical-forest formation (see Table A.1).
- 3) Sewage sludge = uncontaminated municipal and industrial sewage sludge. Commercial and industrial waste = waste from beer production, fruit and wine press houses, distilleries, the dairy-processing industry and sugar manufacture. Organic municipal solid waste = biowaste from the organic-waste collection bin, kitchen and garden waste, non-woody components of municipal garden and park waste. For the detailed feedstock descriptions, see Table A.2.

Since we are concerned with biochar, however, not the entire energetic biomass potential from Nitsch et al. (2004) and Fritsche et al. (2004a) is used, but only the potential of those feedstocks relevant for biochar production. In particular, we do not include the sewage-sludge potential captured as solid fuel in Fritsche et al. (2004a) since this refers to sewage sludge that is highly contaminated and, thus, cannot legally be used as a soil amendment. For this reason, we do not consider it suitable for biochar production and attention is restricted to the type of

sewage sludge that is allowed to be composted after digestion. The same exclusion holds for scrap wood as it usually refers to treated wood, such as old furniture and demolition wood (Fritsche et al. 2004a).²⁸ Moreover, thinning material obtained from the formation of forest edges (Nitsch et al. 2004) is not covered since it affects only the period up to 2020 and is, thus, considered negligible. Likewise, carcass meal and animal fat are not included.

A summary of the dry-mass potentials for bioenergy generation of the biomass residues relevant for biochar production are given in Table 1. The potentials are measured in thousand tonnes of dry mass per annum (kt_{DM}/a). Their detailed derivations can be found in Tables A.1 and A.2 in the data documentation accompanying this study, i.e. Teichmann (2014).^{29, 30}

Table 2: Potential of Digestates from Digestable Biomass Residues, Germany, 2015-2050

Digestates derived from	Dry mass				
	2015*	2020	2030	2040	2050
	kt _{DM} /a				
Sewage sludge	522	576	595	595	595
Solid cattle manure	3,923	3,980	3,904	3,974	3,974
Solid swine manure	1,017	1,022	981	997	997
Solid poultry manure	452	499	537	537	537
Liquid cattle and swine manure	6,235	6,317	6,177	6,285	6,285
Sugar-beet leaf and potato haulm	489	490	482	482	482
Commercial and industrial waste	293	293	293	293	293
Organic municipal solid waste	1,160	1,332	1,392	1,497	1,572
Digestates (biomass residues)	14,091	14,509	14,361	14,660	14,735

Sources: See Table A.3 in Teichmann (2014). Notes: DM = dry mass. a = year. kt = kiloton. * = Values originally referring to 2010.

For the digestable biomass residues in Table 1, we additionally calculate the potential of the digestates that are obtained when the respective feedstocks are all anaerobically digested. That is, we assume that the entire potential of digestable biomass residues is first used for biogas production and, then, biochar is derived from the digestates. This alternative pathway is in line with so-called biomass cascading where the same feedstock is used sequentially for material and energetic purposes to increase its resource efficiency (e.g., Arnold et al. 2009). An overview of the potential of the digestates is given in Table 2, while the underlying calculations – based on the procedure given in Reinhold (2005) – can be found in Table A.3.

Energy crops. The potential of the digestates from energy crops is mainly derived from the current acreage of 0.9 million hectares (ha) devoted to crops for biogas production obtained from FNR (2012a) and the respective 2050 value of 1.0 million ha from Nitsch et al. (2012). As in Nitsch et al. (2012), the reference crop is corn. This is in good accordance with

²⁸ Apart from these exclusions, we assume that possible contaminations of biochar with heavy metals or organic pollutants are manageable and that any legal issues for the use of biochar as a soil amendment will be resolved. – So far, only charcoal from chemically untreated wood is allowed to be spread on fields (DüMV 2012: Table 7).

²⁹ Since the dry-mass values are rarely directly given in Nitsch et al. (2004) and Fritsche et al. (2004a), they had to be deducted from the published (primary) energy contents or acreages. Whenever available, the necessary data were taken from Nitsch et al. (2004) and Fritsche et al. (2004a) or the sources cited therein. In the other cases, third sources were used. In addition, the tables contain detailed explanations concerning the modifications made to account for current developments not yet covered by Nitsch et al. (2004) and Fritsche et al. (2004a). Furthermore, Section A.2 of Teichmann (2014) contains a general discussion of the biomass potentials obtained by Nitsch et al. (2004, “NaturschutzPlus” scenario) and Fritsche et al. (2004a, “Umwelt” scenario).

³⁰ All tables starting with ‘A.’ refer to Teichmann (2014).

current observations that corn accounts for nearly 90% of the acreage used for digestable energy crops (FNR 2012b). The acreage values for corn in between 2015 and 2050 have been interpolated with the help of additional information about the total acreage used for energy-crop cultivation.³¹ For the detailed calculation of the digestates from corn silage, see Tables A.4 and A.5. The respective summary is given in Table 3.

Table 3: Potential Digestates from Energy Crops, Germany, 2015-2050

Feedstocks	Dry mass				
	2015*	2020	2030	2040	2050
	kt _{DM} /a				
Corn-silage digestates	3,589	3,589	3,589	3,971	3,971
Digestates (energy crops)	3,589	3,589	3,589	3,971	3,971

Sources: See Tables A.4 and A.5 in Teichmann (2014).

Notes: DM = dry mass. a = year. kt = kiloton. * = Values originally referring to 2010.

Biomass potentials for biochar production. Following Shackley et al. (2011), we derive the biomass potentials for biochar production as a general percentage share off the above-described technical biomass potentials for bioenergy production, constructing a number of scenarios with varying shares of biomass for biochar.

Concerning the appropriate range of shares, two competing aspects have to be taken into account. On the one hand, the focus of this paper is on biochar deployment in soils as a means of carbon sequestration. This calls for high percentage shares in order to figure out whether biochar can make a significant contribution to GHG mitigation, at least under the most favorable circumstances. On the other hand, the biomass potential for biochar production is limited by the utilization of biomass for renewable energy. Already in 2010, biomass residues with a primary energy content of about 500 petajoule per annum (PJ/a) were used for energy production (Nitsch et al. 2012). In the future, the competition between biomass for energetic use and biomass for biochar production will likely increase due to the general limitation of the biomass potential (Nitsch et al. 2012) and the German government's objectives to raise bioenergy production. In particular, the national biomass action plan for Germany (BMELV and BMU 2010) explicitly refers to the 2020 volume of bioenergy production established by Nitsch (2008), namely 11% of the total primary energy consumption (1,309 PJ). Thereby, it is planned to increasingly use biomass residues (such as logging residues, green waste, liquid manure, straw and other organic waste) in addition to an envisaged rise in the production of wood (e.g., short-rotation coppice) on agricultural land (BMELV and BMU 2010).³²

Taking these limitations as given, we have chosen a total of six biomass scenarios, three for the case when the initial feedstocks of the digestable biomass residues are considered (in addition to the solid biomass residues and digestates from energy crops) and another three scenarios based on the associated digestates, i.e. when biogas production is prioritized for all digestable biomass residues.

³¹ The total energy-crop acreage assumed in this study largely reflects the "NaturschutzPlus" scenario given in Nitsch et al. (2004). Only for the years 2015 and 2020, it has been overwritten by the current total acreage devoted to energy crops given in FNR (2012a), which is higher than projected by Nitsch et al. (2004) when accounting for environmental aspects. As a consequence, some adjustments had to be made in the 2015 and 2020 potentials for the above-mentioned biomass residues in order to accommodate the higher use of acreage for energy crops by reducing the acreage available for nature conservation (see Table A.1).

³² Note, however, that it is under discussion to slow the increase in bioenergy generation (BMWi 2014).

Table 4: Percentage Shares of Biomass for Biochar, Germany, 2015-2050

Scenario	Solid biomass residues					Digestable biomass residues					Digestates (from digestable biomass residues and/or energy crops)				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	%					%					%				
<i>Max 1</i>	10	20	35	35	35	10	20	35	35	35	75	75	75	75	75
<i>Max 2</i>	20	30	45	45	45	-					75	75	75	75	75
<i>Med 1</i>	10	20	20	20	20	10	20	20	20	20	50	50	50	50	50
<i>Med 2</i>	20	30	30	30	30	-					50	50	50	50	50
<i>Min 1</i>	10	10	10	10	10	10	10	10	10	10	25	25	25	25	25
<i>Min 2</i>	20	20	20	20	20	-					25	25	25	25	25

Sources: Own assumptions, derived from the calculations in Table A.6 in Teichmann (2014). Note: - = not applicable.

Starting with the first set of scenarios, a maximum (*Max 1*), medium (*Med 1*) and minimum (*Min 1*) potential of biomass for biochar production is established. In the *Max 1* scenario, the upper limit of biomass for biochar in 2015 is given by the energetic potential of all the biomass residues in Nitsch et al. (2004, “NaturschutzPlus” scenario), adjusted for the same changes in acreage as described in Table A.1, minus the 500 PJ/a already used in 2010 (Nitsch et al. 2012). Regarding the 500 PJ/a as the minimum amount of biomass residues used for bioenergy production, the maximum potential of biomass residues for biochar for 2020-2050 is derived when holding these 500 PJ/a constant (see Table A.6). Further assuming that the residual biomass potential deductible from the energetic potential is spread evenly across all the solid and digestable biomass residues, about 13%, 20%, 35%, 36% and 37% of the total biomass residues can be used for biochar production in 2015, 2020, 2030, 2040 and 2050, respectively (Table A.6). Finally, translating these percentage shares into more accessible numbers, the *Max 1* scenario of 10%, 20% and 35% in 2015, 2020 and 2030-2050 is obtained (Table 4).³³ For the *Min 1* scenario, in contrast, we operate with the lowest share – 10% – throughout the decades, while we assume 10% in 2015 and 20% in 2020-2050 for the medium scenario *Med 1*. With these latter scenarios, we account for varying degrees of possible increases in bioenergy production. For the digestates from energy crops, in turn, we assume that a constant share of 75%, 50% and 25% can be used for biochar production in the *Max 1*, *Med 1* and *Min 1* scenarios, respectively. The shares change across the scenarios in order to reflect different intensities of competition for digestates to be used as fertilizer or as feedstock for composting.

Turning to the second set of scenarios, where all the digestable biomass residues are indeed anaerobically digested, the maximum biomass potential that remains beyond the 500 PJ/a to be used for energy production can be entirely allocated to the solid biomass residues. The corresponding biomass shares for biochar production are 18% (2015), 27% (2020), 44% (2030), 46% (2040) and 47% (2050) (Table A.6). For the ease of exposition, these shares are

³³ Note that the *Max 1* scenario for 2020 respects the limit set by the 11% (1,309 PJ) of biomass to be used for energy production according to Nitsch (2008). Taking the total energetic biomass potential of biomass residues and energy crops of 1,399 PJ from Nitsch et al. (2012) – who have also based their calculations on Nitsch et al. (2004, “NaturschutzPlus” scenario) and are, thus, comparable to our study – and deducting the 1,309 PJ, leaves 90 PJ of the biomass potential for biochar. This corresponds well with the 91.3 PJ of biomass that we have channelled into biochar production (Table A.6). The 2020 *Max 1* biomass potential for biochar even undercuts the given limit when the 11% of biomass for bioenergy are recalculated based on more current data. Using the target to reduce the primary energy consumption in 2020 by 20% from its 2008 value (BMWi and BMU 2010) and the 2008 primary energy consumption of 14,380 PJ (Statistisches Bundesamt 2013a), only 1,265 PJ of biomass would be required for energy production.

approximated by 20% (2015), 30% (2020) and 45% (2030-2050) in the *Max 2* scenario (Table 4). Accounting for a possible increase in bioenergy production, the *Min 2* scenario uses only 20% of the solid biomass residues for biochar production and the *Med 2* scenario increases the share to 30% in the 2020-2050 period. For the digestates (including those from energy crops), we assume that a constant share of 75%, 50% and 25%, respectively, can be used for biochar production in the *Max 2*, *Med 2* and *Min 2* scenarios.

Compared to Shackley et al. (2011), who performed a similar analysis for the UK, our biomass shares for biochar production tend to be more conservative, at least for the solid biomass residues and the initial feedstocks of the digestable biomass residues. In particular, Shackley et al. (2011) differentiate between three scenarios, in which they basically assume that 100%, 75% and 25% of virgin biomass for bioenergy, i.e. feedstocks that are not chemically or biologically treated, and 75%, 50% and 0% of non-virgin biomass for bioenergy are available for biochar. Thus, for the digestates, our shares compare relatively well with those from Shackley et al. (2011) for non-virgin biomass.

Based on the biomass potentials of Tables 1-3 and on the percentage shares given in Table 4, the technical biomass potentials for biochar production for the various feedstocks are summarized in Tables 5 and 6. The total technical biomass potential for biochar in scenarios *Min 1* to *Max 1* ranges from 4,618-6,413 kt_{DM}/a in 2015, from 5,641-19,296 kt_{DM}/a in 2030 and from 5,883-20,093 kt_{DM}/a in 2050 (Table 5). For scenarios *Min 2* to *Max 2*, in turn, it amounts to 7,848-16,688 kt_{DM}/a in 2015, 9,866-25,564 kt_{DM}/a in 2030 and 10,235-26,536 kt_{DM}/a in 2050 (Table 6).

3.2) Biochar Yields and Properties

The biochar yields obtained from the various biomass feedstocks and the biochars' physical and chemical properties depend on both the conversion process applied to transform the biomass into biochar and the specific type of feedstock used (e.g., Cantrell et al. 2012; Libra et al. 2011; Amonette and Joseph 2009; Krull et al. 2009; Antal and Grønli 2003; Antal et al. 2000). For this reason, we derive process- and feedstock-specific biochar yields and properties for all the biomass types used in our analysis.

Conversion Process. In general, the conversion of biomass into biochar can be performed with the help of a variety of thermochemical processes, including pyrolysis, gasification and hydrothermal carbonization (HTC). While the biomass is heated in the absence of oxygen in the pyrolysis process, gasification makes use of some oxygen; HTC, in turn, is distinguished from pyrolysis and gasification (so-called dry pyrolysis processes) by the heating of the biomass in the presence of water and pressure (Libra et al. 2011).³⁴

Both the type of the conversion process and its specific reaction conditions, in particular the highest heating temperature and the solid- and vapor-phase residence times, determine the amount of biochar obtained (e.g., Libra et al. 2011).³⁵ As can be seen from Table 7, the typical amount of biochar decreases with an increase in the temperature from slow to fast pyrolysis to gasification, while the highest shares of biochar can be reached with HTC.

In addition to the biochar yields, the characteristics of the produced biochar (as well as of the resulting liquids and gases) also differ across the conversion processes and their reaction conditions (e.g., Anderson et al. 2013; Demirbaş 2001). For the dry pyrolysis

³⁴ Biochar that is produced during HTC is often called hydrochar or HTC char (e.g., Kammann et al. 2012).

³⁵ Further reaction conditions influencing biochar yields include, for example, the heating rate (e.g., Williams and Besler 1996), pressure (e.g., Mahinpey et al. 2009) or the use of catalysts (e.g., Nowakowski et al. 2007).

processes, for example, it holds that the higher the temperature – and, thus, the lower the biochar yield –, the higher the carbon content of the biochar (e.g., Mašek et al. 2013).³⁶

Table 7: Thermochemical Conversion Processes

		Reaction conditions		Product yields (by dry weight of initial biomass)		
		Temperature (°C)	Vapor residence time	Char (%)	Liquid (%)	Gas (%)
Dry Pyrolysis	Slow Pyrolysis	~400	h-week	35	30	35
	Intermediate Pyrolysis	~500	~10-20 s	20	50	30
	Fast Pyrolysis	~500	~1 s	12	75	13
	Gasification	~800	~10-20 s	10	5	85
Wet Pyrolysis	Hydrothermal Carbonization (HTC)	~180-250	~1-12 h*	50-80	5-20**	2-5

Source: Libra et al. (2011: Table 1). Notes: h = hour. s = second. * = Processing time. ** = Total organic carbon dissolved in process water.

Since the focus of this paper is on the use of biochar for soil carbon sequestration, we restrict our attention to slow-pyrolysis processes – as is common in the related literature (e.g., Shackley et al. 2011; Hammond et al. 2011; Woolf et al. 2010a; Gaunt and Cowie 2009). Despite the high char yields, we particularly refrain from HTC since the effects of hydrochar on soils are still largely unknown (e.g., Kammann et al. 2012). Moreover, hydrochar tends to be considerably less stable in soil than biochar obtained from dry pyrolysis processes (e.g., Kammann et al. 2012; Steinbeiss et al. 2009; Kuzyakov et al. 2009), rendering it less suitable for a carbon-sequestration strategy.³⁷ Among the dry pyrolysis processes, in turn, slow pyrolysis not only maximizes the biochar output (35% on average, see Table 7), but – more importantly – also the total amount of carbon that is transferred from the raw biomass into the biochar (e.g., Cantrell et al. 2012; Mašek et al. 2013). In other words, the share of the biomass carbon that is recovered in the biochar is maximized with slow pyrolysis, amounting to 50% on average (Lehmann et al. 2006; Table 8, column 16). Thus, slow pyrolysis gives the most advantageous starting point when the objective is carbon sequestration via biochar incorporation in soils.³⁸

Feedstock Type. In addition to the conversion process, the biochar yield and its carbon content is also determined by the type of biomass used. That is, for the given slow-pyrolysis technology, biochar yields and carbon contents will differ based on the specific feedstock characteristics. Most notably, these are the feedstocks' shares of cellulose, hemicelluloses and lignin, their contents of inorganic materials (such as metals), i.e. their ash contents, as well as their volatile-matter contents (e.g., Cantrell et al. 2012; Raveendran et al. 1995, 1996). Hemicelluloses, cellulose and lignin – the main biomass constituents – decompose at different temperatures. Raveendran et al. (1996), for example, report that hemicellulose decomposition predominates at 250-350°C, while cellulose decomposes mainly between 300-430°C and lignin decomposition ranges from 250-550°C. Moreover, pyrolysis of lignin tends to yield the highest amounts of char (45-50%) and that of cellulose the lowest (<15%), while

³⁶ This is due to greater releases of oxygen, hydrogen and nitrogen with rising temperature (Mašek et al. 2013).

³⁷ Steinbeiss et al. (2009) arrived at mean residence times (MRTs) of hydrochar of 4-29 years only, while Kuzyakov et al. (2009) derived MRTs of slow-pyrolysis biochars in the range of hundreds and thousands of years. The MRT is the average time that biochar is present (Lehmann et al. 2009).

³⁸ In contrast, fast pyrolysis is usually chosen when the focus is on bio-oil generation, and gasification when it is on syngas production (e.g., Anderson et al. 2013; Mohan et al. 2006).

hemicelluloses come in between with ca. 30% (Raveendran et al. 1996). Thus, the higher the lignin share of the biomass, the more biochar is produced (Mohan et al. 2006). Furthermore, the higher the biomass ash content, usually the higher the char yield (Raveendran et al. 1995; Cantrell et al. 2012) and, thus, the lower the carbon content of the biochar.^{39, 40} In particular, the presence of potassium (K) seems to catalyze biochar formation (Nowakowski et al. 2007). However, there might also exist important interaction effects between the ash content and the other biomass constituents which reverse these observations. For example, for biomass with a very high lignin content, the higher the content of certain ash elements, the lower the char yield (Raveendran et al. 1995). Finally, the higher the volatile-matter content of the biomass, the lower the yield of biochar (Cantrell et al. 2012).

Biochar Yields. The feedstock-specific slow-pyrolysis biochar yields used in our study can be found in Table 8 (column 6). Each biochar yield refers to the percentage of biochar obtained per unit mass of the initial feedstock, based on the dry weight of the feedstock.⁴¹ For each feedstock category, we have calculated the biochar yield as an average of corresponding biochar yields from suitable reference feedstocks obtained from an extended literature survey (Table A.7), in which we cover typical slow-pyrolysis processes ranging from peak temperatures of 350-700°C.⁴² The average pyrolysis temperatures for the different feedstocks obtained in this way range from ca. 420-570°C, or nearly 500°C in total (Table A.7). This temperature range seems to lead to a good compromise between biochar carbon stability and soil fertility since biochars produced at $\geq 500^\circ\text{C}$ tend to be chemically more resistant (Hammes et al. 2006),⁴³ while 400-550°C is a temperature range considered most suitable for soil fertility (Lehmann 2007a).⁴⁴

As shown in Table 8, the biochar yields for the solid biomass residues covered in our study range from 25-34% and those for the digestible biomass residues from 37-49%, while slow pyrolysis of the digestates tends to result in a biochar yield of 49%.⁴⁵

Based on the biochar yields from Table 8, the corresponding amounts of slow-pyrolysis biochar obtained from the biomass potentials of scenarios *Max 1* to *Min 1* are given in Table 9 and those of scenarios *Max 2* to *Min 2* in Table 10. The total biochar potential in the first set

³⁹ Biomass de-ashing prior to biochar production usually increases oil yields (e.g., Fahmi et al. 2007).

⁴⁰ For example, Hammes et al. (2006) found in experimental studies that slow-pyrolysis biochar derived from wood had a higher carbon content (68.2%) than grass biochar (58.6%) due to differences in the ash contents between wood (<0.1%) and grass (7.7%).

⁴¹ Note that we do not differentiate between biochar fresh weight and biochar dry weight due to the very low water contents of biochars. For further details, see comment §§§ in Table 8. Moreover, note comment §§ in Table 8 regarding missing information in some studies whether the char yields were truly based on feedstock dry weights and the corresponding interpretation of the char yields.

⁴² This is the best we can do given the current lack of knowledge concerning feedstock-specific carbon stability and soil impacts of biochar produced at different temperatures and other process conditions. Moreover, for comparability reasons, we focus on slow-pyrolysis processes conducted at atmospheric pressure (with some exceptions, see Table A.7), without ash removal from the initial biomass and without activation of the biochars. – Activation aims at increasing internal surface areas and porosity of chars and can be performed during or after biochar production (Downie et al. 2009). – Furthermore, we include results from both laboratory and pilot-scale pyrolysis plants, covering diverse pyrolysis technologies. Finally, we exclude biochar yields from thermogravimetric analyses since they differ systematically from pyrolysis results (Das et al. 2008); and, concerning the feedstock reference material, we stick to species relevant for Germany, at least Europe. For a more detailed discussion of the data, see Section A.3 in Teichmann (2014).

⁴³ Moreover, while Mašek et al. (2013) also find that carbon stability increases with pyrolysis temperature, they show that the yield of stable carbon tends to be temperature-independent, at least for some woody biochars.

⁴⁴ This assessment is based on the pH value, cation exchange capacity and surface area of biochar from wood (see Lehmann 2007a). Note that, although we abstract from agricultural benefits of biochar, we should not add biochar to soils that might be disadvantageous for soil fertility.

⁴⁵ If not stated otherwise, digestates refer to both digestates from energy crops and from biomass residues.

of scenarios ranges from 1,877-2,757 kt/a in 2015, from 2,168-7,368 kt/a in 2030 and from 2,267-7,693 kt/a in 2050 (Table 9). In the second set of scenarios, it amounts to 3,215-7,546 kt/a in 2015, 3,785-10,166 kt/a in 2030 and 3,933-10,567 kt/a in 2050 (Table 10).

Biochar Properties. Like the biochar yields, the feedstock-specific biochar properties used in this study (Table 8) have been calculated as averages over suitable reference feedstocks (Table A.7).⁴⁶ Generally, biochars derived from solid biomass residues tend to have higher carbon contents (63-82%) than those derived from digestible biomass residues (35-66%) and digestates (42%) (Table 8, column 11). The same holds for the fixed-carbon contents (column 9), with 65-69% for biochars from solid biomass residues, 24-48% for biochars from digestible biomass residues and 28% for biochar from digestates.⁴⁷ Moreover, biochars from solid biomass residues have lower ash (column 10) and N, P, K contents (columns 12-14) than the biochars in the latter two groups. In particular, the biochar ash contents range from 2.0-17.5% for solid biomass residues and from 17.6-43.7% for digestible biomass residues, while digestates have an ash content of 38.8%.

In greater detail, biochars from the woody biomass residues (i.e. forestry residues, industrial wood waste, wood in municipal solid waste, short-rotation coppice) tend to have higher carbon contents and lower ash and N contents than those from cereal straw and the remaining predominantly herbaceous solid biomass residues. Overall, sewage-sludge biochar seems to have the lowest carbon content (35%), while the highest ash contents (>40%) are reached by biochars from solid swine and poultry manure, liquid cattle and swine manure, and sewage sludge.⁴⁸

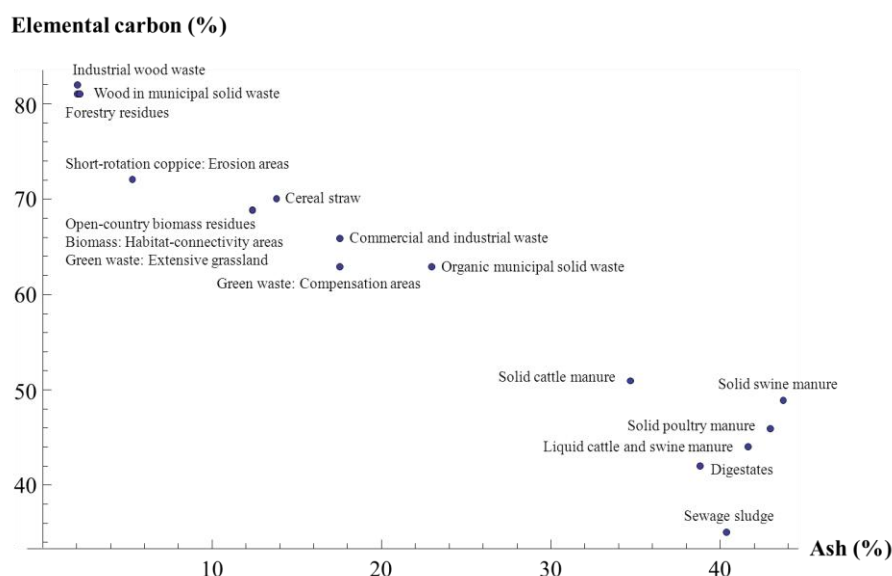


Figure 2: Biochar carbon and ash contents

Source: Table 8 (columns 10 and 11); without sugar-beet leaf and potato haulm.

Judged solely from the biochar carbon and ash contents, there seems to be a trade-off between the relative suitability of the biochars for carbon sequestration and soil fertility. In particular,

⁴⁶ Again, note that we do not differentiate between biochar fresh and dry weights (see Table 8, comment §§§).

⁴⁷ Fixed carbon refers to the mass residue remaining from a biomass, biochar or coal sample (on a dry base) after deducting its ash and volatile-matter contents, thus, not reflecting carbon in a strict sense (Enders et al. 2012b).

⁴⁸ The rankings compare well with those obtained from individual studies, such as Singh et al. (2010).

the high carbon contents of the biochars from solid biomass residues might render them more suitable for carbon sequestration, while their agricultural impact might be limited due to the low ash contents. The opposite might hold for biochars from the digestible biomass residues, which tend to be richer in ash and nutrients,⁴⁹ but have lower carbon contents. As illustrated in Figure 2, there is a nearly perfect inverse proportionality between the biochar carbon and ash contents. At the one extreme, there are the woody biochars with the highest carbon and lowest ash contents. At the other extreme, there are the biochars from the manures, the digestates and the sewage sludge with the lowest carbon and highest ash contents. In between, we find biochars from cereal straw, from the other predominantly herbaceous biomass residues as well as from commercial and industrial waste and organic municipal solid waste.

3.3) Slow-Pyrolysis Plants

Slow pyrolysis can be carried out with the help of a wide variety of production systems, ranging from small-scale traditional kilns (e.g., pit kilns, mound kilns, or brick, metal and concrete kilns) to advanced large-scale pyrolysis units, such as drum and screw pyrolysers or rotary kilns, constructed to process a continuous flow of feedstocks (Brown 2009). In our analysis, we refrain from the use of emission-intensive traditional kilns, but focus on modern low-emission biochar processing plants able to recover the resulting pyrolysis gases and liquids for energy production. Despite an increase in available technologies, however, such combined pyrolysis units are still scarce (Sohi 2012) and some technology parameters still heavily rest on assumptions (Mašek et al. 2013).

In this section, we present the details concerning the scale and number of pyrolysis units assumed for biochar production in Germany. Since the technological characteristics mainly concern energy requirements and outputs, they are covered in the next section on the net avoided GHG emissions per dry tonne of feedstock converted into biochar.

Scale of pyrolysis units. Concerning the optimal size of a pyrolysis plant, there is a trade-off between (i) scale effects and (ii) transport distances to the feedstock locations and farms for biochar application. While scale effects call for larger pyrolysis units, transport costs tend to increase with the transport distance and, thus, support smaller, decentralized pyrolysis units. Since it is beyond the scope of this paper to determine the optimal size distribution and location of pyrolysis plants, however, we illustrate this trade-off with the help of three potential pyrolysis-unit scales. Following the size distributions in Shackley et al. (2011: Table 2), we assume that the smallest pyrolysis unit has an annual capacity of 2,000 t of dry feedstock to be converted into biochar, the medium-scale unit one of 16,000 t and the large-scale unit one of 184,800 t. Thereby, the lower value of 2,000 t_{DM} feedstock/a compares well with the average size of biogas plants currently available in Germany.⁵⁰ Moreover, this smaller scale of pyrolysis units seems to be in line with the German government's objective to increase decentralized biomass utilization (BMELV and BMU 2010). The large-scale units, in contrast, reflect a more centralized system of biochar production.

Number of pyrolysis units. Since our analysis puts strong emphasis on the biomass potentials to evaluate the technical GHG mitigation potentials of biochar, we assume that an

⁴⁹ For example, see also Cantrell et al. (2012) for manure biochars.

⁵⁰ In 2011, the installed electrical capacity of the 7,215 biogas plants operating in Germany amounted to 2,904 megawatts (MW) (FNR 2012c: 34), i.e. an average of 400 kilowatts (kW) per plant. Based on the example presented in FNR (2012c: 45), which largely draws on corn silage and liquid cattle manure as inputs, this corresponds to approximately 10,900 t of fresh feedstock per annum, or an equivalent of ca. 2,000 t of dry feedstock if the dry-mass values from Table A.2 are applied.

appropriate capacity of pyrolysis units will be installed to turn all the potentially available biomass into biochar. For the same reason, we apply each of the possible pyrolysis-unit scales to all of the feedstocks and do not impose any *ex-ante* distribution of pyrolysis-unit scales between feedstocks. Based on the three established pyrolysis-unit scales and an assumed common load factor of 0.8,⁵¹ the required number of pyrolysis units in operation in each period for all the six biomass scenarios is illustrated in Table 11.

Table 11: Number of Pyrolysis Units in Operation, Germany, 2015-2050

Bio-mass sce-nario	Small-scale pyrolysis units (à 2,000 t _{DM} feedstock/a)					Medium-scale pyrolysis units (à 16,000 t _{DM} feedstock/a)					Large-scale pyrolysis units (à 184,800 t _{DM} feedstock/a)				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	units/a					units/a					units/a				
<i>Max 1</i>	4,008	6,702	12,060	12,444	12,558	501	838	1,508	1,556	1,570	43	73	131	135	136
<i>Med 1</i>	3,448	6,141	7,052	7,288	7,353	431	768	881	911	919	37	66	76	79	80
<i>Min 1</i>	2,886	3,071	3,526	3,644	3,677	361	384	441	456	460	31	33	38	39	40
<i>Max 2</i>	10,430	12,128	15,978	16,438	16,585	1,304	1,516	1,997	2,055	2,073	113	131	173	178	179
<i>Med 2</i>	7,668	9,299	10,652	10,959	11,057	958	1,162	1,331	1,370	1,382	83	101	115	119	120
<i>Min 2</i>	4,905	5,257	6,166	6,336	6,397	613	657	771	792	800	53	57	67	69	69

Sources: Own calculations, based on the biomass totals given in Tables 5 and 6 and a common load factor of 0.8 (values rounded).

Notes: DM = dry mass. a = year. t = tonne.

3.4) Soil Application of Biochar

Like other soil additives in agriculture, biochar is typically incorporated in the top 15-30 centimeters of soils. Although it has also been suggested to incorporate biochar deeper into the subsoil to increase its stability if the mere objective is carbon sequestration (Blackwell et al. 2009), we stick with the common topsoil incorporation. Thereby, we assume that biochar is, first, added to soils mechanically (see Section 4.4) and, then, following Hammond et al. (2011), incorporated during usual tillage, i.e. not causing any additional operations.

Furthermore, biochar can be added to soils at different rates and frequencies. As predominant in the literature, we focus on a one-off application of biochar to a given soil.⁵² That is, we assume that biochar is successively added to more and more land.⁵³ Typical biochar deployment rates in field trials range from 5-50 t of biochar per ha (e.g., Blackwell et al. 2009: Table 12.1). Since we abstract from any agricultural benefits and assume an average soil quality, the deployment rates in our study will only be relevant for the calculation of the land area treated with biochar. To evaluate whether the available acreage could be a constraint for biochar application, we use three biochar deployment rates, 10 t/ha, 25 t/ha and 50 t/ha.⁵⁴

Turning to the acreage for biochar application, we assume that biochar is added to arable land. The potential area of arable land available in Germany over the period 2015-2050 has been derived from Nitsch et al. (2004, “NaturschutzPlus” scenario) and Fritsche et al. (2004a, “Umwelt” scenario), with some updates from Statistisches Bundesamt (2013b). It

⁵¹ The load factor corresponds to the load factor assumed for large-scale pyrolysis units in Shackley et al. (2011). In contrast to Shackley et al. (2011), we apply the same load factor to all possible pyrolysis-unit scales.

⁵² It is discussed whether biochar should be applied once or in lower doses at a regular basis (e.g., Sohi 2012).

⁵³ Since we focus on soil carbon sequestration and abstract from agricultural benefits, we do not differentiate the soils by type and quality (cp. Section 2).

⁵⁴ In our study, we consider direct soil application of biochar. An interesting further option refers to the use of biochar as a compost additive with subsequent soil incorporation.

amounts to 11.85 million ha in 2015, 11.56 million ha in 2020 and 11.29 million ha in 2030-2050 (Table A.8).⁵⁵

Table 12: Baseline Scenario for Feedstock Management

Feedstocks	Conventional feedstock management	Comments
Cereal straw	Decomposition in field	If not used otherwise, straw usually remains in the field (Kaltschmitt et al. 2009) and is incorporated into the soil.
Forestry residues	Decomposition in forest	If not used otherwise, forestry residues usually remain in the forest (Kaltschmitt et al. 2009).
Open-country biomass residues	Composting, land spread	According to Nitsch et al. (2004), biomass obtained from open-country conservation measures should not remain on site.
Industrial wood waste	Energetic use	If not considered for material use, industrial wood waste is usually used energetically (Fritsche et al. 2004a). We assume stationary combustion.
Wood in municipal solid waste	Composting, land spread	Wood in municipal solid waste is usually composted (Fritsche et al. 2004a; Kaltschmitt et al. 2009).
Green waste: Compensation areas	Decomposition on site	It is assumed that compensation areas are under less strict nature-conservation restrictions than habitat-connectivity areas. Therefore, it is assumed that green waste can remain on site after cutting (cp. Fritsche et al. 2004a; Kaltschmitt et al. 2009).
Biomass: Habitat-connectivity areas	Composting, land spread	Biomass from nature-conservation areas often has to be removed from site (Fritsche et al. 2004a; Kaltschmitt et al. 2009).
Green waste: Extensive grassland	Composting, land spread	Most of the extensive grassland covers habitat-connectivity areas (Nitsch et al. 2004; Table A.1); green waste from nature-conservation areas often has to be removed from site (Fritsche et al. 2004a; Kaltschmitt et al. 2009).
Short-rotation coppice: Erosion areas	Energetic use	It is assumed that energy crops are primarily grown for energetic use. We assume stationary combustion.
Sewage sludge	Composting, land spread	Analogously to the assumption by Fritsche et al. (2004a) for digestates from sewage sludge, it is also assumed that undigested sewage sludge is composted.
Solid cattle manure	Solid storage, land spread	Solid manure is usually directly spread on land (Fritsche et al. 2004a; Kaltschmitt et al. 2009). Before land spreading, it is stored in straw-based systems (UBA 2013).
Solid swine manure	Solid storage, land spread	
Solid poultry manure	Solid storage, land spread	
Liquid cattle and swine manure	Liquid storage, land spread	Liquid manure is usually directly spread on land (Fritsche et al. 2004a; Kaltschmitt et al. 2009). Before land spreading, it is stored in slurry-based systems (UBA 2013).
Sugar-beet leaf and potato haulm	Decomposition in field	Potato haulm usually remains in the field; the same holds for sugar-beet leaf if not used otherwise (Fritsche et al. 2004a). Sugar-beet leaf and potato haulm are incorporated into the soil.
Commercial and industrial waste	Composting, land spread	According to Fritsche et al. (2004a), ways of disposal for this waste category are not sufficiently known. Since most of this waste can usually be used as fertilizer (Fritsche et al. 2004a; Kaltschmitt et al. 2009), composting is assumed.
Organic municipal solid waste	Composting, land spread	If not used otherwise, organic municipal solid waste is usually composted (Fritsche et al. 2004a; Kaltschmitt et al. 2009).
Digestates	Composting, land spread	Following Fritsche et al. (2004a), it is assumed that digestates are composted. A treatment of digestates becomes increasingly necessary due to the limited possibilities of direct land spread associated with the rising number of biogas plants (FNR 2010).

Sources: Own assumptions based on Fritsche et al. (2004a), Nitsch et al. (2004), Kaltschmitt et al. (2009) and UBA (2013).

3.5) Baseline Scenario

The technical GHG mitigation potential of biochar is measured against the business-as-usual scenario for feedstock management, i.e. the use of the biomass had it not been turned into biochar. As detailed in Table 12, the business-as-usual scenario is based on current or

⁵⁵ As detailed in Section A.4 in Teichmann (2014), the acreage is consistent with the assumptions underlying the derivation of the technical biomass potentials for biochar production.

projected conventional feedstock-management practices, covering (i) decomposition on site for cereal straw, forestry residues, green waste from compensation areas, and sugar-beet leaf and potato haulm; (ii) storage and direct land spread for the solid and liquid manures; (iii) energetic use for industrial wood waste and short-rotation coppice; and (iv) composting plus subsequent land spread for the remaining biomass residues.^{56, 57}

4) Net Avoided GHG Emissions per Dry Tonne of Feedstock

For given biomass potentials for biochar, the technical GHG mitigation potentials of biochar production and soil application in combination with the energetic use of the pyrolysis by-products depend on the GHG emissions that are avoided per dry tonne of feedstock turned into biochar, against the baseline scenario of conventional feedstock management. The net avoided GHG emissions, in turn, consist of (i) the amount of biochar carbon sequestered in soils; (ii) changes in GHG emissions associated with the shift from conventional feedstock management to the conversion of biomass into biochar; (iii) avoided emissions due to the substitution of fossil fuels by renewable energy from the pyrolysis liquids and gases; and (iv) net GHG emissions from the transportation of biomass and biochar as well as from biochar soil addition (Gaunt and Cowie 2009; Woolf et al. 2010a).⁵⁸

This section derives the net avoided GHG emissions per dry tonne of feedstock. The technical GHG mitigation potentials of biochar, i.e. when combining the net avoided GHG emissions with the respective biomass potentials for biochar, are presented further below.

4.1) Carbon Sequestration with Biochar

One of the key characteristics of biochar is its high carbon stability. That is, the carbon contained in biochar tends to be more resistant to chemical and biological (e.g., microbial) decomposition and mineralization into CO₂ than the carbon in other organic matter, such as the original biomass or even compost (e.g., Lehmann et al. 2009; Baldock and Smernik 2002). When incorporated into soil, part of the biochar carbon will, thus, be stored in the soil for much longer periods of time than other SOC.⁵⁹ In this way, biochar can be used to stabilize and sequester the atmospheric CO₂ removed during photosynthesis (Lehmann 2007b). The main reason for the recalcitrance of the biochar carbon seems to be its high proportion of aromatic, i.e. stable, carbon compounds that are formed during pyrolysis at the cost of other more easily degradable carbon structures (e.g., Lehmann 2007a; Baldock and Smernik 2002;

⁵⁶ Note that untreated organic wastes cannot legally be deposited in German landfills (UBA 2013).

⁵⁷ Alternatively, all the feedstocks could be used energetically in the baseline scenario. However, we refrain from this assumption since the biomass scenarios have been constructed in a way that they respect the possible competition between biomass to be used for energetic purposes and for biochar production (cp. Section 3.1).

⁵⁸ Calculating the GHG emissions, we focus on emissions considered most relevant to the analysis. In particular, we do not include any construction-related emissions, such as from the construction of pyrolysis units, power plants or composting facilities. The reason is that GHG emissions from plant construction and dismantling have been found to be negligible (Roberts et al. 2010). Moreover, since we abstract from agricultural benefits of biochar addition to soils, we assume that biochar does not interfere with the usual agricultural practices, such as application rates of mineral or organic fertilizers. To keep the analysis tractable, we also assume that no biomass and biochar losses occur during transport, storage, soil application or any other handling. Further limiting assumptions can be found in the following subsections.

⁵⁹ Some (labile) fraction of the biochar carbon will inevitably get lost in the first years after its application to soil. For an overview, see, e.g., Lehmann et al. (2009).

Kloss et al. 2012).⁶⁰ Thereby, the carbon stability is mainly influenced by the production conditions and feedstock types. In particular, the stability of biochar tends to rise with the production temperature (e.g., Mašek et al. 2013; Harvey et al. 2012; Kloss et al. 2012; Zimmerman 2010; Hammes et al. 2006; Baldock and Smernik 2002; Czimczik et al. 2002). An exception seem to be biochars with a high ash content of >20%, such as manure biochars, where the stable carbon fraction of the biochars was shown to decrease with increasing pyrolysis temperature (Enders et al. 2012a). Moreover, high-ash biochars tend to be generally less stable than low-ash biochars, such as those derived from wood (e.g., Enders et al. 2012a).

Beyond feedstock type and production conditions, a wide range of additional factors, such as soil type, climate, and other environmental conditions, might strongly influence biochar carbon stability in soils (e.g., Mašek et al. 2013; Schmidt et al. 2011; Lehmann et al. 2009; Bird et al. 1999). For this reason, great uncertainties remain concerning the precise fraction of biochar carbon that remains stable in the long-term (e.g., Mašek et al. 2013; Shackley et al. 2011). The pieces of evidence provided by *Terra Preta* soils (e.g., Glaser et al. 2001) and radio-carbon dating of black carbon in other soils, such as European chernozems – 1,160-5,040 years (Schmidt et al. 2002) –, suggest that biochar might be storable up to millennia.⁶¹ The same holds for the soil incubation studies provided by Kuzyakov et al. (2009), who derived MRTs of laboratory-produced biochar of at least 200-2,000 years in soils under temperate climate, and Cheng et al. (2008), who calculated a MRT of 1,335 years for historical biochar at an average annual temperature of 10°C.⁶² While Lehmann et al. (2008) also arrived at MRTs of 718-9,259 years for biochar from vegetation fires in Australian soils, however, the MRT of naturally occurring biochar in Zimbabwean savannah soils ranged only from decades to centuries (Bird et al. 1999) and that in Kenyan soils was even less with 8.3 years (Nguyen et al. 2008).⁶³ These mixed results suggest that biochar stability in soil depends on a variety of factors and cannot be determined conclusively, not least due to methodological differences and shortcomings in quantifying biochar and/or its stable fraction in soils (e.g., Preston and Schmidt 2006; Hammes et al. 2007).⁶⁴

Moreover, there is no common framework to reliably estimate the stable carbon content of modern biochars (e.g., Harvey et al. 2012). A wide range of methods are discussed. The simplest is to derive the stable carbon fraction from the fixed-carbon content of biochar as provided by proximate analysis. However, proximate analysis has been criticized for being inaccurate for high-ash biochars, underestimating their ash contents and, thus, overestimating their fixed-carbon contents (Enders et al. 2012a).⁶⁵ Another method includes the direct measurement of the aromatic carbon fraction (e.g., Baldock and Smernik 2002; Hammes et al. 2006; Novak et al. 2009). As for the determination of the fixed-carbon content, however, this method hardly reflects the environmental degradation processes biochar is exposed to in soil

⁶⁰ For a discussion of other reasons for biochar stability, see Lehmann et al. (2009).

⁶¹ Compared to soil storage, biochar stability in terrestrial (Schmidt and Noack 2000) and ocean (Masiello and Druffel 1998) sediments is even greater, due to the lower exposure to oxygen (e.g., Nguyen and Lehmann 2009).

⁶² Actually, Cheng et al. (2008) reported a half-life of 925 years, i.e. the time needed for half of the biochar to decompose. This translates into a MRT of about 1,335 years when dividing the half-life by the natural logarithm of two ($\ln 2$) (Lehmann et al. 2009), under the assumption that biochar decays exponentially.

⁶³ When recovering biochar from soils, however, potential other reasons for the biochar losses might exist beyond its decomposition. These include erosion or leaching to deeper soil layers (e.g., Bird et al. 1999; Nguyen et al. 2008) and do not necessarily lead to CO₂ emissions (e.g., Lehmann et al. 2009).

⁶⁴ Additionally, potential dangers for the long-term storage of biochar carbon in soil include vegetation fires that might lead to a sudden release of the stored carbon as CO₂ (Pratt and Moran 2010).

⁶⁵ Alternatively, the volatile-matter content (Zimmerman 2010), combinations of the volatile-matter content and the oxygen-to-organic carbon (O:C_{org}) ratio (Spokas 2010) or the volatile-matter content and the O:C_{org} or H:C_{org} ratios (Enders et al. 2012a) have been suggested as stability proxies for biochars. Furthermore, Harvey et al. (2012) developed a recalcitrance index to determine the overall stability of biochars relative to that of graphite.

(Mašek et al. 2013). Methods that capture such processes more realistically include oxidative treatments of biochar (e.g., Mašek et al. 2013; Zimmerman 2010) or soil incubation studies (e.g., Kuzyakov et al. 2009).⁶⁶ However, conclusions for long-term biochar stability derived from short-term experiments have their own complications (Spokas 2010; Lehmann 2007a).

Table 13: Carbon Storage Potential of Biochar

Feedstocks	Biochar C content ^a	Stable C content	C sequestration potential	
	wt%	% of (1)	t C/t _{DM} feedstock ^d	t CO ₂ e/t _{DM} feedstock ^e
	(1)	(2)	(3)	(4)
Cereal straw	70	68 ^b	0.16	0.59
Forestry residues	81		0.17	0.61
Open-country biomass residues	69		0.15	0.53
Industrial wood waste	82		0.16	0.59
Wood in municipal solid waste	81		0.17	0.61
Green waste: Compensation areas	63		0.14	0.50
Biomass: Habitat-connectivity areas	69		0.15	0.53
Green waste: Extensive grassland	69		0.15	0.53
Short-rotation coppice: Erosion areas	72		0.12	0.45
Sewage sludge	35	34 ^c	0.06	0.21
Solid cattle manure	51		0.08	0.30
Solid swine manure	49		0.08	0.29
Solid poultry manure	46		0.07	0.25
Liquid cattle and swine manure	44		0.07	0.25
Sugar-beet leaf and potato haulm	51		0.08	0.29
Commercial and industrial waste	66		0.08	0.30
Organic municipal solid waste	63		0.10	0.35
Digestates	42	34 ^c	0.07	0.26

Sources:

- a) Table 8, column 11.
- b) Shackley et al. (2011); Hammond et al. (2011).
- c) Own assumption.
- d) Own calculation, $(3) = (1)/100 \cdot (2)/100 \cdot \text{char yield (Table 8, column 6)}/100$.
- e) Own calculation, based on column 3 and the conversion factor $1 \text{ t C} = 44/12 \text{ t CO}_2$.

Notes: Values rounded. DM = dry mass. wt% = weight percent. t = tonne.

Due to the described complexities and uncertainties, it is not possible to make reliable assumptions about feedstock-specific biochar carbon stability. Instead, we use uniform shares of stable carbon for biochars derived from solid biomass residues, on the one hand, and digestable biomass residues and digestates, on the other hand. For the biochars from solid biomass residues, we follow Shackley et al. (2011) and Hammond et al. (2011) and assume that 68% of the biochar carbon will persist in the long-term, i.e. for at least 100 years.⁶⁷ This is relatively conservative with respect to the assumptions of 75% by Gaunt and Cowie (2009) and 80% by Lehmann (2007b) and Roberts et al. (2010). To take account of the findings that high-ash biochars tend to be less stable than low-ash biochars (e.g., Enders et al. 2012a), we further assume that only half of this share, i.e. 34%, will be applicable for biochar carbon

⁶⁶ Based on one-year biotic and abiotic incubations of laboratory-produced biochars from different woods, grass and sugar-cane bagasse, Zimmerman (2010) calculated carbon losses of 3-26% after 100 years.

⁶⁷ Underlying the 68% are the assumptions that 15% of the biochar carbon is released in the short-term and that the remaining stable carbon fraction has a MRT of 500 years at a linear decay rate (see Hammond et al. 2011).

from digestable biomass residues and digestates.^{68, 69} This reduction in the proportion of stable biochar carbon is in line with our conservative approach and compares well with the data given in Table 8 (columns 9 and 11), where it can be calculated that the percentages of fixed carbon in the total carbon of the biochars from digestable biomass residues and digestates (52-73%) are also about 30 percentage points lower than those of the biochars from solid biomass residues (84-96%).⁷⁰ Moreover, due to the possible upwards bias in the fixed-carbon contents of the high-ash biochars presented in Table 8 (cp. Enders et al. 2012a), their distances to the fixed-carbon contents of the low-ash biochars might even be higher.

Based on the feedstock-specific biochar yields and carbon contents given in Table 8 (columns 6 and 11) and the assumed shares of biochar carbon considered to be stable in the long-term, the carbon storage potential of the biochars in tonnes of C or CO₂e per tonne of dry feedstock (t C/t_{DM} feedstock or t CO₂e/t_{DM} feedstock) is given in Table 13.⁷¹ We account for this long-term carbon storage potential in the year of biochar production and soil addition.⁷²

4.2) Changes in Emissions Due to Different Feedstock Management

Compared to conventional feedstock management, the conversion of biomass into biochar is associated with a change in GHG emissions. In particular, biomass decomposition during conventional manure management or composting and after biomass soil additions often causes CH₄ and N₂O emissions that can be avoided with biochar production, while the soil incorporation of these feedstocks also leads to some carbon sequestration via SOC formation, which needs to be accounted for in the GHG mitigation potential of biochar.⁷³ In the same way, the GHG mitigation potential of biochar has to be reduced by the N₂O emissions from the soil application of biochar itself and from the SOC losses associated with the biomass removal. Furthermore, the diversion of biomass away from an energetic use towards biochar production not only alters CO₂ emissions, but also those of CH₄ and N₂O. The calculation of the net avoided GHG emissions from a change in feedstock management is mainly based on the methodologies provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (in particular, De Klein et al. 2006; Dong et al. 2006; Pipatti et al. 2006; Gómez et al. 2006) and the *National Inventory Report for the German Greenhouse Gas Inventory 1990-2011* (UBA 2013), with some additions and modifications from further sources cited below.⁷⁴

⁶⁸ See Table 8 (column 10) for the biochar ash contents and Section 3.2 for the corresponding description.

⁶⁹ Further below, we will provide a sensitivity check for this assumption.

⁷⁰ Note, however, that the values for fixed carbon and total carbon do not compare perfectly since the respective means are not always based on the same underlying feedstocks due to data availability (see Table A.7) and since fixed carbon and total carbon *per se* are not perfectly comparable from a methodological point of view.

⁷¹ Following Woolf et al. (2010b), we assume that biochar will not contribute to increases in non-biochar SOC. Moreover, abstracting from possible agricultural benefits, we do not consider any impact of biochar on increases in below- or above-ground biomass yields that could contribute to increases in SOC. Further, as also implicit in Shackley et al. (2011), we assume that no carbon gets lost during biochar storage prior to soil addition.

⁷² Note that we assume that biochar production and soil incorporation take place in the same year.

⁷³ Following the approaches in the literature (e.g., Gaunt and Cowie 2009), we assume that biomass is turned into biochar immediately after it has become available such that no emissions from biomass storage will arise (such as from manure management). Instead, biochar is stored for some time prior to soil addition. However, we assume that there will be no emissions from biochar storage.

⁷⁴ Note that we abstract from GHG emissions from the harvesting of cereal straw, forestry residues, green waste from compensation areas, and sugar-beet leaf and potato haulm as well as from GHG emissions related to any auxiliary activities, such as in composting facilities or during manure management. GHG emissions from the transportation of the raw biomass materials and composts as well as their soil additions can be found in Section 4.4 alongside the transport emissions associated with biochar production and soil addition.

GHG emissions from manure, composting, soil, and biomass combustion. In what follows, we focus on GHG emissions from manure management, composting, soils amended with organic material and the stationary combustion of biomass. Avoided GHG emissions from the substitution of fossil fuels by biomass are analyzed separately in the next subsection.

CH₄ emissions. Methane is produced when biomass decomposes under anaerobic conditions, i.e. without oxygen. Thus, CH₄ emissions in Germany relevant for this study arise from manure management (Dong et al. 2006) and the anaerobic sections of composts (Pipatti et al. 2006). Another source of CH₄ emissions is the stationary combustion of biomass for energetic use (Gómez et al. 2006). The methane emissions from conventional feedstock management measured in tonnes of CH₄ and CO₂e per dry tonne of feedstock (t CH₄/t_{DM} feedstock and t CO₂e/t_{DM} feedstock) are derived and summarized in Table 14.

Table 14: CH₄ Emissions from Conventional Feedstock Management

Feedstocks	Conventional feedstock management (see Table 12)	CH ₄ emissions from			Total CH ₄ emissions	
		Manure management ^a	Com-posting ^c	Energetic use of biomass ^d	t CH ₄ /t _{DM} feedstock ^e	t CO ₂ e/t _{DM} feedstock ^f
(1)	(2)	(3)	(4)	(5)		
Cereal straw	Decomposition in field	-	-	-	-	-
Forestry residues	Decomposition in forest	-	-	-	-	-
Open-country biomass residues	Composting, land spread	-	0.011	-	0.011	0.276
Industrial wood waste	Energetic use	-	-	0.0002	0.0002	0.005
Wood in municipal solid waste	Composting, land spread	-	0.012	-	0.012	0.294
Green waste: Compensation areas	Decomposition on site	-	-	-	-	-
Biomass: Habitat-connectivity areas	Composting, land spread	-	0.011	-	0.011	0.276
Green waste: Extensive grassland	Composting, land spread	-	0.011	-	0.011	0.276
Short-rotation coppice: Erosion areas	Energetic use	-	-	0.0002	0.0002	0.005
Sewage sludge	Composting, land spread	-	0.003	-	0.003	0.084
Solid cattle manure	Solid storage, land spread	0.004	-	-	0.004	0.100
Solid swine manure	Solid storage, land spread	0.022	-	-	0.022	0.550
Solid poultry manure	Solid storage, land spread	0.004	-	-	0.004	0.100
Liquid cattle and swine manure	Liquid storage, land spread	0.021 ^b	-	-	0.021	0.525
Sugar-beet leaf and potato haulm	Decomposition in field	-	-	-	-	-
Commercial and industrial waste	Composting, land spread	-	0.012	-	0.012	0.300
Organic municipal solid waste	Composting, land spread	-	0.007	-	0.007	0.186
Digestates	Composting, land spread	-	0.003	-	0.003	0.086

Sources:

- Table A.11, column 9.
- Weighted average of the values for liquid cattle manure and liquid swine manure (Table A.11, column 9), where the weights are given by the shares of liquid cattle (swine) manure in total liquid manure of 83% (17%) as derived from the corresponding dry-mass values of Table A.11, column 2, i.e. $0.021 = 0.013 \cdot 0.83 + 0.060 \cdot 0.17$.
- Own calculation, based on the procedure in Detzel et al. (2003), i.e. assuming that 0.7% of the carbon content of digestates and sewage sludge and 1.8% of the carbon content of the other feedstocks are emitted as methane during composting. Thus, the emission factors are derived as (2) = C content (Table 8, column 1)/100 · 0.7/100 · 16/12 and (2) = C content (Table 8, column 1)/100 · 1.8/100 · 16/12, respectively. Note that the 1.8% (0.7%) used by Detzel et al. (2003) referred to biowaste and green waste (digestates) only. Further note that the default emission factor from Pipatti et al. (2006: Table 4.1) is 0.01 kg CH₄/kg_{DM} waste treated.
- Own calculation, based on the utility-source emission factor of 11 kg CH₄/TJ_{energy input} for *Wood/Wood Waste Boilers* from Gómez et al. (2006: Table 2.6) and the higher heating value (HHV) of 19.3 MJ/kg_{db} for both feedstocks from Table 8, column 5. Note that UBA (2013) does not give biomass-related CH₄ emission factors. Also note that Gómez et al. (2006) base the emission factors on the lower heating values (LHVs) of the biomass/fuels. Due to the lack of consistent data, however, we have to use the HHVs. The bias introduced by this procedure is considered negligible due to the generally low emissions. Thus, the calculations are (3) = $11 \cdot 19.3/1,000,000$.
- Own calculation, (4) = (1) + (2) + (3).
- The CO₂e are calculated by multiplying the CH₄ emissions (column 4) by their 100-year GWP of 25 (Forster et al. 2007).

Notes: Values rounded. DM = dry mass. db= dry base. t = tonne. kg = kilogram. MJ = megajoule. TJ = terajoule. - = not applicable. Tables numbered with the leading "A." refer to Teichmann (2014).

CO₂ emissions. The input of unpyrolyzed biomass into soil contributes to the formation of SOC and, thus, to the storage of carbon in soil (Aalde et al. 2006). As with biochar carbon, however, the long-term stability of the non-biochar carbon in soil is not only determined by the chemical properties of the incorporated feedstocks, but also by their complex – and still largely unquantifiable – physical, chemical and biological interactions with the surrounding soil ecosystem (Schmidt et al. 2011). According to Sohi (2012), about 10% of the carbon in fresh or composted biomass becomes stabilized over time.⁷⁵ Due to the lack of more specific data, we apply these 10% to all of the feedstocks (Table 15).^{76, 77} The long-term carbon storage potential of the unpyrolyzed biomass is assigned to the year of biochar production and soil application and will be balanced against the sequestration potential from biochar carbon.

N₂O emissions. Manure management (Dong et al. 2006) and composting (Pipatti et al. 2006) are associated with specific N₂O emissions. Furthermore, the addition of decomposing biomass (including manures and composts) to soil leads to increases in the N input and, thereby, to a rise in N₂O emissions from soil (De Klein et al. 2006). While N₂O emissions from composting occur directly, N₂O emissions from manure management and soil can occur both directly and indirectly, the latter through N volatilization and leaching/runoff.⁷⁸ Another source of N₂O emissions is the stationary combustion of biomass for energetic use (Gómez et al. 2006). A detailed derivation and summary of the N₂O emissions from conventional feedstock management can be found in Table 16, both measured in kilograms of N₂O and tonnes of CO₂e per dry tonne of feedstock (kg N₂O/t_{DM} feedstock and t CO₂e/t_{DM} feedstock).

If the feedstocks are converted into biochar instead, N₂O emissions arise from biochar soil additions and SOC losses from biomass removal. First, we follow Woolf et al. (2010b) in assuming that biochar inputs to soil will contribute to N₂O emissions from soil largely in the same way as the original biomass. However, this might be an overestimation of soil N₂O emissions from biochar since biochar N might be more stable than biomass N (e.g., Knicker et al. 1996). Second, when turning the feedstocks into biochar, the associated SOC losses from the removal of the fresh biomass or composts from soil will induce N₂O emissions from mineral soils due to N mineralization (De Klein et al. 2006).⁷⁹ In contrast, increases in biochar carbon stocks in soil are treated like general increases in SOC stocks in that they are not counted as measures of N sequestration (De Klein et al. 2006).⁸⁰ This is a simplifying assumption since biochar-soil interactions might reduce or increase soil N₂O emissions.⁸¹ The N₂O emissions from biochar soil additions and SOC losses are listed in Table 17.^{82, 83}

⁷⁵ This finding was derived from Schmidt et al. (2011). Schmidt et al. (2011: Figure 1) display a median MRT of nearly 50 years for bulk soil organic matter (SOM) from long-term field experiments in temperate climate. A MRT of 50 years translates into roughly 10% of bulk SOM remaining stable in soil after 100 years, based on the relation from Lehmann et al. (2009) that biomass half-life = MRT · ln 2.

⁷⁶ As reported by Knappe et al. (2012), the ecological balance for organic-waste management in Germany assumes that a share of 8% of the organic carbon added to soils becomes sequestered during humus build-up.

⁷⁷ We will provide a sensitivity check for this assumption.

⁷⁸ While direct N₂O emissions from soil refer to N₂O emissions that occur straight from the site to which the N was added, indirect N₂O emissions relate to N₂O emissions that are caused on another site by the N applied to a given land – which can take place through (i) the atmospheric transport of N in the form of N-containing gases like ammonia and their subsequent re-deposition (volatilization) or (ii) the terrestrial transport of N through the vertical soil profile (leaching) or in overland water flows (runoff) (De Klein et al. 2006). The same holds for N₂O emissions from manure-management sites (Dong et al. 2006).

⁷⁹ Since we assign the long-term SOC losses to the year of the feedstock-management change, we also assume that the associated N₂O emissions occur in the year of biochar production.

⁸⁰ Moreover, biochar inputs to soil do not lead to increases in non-biochar SOC stocks (see above).

⁸¹ For an overview, see Van Zwieten et al. (2009). Moreover, biochar soil additions might also impact CH₄ emissions from soil. Again, see Van Zwieten et al. (2009).

⁸² Note that we assume that no nitrogen gets lost during biochar storage prior to soil addition.

Table 15: Carbon Storage under Conventional Feedstock Management

Feedstocks	Conventional feedstock management (see Table 12)	C content ^a	C sequestration potential	
		wt% _{db}	t C/t _{DM} feedstock ^e	t CO ₂ e/t _{DM} feedstock ^f
		(1)	(2)	(3)
Cereal straw	Decomposition in field	47 ^b	0.047	0.172
Forestry residues	Decomposition in forest	49 ^b	0.049	0.180
Open-country biomass residues	Composting, land spread	18 ^c	0.018	0.067
Industrial wood waste	Energetic use	49	-	-
Wood in municipal solid waste	Composting, land spread	20 ^c	0.020	0.072
Green waste: Compensation areas	Decomposition on site	45 ^b	0.045	0.165
Biomass: Habitat-connectivity areas	Composting, land spread	18 ^c	0.018	0.067
Green waste: Extensive grassland	Composting, land spread	18 ^c	0.018	0.067
Short-rotation coppice: Erosion areas	Energetic use	47	-	-
Sewage sludge	Composting, land spread	27 ^c	0.027	0.099
Solid cattle manure	Solid storage, land spread	31 ^d	0.031	0.112
Solid swine manure	Solid storage, land spread	36 ^d	0.036	0.133
Solid poultry manure	Solid storage, land spread	27 ^d	0.027	0.098
Liquid cattle and swine manure	Liquid storage, land spread	37 ^d	0.037	0.135
Sugar-beet leaf and potato haulm	Decomposition in field	43 ^b	0.043	0.158
Commercial and industrial waste	Composting, land spread	20 ^c	0.020	0.073
Organic municipal solid waste	Composting, land spread	12 ^c	0.012	0.045
Digestates	Composting, land spread	28 ^c	0.028	0.102

Sources:

- Table 8, column 1.
- Due to the lack of data, it is assumed that the biomass that is assumed to decompose on site enters the soil without prior carbon losses.
- The carbon contents have been corrected for the total carbon losses during composting – largely from CO₂ emissions (Pipatti et al. 2006) and including those from CH₄ emissions (see Table 14) – amounting to 25% (60%) of the carbon in the digestates and sewage sludge (the remaining feedstocks) (Detzel et al. 2003), i.e. (1) = C content (Table 8, column 1) · (1 – 0.25) for digestates and sewage sludge and (1) = C content (Table 8, column 1) · (1 – 0.6) for the remaining feedstocks. Note that the 25% (60%) used by Detzel et al. (2003) referred to digestates (biowaste and green waste) only.
- The carbon contents have been corrected for the C lost due to CH₄ (Table 14) and CO₂ emissions from manure management. The CO₂ emissions have been derived from Pattey et al. (2005) and Laguë et al. (2005) (see Table A.14, column 3). Thus, (1) = C content (Table 8, column 1) – CH₄ emissions (Table 14, column 1)/(16/12) · 100 – CO₂ emissions (Table A.14, column 3)/(44/12) · 100.
- Own calculation, based on the finding in Sohi (2012) – derived from Schmidt et al. (2011) – that 10% of the carbon in the feedstocks is stabilized in soil in the long-term (100 years), i.e. (2) = (1)/100 · 0.10.
- Own calculation, based on column 2 and the conversion 1 t C = 44/12 t CO₂.

Notes: Values rounded. DM = dry mass. db = dry base. wt% = weight percent. t = tonne. - = not applicable. Tables numbered with the leading “A.” refer to Teichmann (2014).

GHG emissions from forgone fossil-fuel substitution by biomass. The energetic use of biomass substitutes for fossil-fuel combustion. In diverting this biomass – industrial wood waste and short-rotation coppice – into biochar production, the GHG emissions from fossil fuels that could have been offset by the biomass need to be accounted for as a reduction in the GHG mitigation potential of biochar. Thereby, the fossil fuels relevant for stationary

⁸³ Furthermore, we assume that no replacement of lost nutrients (in particular, nitrogen) takes place in the form of mineral fertilizers for the feedstocks that are diverted from arable land, i.e. cereal straw, sugar-beet leaf and potato haulm, as well as all the composts and manures, since nutrients are returned to the fields via biochar. While this approach is in line with the literature (e.g., Woolf et al. 2010a), we acknowledge that it induces strong simplifications since often less nutrients per dry tonne of feedstock are returned via biochar than originally removed – e.g., compare the N contents of the feedstocks given in Table 16 (column 8) with those of biochar given in Table 8 (column 12) combined with the char yields of Table 8 (column 6) – but, at the same time, biochar might improve the nutrient-retention capacity of soils (see above). A thorough calculation of possible nutrient replacements – and the associated GHG emissions from mineral fertilizers – would, thus, require a detailed consideration of the agricultural impact of biochar, which is, however, beyond the scope of this paper.

combustion in Germany are lignite, hard coal, and natural gas (UBA 2013). Since the avoided GHG emissions from biomass combustion depend on the type of fossil fuel substituted and since the future energy mix is uncertain, we calculate the associated GHG emissions separately for each of the three fossil fuels (Table 18).⁸⁴ Moreover, to simplify the analysis, we assume that both the biomass and the fossil fuels are used solely for electricity generation.

4.3) Net Avoided GHG Emissions Due to Fossil-Fuel Substitution

The liquids and gases obtained as by-products from pyrolysis can be used to replace fossil fuels in energy generation. However, the GHG emissions that are avoided due to the fossil-fuel substitution have to be balanced against the emissions that arise from biochar production in the form of energy inputs required to dry the feedstocks and to run the pyrolysis process. We assume that the necessary heat energy is provided by fossil fuels. The reason is that the demand for this energy is newly created by biochar production.⁸⁵

Energy outputs. For the ease of exposition, we consider the pyrolysis by-products as a combined residual of the pyrolysis process which captures all the energy in the dried feedstocks that is not transferred to biochar or subject to inefficiencies in the energy recovery. Although we acknowledge that this is a simplification, it is justified by our focus on biochar production rather than on precursors for energy generation. With some modifications, the calculation of the energy that is recovered in the by-products to offset fossil-fuel combustion, E_{out} , is based on equations (3) and (4) in Woolf et al. (2010b). That is, it is given by

$$E_{out} = \eta_p \cdot E_{max}, \quad (I)$$

where E_{max} is the theoretically recoverable energy per unit of dry-matter feedstock put into the pyrolysis process (measured in MJ/kg_{db}) and η_p refers to the percentage of E_{max} that is recovered in practice, i.e. the pyrolysis energy efficiency. We assume $\eta_p = 80\%$, i.e. the lower bound of the 80-85% range given in Shackley et al. (2011). E_{max} , in turn, is calculated as

$$E_{max} = HHV_{feed} - char \cdot HHV_{char}, \quad (II)$$

where HHV_{feed} is the higher heating value of the original dry-matter feedstock measured in MJ/kg_{db} and given in Table 19 (column 1),⁸⁶ $char$ is the percentage of the dry-matter feedstock (wt%_{db}) that is converted to biochar (Table 19, column 2), and HHV_{char} is the higher heating value of the biochar in MJ/kg (Table 19, column 3) (see Woolf et al. 2010b).

The value of E_{out} (Table 19, column 5) obtained by this procedure is the basis for the calculation of the combustion-related emissions from the pyrolysis by-products. As for the biomass under conventional feedstock management, we assume that the pyrolysis by-products are used for stationary combustion. The associated GHG emissions can be found in Table 19 (columns 6-8).

⁸⁴ Due to its local, long-term availability and relative cheapness, lignite is rated to remain relevant in Germany in the future (McKinsey 2007). Note that we do not consider CCS since this technology is currently not available in Germany and almost certainly will not be established before 2030 (von Hirschhausen et al. 2012).

⁸⁵ Apart from the energy inputs, we assume that the pyrolysis process itself is not associated with GHG emissions. That is, any GHGs in the pyrolysis gases (cp. footnote 20) are either eliminated or completely combusted. This is in accordance with Fritsche et al. (2004b: 286) for flash pyrolysis.

⁸⁶ Note that Woolf et al. (2010b) use the lower heating value (LHV) instead. We use the HHVs due to the lack of consistent data for LHVs. Since the HHVs are measured on a dry base, however, the differences to the LHVs are considered to be of minor relevance.

Table 19: GHG Emissions from the Combustion of the Pyrolysis By-Products

Feedstocks	Feedstock characteristics	Biochar characteristics		Energy in by-products		GHG emissions		
	HHV ^a	Char ^b	HHV ^c	E_{max} ^d	E_{out} ^e	CH ₄ ^f	N ₂ O ^g	Total CO ₂ e ^h
	MJ/kg _{db}	wt% _{db}	MJ/kg	MJ/kg _{db}		kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cereal straw	17.9	34	24.7	9.5	7.6	0.008	0.001	0.0004
Forestry residues	19.7	30	29.8	10.8	8.6	0.009	0.001	0.0005
Open-country biomass residues	18.7	31	29.8	9.5	7.6	0.008	0.001	0.0004
Industrial wood waste	19.3	29	30.3	10.5	8.4	0.008	0.001	0.0005
Wood in municipal solid waste	19.7	30	29.8	10.8	8.6	0.009	0.001	0.0005
Green waste: Compensation areas	18.2	32	29.8	8.7	6.9	0.007	0.001	0.0004
Biomass: Habitat-connectivity areas	18.7	31	29.8	9.5	7.6	0.008	0.001	0.0004
Green waste: Extensive grassland	18.7	31	29.8	9.5	7.6	0.008	0.001	0.0004
Short-rotation coppice: Erosion areas	19.3	25	29.8	11.9	9.5	0.009	0.001	0.0005
Sewage sludge	17.0	49	17.5	8.4	6.7	0.007	0.001	0.0004
Solid cattle manure	17.3	47	18.8	8.5	6.8	0.007	0.001	0.0004
Solid swine manure	19.4	47	18.2	10.8	8.7	0.009	0.001	0.0005
Solid poultry manure	14.5	44	15.4	7.7	6.2	0.006	0.001	0.0003
Liquid cattle and swine manure	17.6	45	19.9	8.6	6.9	0.007	0.001	0.0004
Sugar-beet leaf and potato haulm	16.9	45	18.0	8.8	7.0	0.007	0.001	0.0004
Commercial and industrial waste	16.9	37	18.0	10.2	8.2	0.008	0.001	0.0004
Organic municipal solid waste	15.2	45	18.0	7.1	5.7	0.006	0.001	0.0003
Digestates	16.8	49	11.6	11.1	8.9	0.009	0.001	0.0005

Sources:

- Table 8, column 5.
- Table 8, column 6.
- Table 8, column 15.
- Own calculation, based on equation (II), i.e. (4) = (1) – (2)/100 · (3).
- Own calculation, based on equation (I), i.e. (5) = (4) · 80/100.
- Own calculation, based on the default emission factor of 1 kg CH₄/TJ_{energy input} for *Other Biogas** from Gómez et al. (2006: Table 2.2) and E_{out} (column 5). Thus, (6) = 1 · E_{out} /1,000,000 · 1,000.
- Own calculation, based on the default emission factor of 0.1 kg N₂O/TJ_{energy input} for *Other Biogas** from Gómez et al. (2006: Table 2.2) and E_{out} (column 5). Thus, (7) = 0.1 · E_{out} /1,000,000 · 1,000. Note that we only consider direct N₂O emissions since there is no information on indirect N₂O emissions (volatilization) from combustion-related sources in UBA (2013).
- Own calculation, multiplying the CH₄ (N₂O) emissions by their respective 100-year GWP of 25 (298) as given in Forster et al. (2007) and summing them up, i.e. (8) = (6) · 25/1,000 + (7) · 298/1,000.

Notes: Values rounded. DM = dry mass. db = dry base. wt% = weight percent. kg = kilogram. t = tonne. MJ = megajoule. TJ = terajoule. HHV = higher heating value. * = *Other Biogas* was used as a reference due to the lack of more specific data.

In the calculations of the GHG emissions from fossil fuels that can be offset by the energetic use of the pyrolysis by-products (Table 20), in turn, we consider the same fossil fuels like in Section 4.2 – lignite, hard coal, and natural gas – and also assume that electricity is generated.

Energy inputs. Following Kim and Parker (2008), the heat energy required for biochar production, E_{in} , consists of the energy consumed to dry the feedstocks (E_{dry}), to further heat the dried feedstocks from 105°C to the pyrolysis target temperature (E_{target}), and to decompose the feedstocks during pyrolysis (the reaction energy for pyrolysis or heat of reaction, E_{react}), i.e.

$$E_{in} = E_{dry} + E_{target} + E_{react}, \quad (\text{III})$$

measured in MJ/kg_{db}, i.e. per unit of dry feedstock.

Using equation (2) from Kim and Parker (2008) and reformulating it on a dry-feedstock basis, E_{dry} is given by

$$E_{dry} = w/(1 - w) \cdot [\Delta H_{vap} + \Delta T_{dry} \cdot c_w] + \Delta T_{dry} \cdot c_{feed}, \quad (IV)$$

where w refers to the water content of the feedstock on an as-received fresh-weight basis in wt% (Table 21, column 1), $\Delta H_{vap} = 2.09$ MJ/kg is the latent heat for vaporization of water, $\Delta T_{dry} = 85^\circ\text{C}$ reflects the difference between 105°C and ambient temperature (20°C), $c_w = 0.00418$ MJ/(kg \cdot $^\circ\text{C}$) is the heat capacity of water, and c_{feed} is the heat capacity of the dry feedstock in MJ/(kg_{db} \cdot $^\circ\text{C}$) as displayed in Table 21 (column 3) (see Kim and Parker 2008).

Table 21: Pyrolysis Energy Inputs

Feedstocks	Feedstock characteristics			No process heat recovery				Process heat recovery			
	Water ^a	Ash ^b	c_{feed}^c	Energy inputs			Net energy	Energy inputs			Net energy
				E_{dry}^d	E_{target}^e	E_{inf}^f	$E_{max} - E_{in}^g$	E'_{dry}^h	E'_{target}^i	E'_{inf}^j	$E'_{max} - E'_{in}^k$
				wt% [§]	wt% _{db}	MJ/(kg _{db} $^\circ\text{C}$)	MJ/kg _{db}	MJ/kg _{db}	MJ/kg _{db}	MJ/kg _{db}	MJ/kg _{db}
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Cereal straw	7.9	6.9	0.0022	0.4	0.9	1.3	8.2	0.2	0.2	0.4	9.1
Forestry residues	10.8	0.9	0.0023	0.5	0.9	1.4	9.4	0.3	0.2	0.5	10.2
Open-country biomass residues	7.8	4.6	0.0022	0.4	0.9	1.3	8.2	0.2	0.2	0.4	9.0
Industrial wood waste	8.1	0.8	0.0023	0.4	0.9	1.3	9.2	0.3	0.2	0.4	10.1
Wood in municipal solid waste	10.9	0.9	0.0023	0.5	0.9	1.4	9.4	0.3	0.2	0.5	10.2
Green waste: Compensation areas	6.3	6.5	0.0022	0.4	0.9	1.2	7.4	0.2	0.2	0.4	8.3
Biomass: Habitat-connectivity areas	7.8	4.6	0.0022	0.4	0.9	1.3	8.2	0.2	0.2	0.4	9.0
Green waste: Extensive grassland	7.8	4.6	0.0022	0.4	0.9	1.3	8.2	0.2	0.2	0.4	9.0
Short-rotation coppice: Erosion areas	17.9	1.3	0.0023	0.7	0.9	1.6	10.2	0.6	0.2	0.8	11.1
Sewage sludge	79.5	33.7	0.0019	9.6	0.7	10.4	-2.0	9.5	0.1	9.7	-1.2
Solid cattle manure	63.6	16.9	0.0021	4.5	0.8	5.3	3.2	4.3	0.2	4.5	4.0
Solid swine manure	78.5	19.7	0.0021	9.1	0.8	9.9	0.9	9.0	0.2	9.1	1.7
Solid poultry manure	13.4	21.9	0.0020	0.6	0.8	1.4	6.4	0.4	0.2	0.6	7.2
Liquid cattle and swine manure	90.2	14.8	0.0021	22.7	0.8	23.5	-14.9	22.5	0.2	22.7	-14.1
Sugar-beet leaf and potato haulm	84.0	25.0	0.0020	13.0	0.8	13.8	-5.0	12.9	0.2	13.0	-4.2
Commercial and industrial waste	61.3	6.28	0.0022	4.1	0.9	4.9	5.3	3.9	0.2	4.1	6.2
Organic municipal solid waste	70.9	23.1	0.0020	6.1	0.8	6.9	0.2	6.0	0.2	6.2	0.9
Digestates	85.3	28.6	0.0019	14.4	0.8	15.1	-4.0	14.2	0.2	14.4	-3.3

Sources:

- Table 8, column 4.
- Table 8, column 3.
- Own calculation, based on the ash contents in column 2 and on mean values for c_{feed} of general organic (inorganic) material of 2.3 (1.05) kJ/(kg_{db} \cdot $^\circ\text{C}$). These mean values were derived from typical values for c_{feed} of organic material – 2.1-2.5 kJ/(kg \cdot $^\circ\text{C}$) – and inorganic material – 0.8-1.3 kJ/(kg \cdot $^\circ\text{C}$) – as cited by Kim and Parker (2008). That is, (3) = (2)/100 \cdot 1.05/1,000 + [100 – (2)]/100 \cdot 2.3/1,000.
- Own calculation, based on equation (IV), i.e. (4) = (1)/[100 – (1)] \cdot [2.09 + (105 – 20) \cdot 0.00418] + (105 – 20) \cdot (3).
- Own calculation, based on equation (V), i.e. (5) = (500 – 105) \cdot (3).
- Own calculation, based on equation (III), i.e. (6) = (4) + (5). Note that E_{react} is assumed to be zero.
- Own calculation, (7) = E_{max} (Table 19, column 4) – (6).
- Own calculation, based on equation (IV'), i.e. (8) = (1)/[100 – (1)] \cdot [2.09 + (105 – 20) \cdot 0.00418] + (1 – 0.8) \cdot (105 – 20) \cdot (3).
- Own calculation, based on equation (V'), i.e. (9) = (1 – 0.8) \cdot (500 – 105) \cdot (3).
- Own calculation, analogously to f), i.e. (10) = (8) + (9).
- Own calculation, (11) = E_{max} (Table 19, column 4) – (10).

Notes: Values rounded. wt% = weight percent. db = dry base. kg = kilogram. kJ = kilojoule. MJ = megajoule. § = Based on as-received fresh weight.

Similarly, E_{target} is derived from equation (3) in Kim and Parket (2008), i.e.

$$E_{target} = \Delta T_{target} \cdot c_{feed}, \quad (V)$$

where $\Delta T_{target} = 500^{\circ}\text{C} - 105^{\circ}\text{C} = 395^{\circ}\text{C}$ and the 500°C refer to the total average pyrolysis temperature obtained from the slow-pyrolysis processes covered in this study (Section 3.2).

Concerning E_{react} , we assume that, on average, it is zero. The reasons are, first, that pyrolysis might be both an endothermic (e.g., Kim and Parker 2008) and an exothermic (e.g., Ro et al. 2010) process and, second, that we lack corresponding feedstock-specific data. Moreover, the heat of reaction tends to be the smallest part of E_{in} (e.g., Kim and Parker 2008; Ro et al. 2010).

While our calculation of E_{in} does not take account of any recovery of process heat, we also present an alternative energy input, E'_{in} , required when some of the process heat is recovered and used in the biochar production process. Along Woolf et al. (2010b), we assume that the process heat is recovered without condensing the exhaust-gas stream. Moreover, we apply the same efficiency for the process-heat recovery as for the recovery of the energy in the pyrolysis by-products, i.e. $\eta_p = 80\%$. This leads to modified energy requirements for drying the feedstocks, E'_{dry} , and for heating the dried feedstocks to the pyrolysis target temperature, E'_{target} , i.e.

$$E'_{dry} = w/(1 - w) \cdot [\Delta H_{vap} + \Delta T_{dry} \cdot c_w] + (1 - \eta_p) \cdot \Delta T_{dry} \cdot c_{feed}, \quad (\text{IV}')$$

$$E'_{target} = (1 - \eta_p) \cdot \Delta T_{target} \cdot c_{feed}. \quad (\text{V}')$$

As can be seen from Table 21, for each of the two cases of process-heat recovery, the demand for external energy to reach the pyrolysis target temperature is nearly constant across the different feedstocks (columns 5 and 9), while the high variability in the feedstocks' water contents translates into a high variability in the energy required to dry the feedstocks (columns 4 and 8). For the groups of wet feedstocks (i.e. the digestible biomass residues and the digestates), the energy necessary to dry the feedstocks by far exceeds the energy to reach the pyrolysis target temperature, both with and without the recovery of process heat. The only exception is the relatively dry solid poultry manure. For sewage sludge, liquid cattle and swine manure, sugar-beet leaf and potato haulm, and digestates – i.e. the feedstocks with the highest water contents –, the high amount of energy consumed in the drying process even means that the total energy input necessary for their conversion into biochar exceeds the energy theoretically recoverable from the pyrolysis by-products, regardless whether process heat is recovered or not (columns 7 and 11).

The entire external energy requirements E_{in} and E'_{in} are sourced from fossil fuels, either lignite, hard coal, or natural gas. In calculating the GHG emissions associated with the heat provision (Tables 22 and 23), we take account of the different thermal efficiencies of the fossil fuels based on new industrial boilers.

4.4) Net GHG Emissions from Transports and Soil Additions

Finally, GHG emissions arise from the transportation of biomass to the pyrolysis units, from the transportation of biochar from the pyrolysis units to the farms where the biochar is applied to the soil, and from the agricultural machinery used for the biochar soil application, adjusted for the corresponding emissions from biomass transports and soil additions arising under conventional feedstock management.

In principle, GHG emissions from mobile combustion include direct emissions of CO_2 , CH_4 , and N_2O as well as indirect GHG emissions from precursors, such as nitric oxides (NO_x) (Davies Waldron et al. 2006). For the minor relevance of non- CO_2 emissions, however, we

consider only CO₂ emissions, both for any road transports and soil additions.⁸⁷ Moreover, we do not cover any fugitive emissions, i.e. emissions related to the production of transport fuels.

Biochar-related road transports. First, the biomass to be converted into biochar has to be delivered to the pyrolysis units; afterwards, the biochar has to be transported from the pyrolysis units to the farms for soil addition. The associated GHG emissions depend on the distances between the pyrolysis units and the sources of biomass/farms for biochar soil application, which are determined by the size and, thus, the number of pyrolysis units. Following Woolf et al. (2010b), we derive a broad measure of distance, whereby the mean transport distance, D_{its} , in kilometers (km) for both biomass and biochar is calculated as

$$D_{its} = 1/2 \cdot (area/PU_{its})^{1/2}, \quad (VI)$$

where $area = 348,672 \text{ km}^2$ refers to Germany's total land area (CIA 2013) and PU_{its} is the number of pyrolysis units of scale i at time t for biomass scenario s as given in Table 11. Thus, we assume that the pyrolysis units are distributed evenly across Germany and that the distances for the transportation of biomass to the pyrolysis units and for the transportation of biochar from the pyrolysis units to the farms are symmetric. The mean transport distances are given in Table A.18.

The CO₂ emissions from road transport are driven by the carbon content of the transport fuel; thus, they depend on the amount and type of transport fuel used (Davies Waldron et al. 2006). We assume that both biomass and biochar are transported by trucks powered by diesel engines.⁸⁸ Based on the current maximum blend of 7% biodiesel, we assume for all periods that 93% of the diesel consumption is provided by fossil diesel fuel and the remainder by biodiesel.⁸⁹ For fossil diesel fuel, we use the CO₂ emission factor of 74.0 t CO₂ per terajoule (TJ) as applied by UBA (2013: Table 347, p. 741) and the heating value of 35.87 MJ per liter (l) of diesel fuel (FNR 2012c: 28). Assuming that 18 t of biomass or biochar are transported per journey,⁹⁰ the average diesel-fuel consumption in liters per tonne of freight and kilometer can be found in Table A.19. The CO₂ emissions (per dry tonne of feedstock) from the transportation of biomass in the *Max 1* and *Max 2* scenarios are summarized in Tables 24 and 25; those for the transportation of biochar in Tables 26 and 27.⁹¹ The corresponding transport emissions for the remaining biomass scenarios are displayed in Tables A.22-A.29.

⁸⁷ According to UBA (2013: 196), N₂O and CH₄ emissions (on a CO₂e-basis) in road transport in 2011 reached 1,338.3 gigagrams (Gg) and 148.1 Gg, respectively, while the corresponding CO₂ emissions from fossil fuels amounted to 147,867.4 Gg. Thus, N₂O and CH₄ emissions accounted for just 1% of the total road-transport emissions. – Note that UBA (2013) uses the 100-year GWPs of 21 for CH₄ and 310 for N₂O. – Moreover, the transport-related CO₂ emissions in our analysis are generally very low (see below). Thus, the non-CO₂ emissions are considered negligible for the purposes of this study.

⁸⁸ Diesel engines are the predominant engines for trucks, semi-trailers and tractors in Germany (Kunert and Radke 2013). For the short- and medium-term at least, they are also expected to remain the leading standard for heavy trucks (BMVBS 2013).

⁸⁹ Due to the current discussions about the GHG impact of first-generation biofuels and the associated reluctance to increase their share in the transport sector (e.g., BMVBS 2013; EC 2012), we stay conservative and hold the 7% biodiesel share constant for all periods.

⁹⁰ As can be derived from FNR (2005: Tables 6-11 and 6-16), the cheapest mode of transport for wood chips tend to be truck combinations with a transport volume of 80 m³ and a payload of 23 t. Using these types of trucks as a reference for all biomass feedstocks and for biochar and assuming an average load factor of 0.8, about 18 t of freight can be carried per truck. Note that the volume constraint of 80 m³ might be violated at 18 t for freight densities below 0.225 t/m³. Due to the lack of data for the densities of all the feedstocks and biochars, however, we simplify the analysis by abstracting from the volume constraint.

⁹¹ Accounting for the fact that biomass is transported undry, the CO₂ emissions from the transportation of biomass per dry tonne of feedstock and kilometer can be found in Table A.20. The corresponding CO₂ emissions

Road transports in the baseline scenario. Under conventional feedstock management, no biomass transport occurs for the feedstocks that are assumed to decompose on site. Further assuming that manure management and soil application of the manures take place at or close to the sites where the manures become available, we do not associate any transport emissions to the solid and liquid manures. The transport emissions associated with the feedstocks to be composted or used energetically, in turn, can be found in Table 28. The calculations are based on the same assumptions concerning average load and diesel fuel as for biomass (biochar) transportation to (from) the pyrolysis units. However, the transport distances differ from the above assumptions. According to Kern et al. (2012a: 20), there are currently approximately 1,000 large composting facilities in operation in Germany. Inserting this number into equation (VI), the mean transport distance for biomass to be composted would amount to ca. 9 km. We hold this transport distance constant across time. Moreover, applying symmetry, 9 km is also the assumed distance for the composts to be transported from the composting facilities to the farms. With respect to the composted biomass, we assume that the yield of composts, on a dry basis, is 64% of the respective dry feedstocks and that the fresh-weight composts have an average water content of 40%.⁹² Finally, concerning the feedstocks to be used energetically in the baseline scenario, we assume the same average transport distance of 9 km.

Biochar soil addition. The CO₂ emissions from off-road agricultural machinery are calculated in the same way as those from road transport, i.e. they are fuel-driven (Davies Waldron et al. 2006). Since tractors are usually powered by diesel engines (Kunert and Radke 2013), we assume the same 7% share of biodiesel in overall diesel consumption as above and also use the same CO₂ emission factor (74.0 t CO₂/TJ) and heating value (35.87 MJ/l) for fossil diesel fuel.⁹³ Following Shackley et al. (2011: Box 3) in assuming that biochar soil addition across all scenarios takes place with a fertilizer spreader pulled by a tractor and carrying 6 t of biochar per journey, and further assuming that each journey takes 3 km, the CO₂ emissions from biochar soil addition are summarized in Table 29.⁹⁴

Soil additions in the baseline scenario. Turning to the feedstock management in the baseline scenario, no active soil incorporation takes place for forestry residues and green waste from compensation areas, while the remaining feedstocks assumed to decompose on site – cereal straw as well as sugar-beet leaf and potato haulm – are actively incorporated into soil (see Table 12). For these latter biomass residues, however, we assume that their soil incorporation takes place during usual tillage, which does not depend on whether the feedstocks remain on the fields or not. While also leaving usual tillage unaffected, the soil addition of manures and composts, however, is avoided when these feedstocks are turned into biochar. The associated CO₂ emissions can be found in Table 30. For both the solid and the

from the transportation of biochar are detailed in Table A.21. Note that we do not differentiate between biochar fresh weight and biochar dry weight (see comment §§§ in Table 8).

⁹² The assumptions follow Knappe et al. (2012: Figures D-2 and D-5), who report a finished-compost yield of 421 kg fresh mass (256 kg dry mass) per tonne of fresh-weight household biowaste (40% dry-matter content) and a finished-compost yield of 438 kg fresh mass (256 kg dry mass) per tonne of fresh-weight green waste (40% dry-matter content). Due to the lack of more detailed data, we apply the respective percentages to all of the feedstocks to be composted.

⁹³ UBA (2013: Table 77) reports CH₄ and N₂O emission factors for agricultural machinery and vehicles for diesel fuel of 4.24 kg CH₄/TJ and 1.0 kg N₂O/TJ. Using the 100-year GWPs of 25 for CH₄ and 298 for N₂O (Forster et al. 2007), the emission factors amount to 0.106 t CO₂e/TJ for CH₄ and 0.298 t CO₂e/TJ for N₂O. Compared to the diesel-related CO₂ emissions of 74.0 t CO₂/TJ, the combined CH₄ and N₂O emissions of 0.404 CO₂e/TJ can be considered negligible, justifying our focus on CO₂ emissions.

⁹⁴ As for the road transport emissions from biomass and biochar, we abstract from differences in the densities of the biochars. Assuming that 6 t of biochar are carried per journey regardless of the amount of biochar applied per hectare further means that we ignore any scale effects in biochar soil addition, as do Shackley et al. (2011).

liquid manures, we assume that 70% of the fresh biomass remains after storage.⁹⁵ The assumptions for the yields and water contents of the composts are the same as above. All remaining assumptions are as for biochar soil addition.

Table 29: CO₂ Emissions from the Soil Addition of Biochar

	2015	2020	2030	2040	2050
	t CO ₂ /t _{DM} feedstock				
Feedstocks	(1)	(2)	(3)	(4)	(5)
Cereal straw	0.000117	0.000112	0.000095	0.000090	0.000085
Forestry residues	0.000103	0.000098	0.000084	0.000079	0.000075
Open-country biomass residues	0.000107	0.000102	0.000087	0.000082	0.000077
Industrial wood waste	0.000100	0.000095	0.000081	0.000077	0.000072
Wood in municipal solid waste	0.000103	0.000098	0.000084	0.000079	0.000075
Green waste: Compensation areas	0.000110	0.000105	0.000090	0.000085	0.000080
Biomass: Habitat-connectivity areas	0.000107	0.000102	0.000087	0.000082	0.000077
Green waste: Extensive grassland	0.000107	0.000102	0.000087	0.000082	0.000077
Short-rotation coppice: Erosion areas	0.000086	0.000082	0.000070	0.000066	0.000062
Sewage sludge	0.000168	0.000161	0.000138	0.000130	0.000122
Solid cattle manure	0.000162	0.000154	0.000132	0.000124	0.000117
Solid swine manure	0.000162	0.000154	0.000132	0.000124	0.000117
Solid poultry manure	0.000151	0.000144	0.000123	0.000117	0.000110
Liquid cattle and swine manure	0.000155	0.000148	0.000126	0.000119	0.000112
Sugar-beet leaf and potato haulm	0.000155	0.000148	0.000126	0.000119	0.000112
Commercial and industrial waste	0.000127	0.000121	0.000104	0.000098	0.000092
Organic municipal solid waste	0.000155	0.000148	0.000126	0.000119	0.000112
Digestates	0.000168	0.000161	0.000138	0.000130	0.000122

Sources: Own calculation, multiplying the tractor-related diesel consumption per tonne of freight and kilometer (Table A.19, row G) by the assumed average length of a journey of 3 km, the assumed share of fossil diesel of 93%, the diesel heating value of 35.87 MJ/l (FNR 2012c: 28) and the CO₂ emission factor for diesel fuel of 74.0 t CO₂/TJ (UBA 2013: Table 347, p. 741), and expressing the emissions on a dry-feedstock basis, i.e. = tractor diesel consumption (Table A.19, row G) · 3 · 0.93 · char yield (Table 8, column 6)/100 · 35.87 · 74.0/1,000,000.

Notes: Values rounded. DM = dry mass. km = kilometer. t = tonne. l = liter. MJ = megajoule. TJ = terajoule. Tables numbered with the leading “A.” refer to Teichmann (2014).

4.5) Total Net Avoided GHG Emissions per Dry-Feedstock Tonne

In this section, we summarize the total net GHG emissions that are avoided per dry tonne of feedstock that is turned into slow-pyrolysis biochar.

Assuming for the ease of exposition that the type of fossil fuel that is used as an energy input into the pyrolysis process is also the one which is replaced by the pyrolysis by-products or – under conventional feedstock management – the original biomass, the net avoided GHG emissions obtained when combining the calculations from Sections 4.1 to 4.3 can be found in Table 31. Further including the net avoided GHG emissions from transports and soil additions from Section 4.4 as summarized in Tables A.30-A.35, the total net avoided GHG emissions for the *Max 1* and *Max 2* scenarios for the year 2030 are detailed in Tables 32 and 33, while the corresponding summary for the remaining scenarios and periods can be found in Tables A.36-A.51.

⁹⁵ Following Fritsche et al. (2004a: 83), we assume that a share of 30% of the solid manures (fresh weight) is lost during storage. Due to the lack of more detailed data, we apply this percentage share also to the liquid manures.

Table 30: CO₂ Emissions from the Soil Addition of Composts and Manures

Feedstocks	Conventional feedstock management (see Table 12)	2015	2020	2030	2040	2050
		t CO ₂ /t _{DM} feedstock				
		(1)	(2)	(3)	(4)	(5)
Cereal straw	Decomposition in field	-	-	-	-	-
Forestry residues	Decomposition in forest	-	-	-	-	-
Open-country biomass residues	Composting, land spread	0.000367	0.000350	0.000299	0.000282	0.000266
Industrial wood waste	Energetic use	-	-	-	-	-
Wood in municipal solid waste	Composting, land spread	0.000367	0.000350	0.000299	0.000282	0.000266
Green waste: Compensation areas	Decomposition on site	-	-	-	-	-
Biomass: Habitat-connectivity areas	Composting, land spread	0.000367	0.000350	0.000299	0.000282	0.000266
Green waste: Extensive grassland	Composting, land spread	0.000367	0.000350	0.000299	0.000282	0.000266
Short-rotation coppice: Erosion areas	Energetic use	-	-	-	-	-
Sewage sludge	Composting, land spread	0.000367	0.000350	0.000299	0.000282	0.000266
Solid cattle manure	Solid storage, land spread	0.000661	0.000631	0.000540	0.000509	0.000479
Solid swine manure	Solid storage, land spread	0.001120	0.001068	0.000914	0.000862	0.000811
Solid poultry manure	Solid storage, land spread	0.000278	0.000265	0.000227	0.000214	0.000201
Liquid cattle and swine manure	Liquid storage, land spread	0.002456	0.002343	0.002004	0.001891	0.001779
Sugar-beet leaf and potato haulm	Decomposition in field	-	-	-	-	-
Commercial and industrial waste	Composting, land spread	0.000367	0.000350	0.000299	0.000282	0.000266
Organic municipal solid waste	Composting, land spread	0.000367	0.000350	0.000299	0.000282	0.000266
Digestates	Composting, land spread	0.000367	0.000350	0.000299	0.000282	0.000266

Sources: Own calculation, based on the assumption that 64% of the biomass (dry mass) to be composted is transformed into compost (dry mass) and that composts (fresh weight) have an average water content of 40% (derived from Knappe et al. 2012: Figures D-2 and D-5, referring to finished compost from household biowaste and from greenwaste) and on the assumption that 30% of the manures (fresh weight) get lost during storage (Fritsche et al. 2004a: 83, for solid manure). Due to the lack of more specific data, the respective values were applied to all of the composts and manures. Thus, the CO₂ emissions were calculated by multiplying the tractor-related diesel consumption per tonne of freight and kilometer (Table A.19, row G) by the assumed average length of a journey of 3 km, the assumed share of fossil diesel of 93%, the diesel heating value of 35.87 MJ/l (FNR 2012c: 28) and the CO₂ emission factor for diesel fuel of 74.0 t CO₂/TJ (UBA 2013: Table 347, p. 741), and by accounting for the fact that fresh biomass is transported instead of dry biomass, i.e. = tractor diesel consumption (Table A.19, row G) · 3 · 0.93 · 64/(100 – 40) · 35.87 · 74.0/1,000,000 for all the feedstocks to be composted; and = tractor diesel consumption (Table A.19, row G) · 3 · 0.93 · 70/(100 – water content (Table 8, column 4)) · 35.87 · 74.0/1,000,000 for all the solid and liquid manures.

Notes: Values rounded. DM = dry mass. km = kilometer. l = liter. t = tonne. MJ = megajoule. TJ = terajoule. - = not applicable. Tables numbered with the leading “A.” refer to Teichmann (2014).

As can be seen from the total net avoided GHG emissions obtained for the year 2030 (Tables 32-33 and A.36-A.39), for example, the net avoided GHG emissions from transports and soil additions do not cause great differences between the scenarios. This holds for both a comparison of the respective total net avoided GHG emissions across the pyrolysis-unit scales (for a given biomass scenario) and a comparison across the biomass scenarios (for a given pyrolysis-unit scale). Moreover, this observation is in line with Woolf et al. (2010a), Roberts et al. (2010) and Hammond et al. (2011), who also found negligible emissions from transports and soil additions.

As further revealed by Tables 32-33 and A.36-A.51, the biochar strategy does not always lead to positive net avoided GHG emissions. In other words, biochar does not always avoid more GHG emissions than the respective conventional feedstock management of the baseline scenario. In particular, negative net avoided GHG emissions occur under all scenarios for the digestable feedstocks sewage sludge, liquid cattle and swine manure, and sugar-beet leaf and potato haulm as well as for digestates. Among the group of solid feedstocks, the same holds for industrial wood waste (except for the case when natural gas is used as fossil fuel) and short-rotation coppice (except for the case of natural gas if process heat is recovered). These results are driven by the non-transport-related emissions (Table 31).

For sewage sludge, liquid cattle and swine manure, sugar-beet leaf and potato haulm, and digestates, the main cause for this negative GHG mitigation balance associated with biochar is the huge amount of energy required for biochar production (see Table 31; Figure 3), driven by the energy necessary to dry these wet feedstocks (see Table 21). Indeed, sewage sludge, liquid cattle and swine manure, sugar-beet leaf and potato haulm, and digestates have the highest water contents of all the feedstocks considered (Table 8). Moreover, as already outlined above (Table 21), they are the feedstocks where the energy requirements for biochar production, E_{in} , even exceed the energy theoretically recoverable from the pyrolysis by-products, E_{max} . As can be seen in Figure 3, for the case of hard coal being used as fossil fuel and process heat recovered during pyrolysis, the emissions associated with E_{in} alone outweigh the total positive emissions reductions for all the four feedstocks.^{96, 97}

For industrial wood waste and short-rotation coppice, in turn, the unfavorable GHG mitigation balance is driven by the baseline scenario, i.e. the assumed energetic use of the feedstocks under conventional feedstock management (see Table 31; Figure 3).⁹⁸ At the same time, the exceptions occurring when natural gas is used as fossil fuel reveal that biochar can be more profitable than biomass combustion from a GHG-mitigation perspective if a fossil fuel with a low carbon intensity is replaced and if the pyrolysis process is most efficient, i.e. if process heat is recovered. The dependency on the fossil-fuel type is in line with Woolf et al. (2010a), who found that – for certain feedstocks and soil fertilities – more GHG emissions could be avoided from biochar soil incorporation than combustion of the original feedstock if natural gas was used as fossil fuel, while biomass combustion was more favorable than biochar carbon sequestration when coal was used.⁹⁹

Focusing exclusively on the feedstocks associated with positive net avoided GHG emissions and ignoring net GHG emissions from transports and soil additions, Table 31 (columns 11-16) reveals that the net avoided GHG emissions vary considerably across the feedstocks. With some exceptions, solid biomass residues tend to avoid more net GHG emissions than the digestable biomass residues. In the group of the solid biomass residues, feedstocks that are composted in the baseline scenario are associated with greater net GHG emission reductions than feedstocks that decompose on site. This is mainly driven by the avoided CH₄ emissions from composting (Figure 3). That is, the greatest net avoided GHG emissions are associated with wood in municipal solid waste, open-country biomass residues, biomass from habitat-connectivity areas and green waste from extensive grassland.¹⁰⁰

⁹⁶ While solid swine manure also has a very high water content (Table 8), the GHG emissions from E_{in} are compensated for by the emissions reductions associated with the baseline scenario, i.e. CH₄ and N₂O emissions from manure management (Figure 3).

⁹⁷ The negative GHG mitigation balance for liquid cattle and swine manure and sugar-beet leaf and potato haulm is not sensitive to changes in the assumptions. For sewage sludge and digestates, however, a positive GHG mitigation balance might be obtained under certain circumstances. Assuming, e.g., that 68% of the biochar carbon remains stable for the digestable biomasses and digestates, instead of 34%, the net avoided GHG emissions associated with sewage sludge and digestates become positive if natural gas is used as fossil fuel (Tables A.52-A.58). A *ceteris paribus* reduction in the long-term stability of biomass carbon to zero, however, does not lead to any changes in signs (Tables A.59-A.65).

⁹⁸ Note that the GHG mitigation balance for the other feedstocks could also change substantially if it would be assumed that they were also used energetically in the baseline scenario.

⁹⁹ In Hammond et al. (2011), however, biochar from short-rotation coppice was always more favorable than direct biomass combustion when compared to the average grid carbon intensity.

¹⁰⁰ Despite differences in the detailed calculations and despite the exclusion of emissions from transports and soil additions, the net avoided GHG emissions obtained for the solid biomass residues compare well with those derived for comparable feedstocks in the literature. For example, Hammond et al. (2011) calculated avoided GHG emissions of 0.7-1.3 t CO₂e per oven-dry tonne of feedstock for a variety of straw types, woody biomasses and *miscanthus*. Likewise, Gaunt and Cowie (2009) obtained net avoided GHG emissions of 0.9-1.06 t CO₂e/t_{DM} feedstock for wheat straw that would otherwise decompose in the field.

Differences between the feedstocks in the group of digestible biomass residues, in contrast, do not seem to be systematically driven by the different baseline scenarios, i.e. composting and manure management. Instead, feedstock characteristics tend to dominate. In particular, the different water, C and N contents of the digestible feedstocks (Table 8) translate into different energy requirements for feedstock drying, different amounts of biochar carbon to be sequestered and different CH₄ and N₂O emissions from conventional feedstock management (Figure 3). The feedstock associated with the lowest net avoided GHG emissions in this group is organic municipal solid waste.

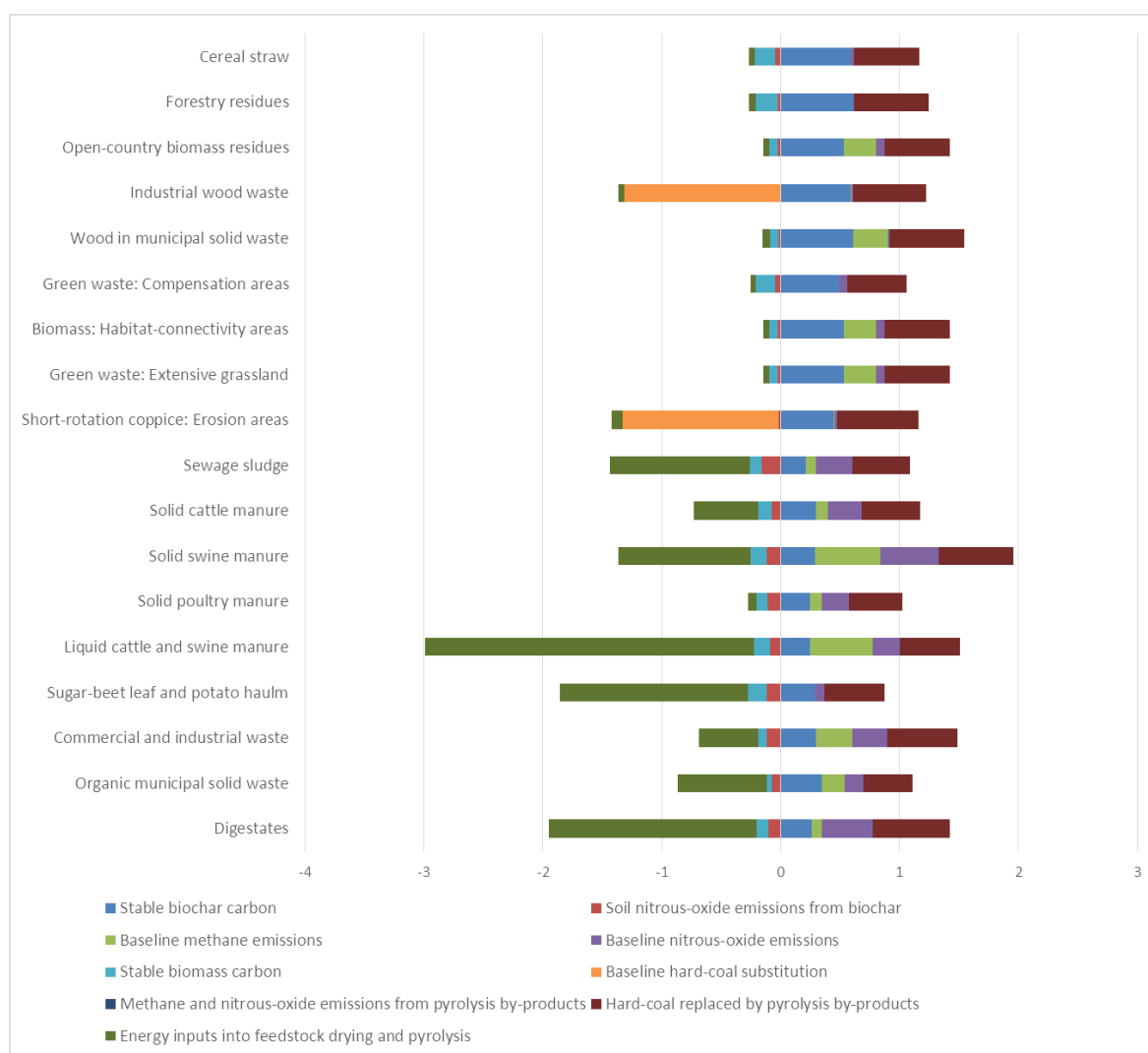


Figure 3: Components of total net avoided GHG emissions (t CO₂e/t_{DM} feedstock)

Source: Table 31 (columns 1, 2, 3, 4, 5, 6b, 7, 8b, 10b), i.e. reflecting the case of hard coal and process heat recovery; without GHG emissions from transports and soil additions.

Note: Any GHG emissions are displayed with negative sign; C removals or avoided GHG emissions with positive sign.

Concerning the type of fossil fuel used as a reference, Table 31 (columns 11-16) further shows a clear pattern for the solid feedstocks. The net avoided GHG emissions decrease from lignite to hard coal to natural gas. The reason is that, for solid feedstocks, the energy recovered in the pyrolysis by-products to offset fossil fuels substantially dominates the energy input required for biochar production (Table 19, column 5 and Table 21, columns 6 and 10). Thus, the greatest amount of GHG emissions can be avoided when replacing lignite, i.e. the fossil fuel

with the highest carbon intensity. For the digestible biomass residues, in contrast, the relation tends to be the opposite way. Except for solid poultry manure and commercial and industrial waste under process heat recovery, the most GHG emissions are avoided when natural gas is the reference fuel. The reason is that the energy recovered in the pyrolysis by-products either does not dominate the energy required for biochar production or dominates it only slightly.

Furthermore, for any given fossil-fuel type, more GHG emissions can be avoided with process heat recovery than without since the recovery of process heat reduces the necessary energy inputs into biochar production.

Finally, among the factors that lead to avoided GHG emissions or carbon-dioxide removals, the amount of carbon sequestered by biochar soil incorporation and the substitution of fossil fuels by the pyrolysis by-products stand out, the former at least for solid biomass residues (Table 31; Figure 3).¹⁰¹ Depending on the type of feedstock and the fossil fuel offset, however, the role of the pyrolysis by-products is often equally or even more important than that of biochar carbon sequestration.¹⁰² Moreover, for certain feedstocks, avoided baseline CH₄ and/or N₂O emissions are also crucial. The single most important contributor to GHG emissions, in turn, is the energy required for biochar production; however, only for the non-solid biomass residues and with the exception of solid poultry manure.

5) Revision of Assumptions and Net Avoided GHG Emissions

Based on the result that the biochar strategy does not lead to fewer GHG emissions than conventional feedstock management for sewage sludge, liquid cattle and swine manure, sugar-beet leaf and potato haulm, and digestates, we drop these feedstocks from our further analysis.¹⁰³ As a consequence, we adjust (i) the biomass scenarios and corresponding technical biomass potentials for biochar production, (ii) the number of pyrolysis units, (iii) the mean transport distances for biomass and biochar transportation and the associated transport emissions, and (iv) the total net avoided GHG emissions per dry tonne of feedstock. The revised biomass potentials and total net avoided GHG emissions enter the calculations of the technical GHG mitigation potentials of biochar, which we turn to in the next section.

5.1) Revised Biomass Potentials for Biochar Production

The biomass scenarios *Max 1*, *Med 1*, *Min 1*, *Max 2*, *Med 2* and *Min 2* in Section 3.1 were derived from the maximum residual biomass potential obtained when deducting the minimum energy requirement of 500 PJ/a from the total (updated) technical biomass potential for bioenergy given by Nitsch et al. (2004, “NaturschutzPlus” scenario) (cp. Table A.6) by assigning the maximum residual biomass potential uniformly to all the respective feedstocks

¹⁰¹ For the solid feedstocks, the results are broadly in line with Hammond et al. (2011), who report for certain straw types, woody biomasses and *miscanthus* that a share of 41-62% of the carbon abatement is provided by biochar carbon sequestration.

¹⁰² This result differs somewhat from Hammond et al. (2011) and Woolf et al. (2010a), who work with average fuel mixes instead of considering the fossil-fuel types separately. Moreover, for the digestible biomass residues, the smaller contribution of biochar carbon sequestration is also associated with the lower carbon storage potential of biochar assumed in our study (see Table 13).

¹⁰³ While a negative GHG mitigation balance is also often associated with biochar from industrial wood waste and short-rotation coppice, we keep these feedstocks since positive net avoided GHG emissions are obtained under certain scenario assumptions.

considered for biochar production (except digestates). Directing now fewer feedstocks into biochar production when excluding sewage sludge, liquid cattle and swine manure, sugar-beet leaf and potato haulm (and digestates), the application of the same procedure means that greater amounts of the remaining feedstocks can be made available for biochar.¹⁰⁴

More precisely, for the *Max 1*, *Med 1* and *Min 1* scenarios – i.e. for the set of scenarios where all the solid biomass residues and all the initial feedstocks of the (remaining) digestable biomass residues are considered for biochar production –, the change in the list of feedstocks results in about 15%, 23%, 40%, 41% and 42% of the total biomass potential for bioenergy that can be maximally used for biochar production in 2015, 2020, 2030, 2040 and 2050, respectively (Table A.66). Approximating these percentages by more accessible numbers, we, thus, arrive at the revised *Max 1* scenario of 15% in 2015, 25% in 2020 and 40% in 2030-2050 (Table 34). In the revised *Min 1* scenario, in turn, we assign the lowest share – 15% – to all periods, while we operate with 15% in 2015 and 25% in 2020-2050 in the revised *Med 1* scenario. Furthermore, the scenarios do not include digestates anymore.

Apart from the exclusion of digestates, however, no changes occur for the *Max 2*, *Med 2* and *Min 2* scenarios since they assume that all the digestable biomass residues will be digested before entering biochar production and are, thus unaffected by the elimination of sewage sludge, liquid cattle and swine manure, and sugar-beet leaf and potato haulm.

Table 34: Revised Percentage Shares of Biomass for Biochar, Germany, 2015-2050

Scenario	Solid biomass residues					Digestable biomass residues				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	%					%				
<i>Max 1</i>	15	25	40	40	40	15	25	40	40	40
<i>Max 2</i>	20	30	45	45	45	-				
<i>Med 1</i>	15	25	25	25	25	15	25	25	25	25
<i>Med 2</i>	20	30	30	30	30	-				
<i>Min 1</i>	15	15	15	15	15	15	15	15	15	15
<i>Min 2</i>	20	20	20	20	20	-				

Sources: Own assumptions, derived from the calculations in Table A.66 in Teichmann (2014). Note: - = not applicable.

The technical biomass potentials available for biochar production for the reduced set of feedstocks and revised biomass scenarios can be found in Tables 35 and 36. The corresponding biochar potentials are illustrated in Tables 37 and 38.¹⁰⁵

As can be seen from Tables 35-36, the total technical biomass potentials in the *Max 1*, *Med 1* and *Min 1* scenarios and in the *Max 2*, *Med 2* and *Min 2* scenarios, respectively, coincide in 2015, the former (3,965 kt_{DM}/a) slightly exceeding the latter (3,428 kt_{DM}/a).¹⁰⁶ In 2030, the total technical biomass potential for biochar in scenarios *Min 1* to *Max 1* ranges

¹⁰⁴ The exclusion of digestates does not have an impact on the calculation of the biomass shares for biochar.

¹⁰⁵ Compared to the potentials in Tables 5-6 and 9-10, the newly obtained total technical biomass and biochar potentials are always lower than their respective original counterparts. While, in the *Max 1*, *Med 1* and *Min 1* scenarios, the revised total biomass and biochar potentials for the group of solid biomass residues exceed those obtained originally, the revised potentials for the digestable biomass residues undercut the original values. Moreover, the potentials are diminished by the missing digestates. For the *Max 2*, *Med 2* and *Min 2* scenarios, in turn, the reduction in the biomass and biochar potentials is entirely driven by the exclusion of digestates.

¹⁰⁶ The 2015 differences in the total technical biomass potentials between the *Max 1*, *Med 1* and *Min 1* (*Max 2*, *Med 2* and *Min 2*) scenarios in Table 5 (Table 6) were driven by differences in the amounts of digestates.

from 5,494-14,650 kt_{DM}/a; in 2050, from 5,689-15,171 kt_{DM}/a (Table 35). For scenarios *Min 2* to *Max 2*, the range is from 5,378-12,101 kt_{DM}/a in 2030 and from 5,559-12,507 kt_{DM}/a in 2050 (Table 36). Thus, the greatest biomass potentials in 2030 and 2050 are available in the *Max 1* scenario and the smallest in the *Min 2* scenario. Moreover, across the different sets of scenarios, the total technical biomass potentials compare as follows: *Max 1* > *Max 2*, *Med 1* > *Med 2* and *Min 1* > *Min 2*.¹⁰⁷ The feedstocks associated with the highest potential amounts of biomass for biochar are forestry residues, short-rotation coppice from erosion areas (from 2030 onwards), and solid cattle manure (in the *Max 1*, *Med 1* and *Min 1* scenarios).

The technical biomass potentials from the *Max 1*, *Med 1* and *Min 1* scenarios are converted into 1,424 kt/a biochar in 2015, 1,857-4,951 kt/a in 2030 and 1,925-5,133 kt/a in 2050 (Table 37). For the *Max 2*, *Med 2* and *Min 2* scenarios, in turn, biochar production amounts to 1,049 kt/a in 2015, 1,586-3,569 kt/a in 2030 and 1,641-3,693 kt/a in 2050 (Table 38). As for the biomass potentials, the ranking of the biochar potentials is *Max 1* > *Max 2*, *Med 1* > *Med 2*, and *Min 1* > *Min 2*. Driven by the biomass potentials, the largest amounts of biochar can be obtained from forestry residues, short-rotation coppice from erosion areas (from 2030 onwards), and solid cattle manure (in the *Max 1*, *Med 1* and *Min 1* scenarios).

Exploiting the maximum biochar potentials in each year, i.e. those associated with the *Max 1* scenario – 1,424 kt/a in 2015, 2,601 kt/a in 2020, 4,951 kt/a in 2030, 5,064 kt/a in 2040 and 5,133 kt/a in 2050 (Table 37) –, and adding biochar sequentially to more and more land, the acreage of arable land assumed available in Germany in 2015-2050 (Table A.8) would be covered shortly before 2050 at a biochar deployment rate of 10 t/ha when considering the lower acreage of 11.29 million ha.¹⁰⁸ For the higher deployment rates of 25 t/ha and 50 t/ha, the acreage would not be exhausted over the considered time horizon. Since biochar application in the case of 10 t/ha could be repeated on the same spot after 20 or 30 years, the acreage is not regarded as a limiting factor.

5.2) Revised Number of Pyrolysis Units

Based on the revised technical biomass potentials for biochar, the number of pyrolysis units in operation in each period for each given biomass scenario is presented in Table 39.

Table 39: Revised Number of Pyrolysis Units in Operation, Germany, 2015-2050

Bio-mass sce-nario	Small-scale pyrolysis units (à 2,000 t _{DM} feedstock/a)					Medium-scale pyrolysis units (à 16,000 t _{DM} feedstock/a)					Large-scale pyrolysis units (à 184,800 t _{DM} feedstock/a)				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	units/a					units/a					units/a				
<i>Max 1</i>	2,478	4,556	9,157	9,352	9,482	310	569	1,145	1,169	1,185	27	49	99	101	103
<i>Med 1</i>	2,478	4,556	5,723	5,845	5,926	310	569	715	731	741	27	49	62	63	64
<i>Min 1</i>	2,478	2,733	3,434	3,507	3,556	310	342	429	438	444	27	30	37	38	38
<i>Max 2</i>	2,143	3,644	7,563	7,705	7,817	268	455	945	963	977	23	39	82	83	85
<i>Med 2</i>	2,143	3,644	5,043	5,137	5,211	268	455	630	642	651	23	39	55	56	56
<i>Min 2</i>	2,143	2,429	3,361	3,424	3,474	268	304	420	428	434	23	26	36	37	38

Sources: Own calculations, based on the biomass totals given in Tables 35 and 36 and a common load factor of 0.8 (values rounded).

Notes: DM = dry mass. a = year. t = tonne.

¹⁰⁷ Just focusing on the solid biomass residues, however, the technical biomass potentials under the second set of scenarios is always larger, i.e. *Max 2* > *Max 1*, *Med 2* > *Med 1*, *Min 2* > *Min 1*.

¹⁰⁸ Note that we assume that the given biochar potential is available annually throughout each considered decade.

Driven by the lower total technical biomass potentials in all the biomass scenarios, the revised numbers of pyrolysis units are always smaller than the corresponding original numbers given in Table 11.

5.3) Revised Transport Distances and Emissions

The revised numbers of pyrolysis units lead to changes in the mean transport distances between the pyrolysis units and the sources of biomass as well as the farms for biochar application. The revised mean transport distances can be found in Table A.67.

The corresponding revised GHG emissions from the transportation of biomass to the pyrolysis units for the *Max 1* and *Max 2* scenarios are displayed in Tables 40 and 41, while those for the remaining biomass scenarios can be found in Tables A.68-A.71. The revised GHG emissions from the transportation of biochar, in turn, are presented in Tables 42 and 43 for the *Max 1* and *Max 2* scenarios and in Tables A.72-A.75 for the remaining biomass scenarios. While the transport emissions have increased due to the lower numbers of pyrolysis units and, thus, the greater mean transport distances, they are still not substantial.

5.4) Revised Total Net Avoided GHG Emissions per Dry-Feedstock Tonne

Based on the recalculated transport emissions, the revised net avoided GHG emissions from all transports and soil additions are displayed in Tables A.76-A.81.

Further, the revised total net avoided GHG emissions per dry tonne of feedstock turned into biochar can be found in Tables 44 and 45 for the *Max 1* and *Max 2* scenarios in 2030 and in Tables A.82-A.93 for all the remaining biomass scenarios and periods. Due to the low level of transport emissions, the revised total net avoided GHG emissions hardly differ from those obtained in Section 4.5.

6) Technical GHG Mitigation Potentials of Biochar

Multiplying the total net avoided GHG emissions per tonne of dry-matter feedstock from Tables 44-45 and A.82-A.93 by the respective technical biomass potentials for biochar production from Tables 35-36, we obtain the technical GHG mitigation potentials that can be achieved by biochar soil incorporation in Germany in combination with the energetic use of the pyrolysis by-products. For 2015, they are displayed in Tables 46 and 47. Tables 48-50, in turn, contain the technical GHG mitigation potentials for the *Max 1*, *Min 1* and *Max 2* scenarios in 2030, while the GHG mitigation potentials for all the remaining biomass scenarios and periods can be found in Tables A.94-A.102.

After a detailed discussion of the total technical GHG mitigation potentials of biochar, we analyze the technical GHG mitigation potentials per type of feedstock.

6.1) Total Technical GHG Mitigation Potentials

Differentiated by the type of biomass scenario, the total technical GHG mitigation potential of biochar in 2015 is largest in the *Max 1* (= *Med 1* = *Min 1*) scenario for all the cases where natural gas is used as fossil fuel and else in the *Max 2* (= *Med 2* = *Min 2*) scenario (Tables 46

and 47).¹⁰⁹ For 2030 and 2050, in turn, the greatest total technical GHG mitigation potentials are always achieved in the *Max 1* scenario, while the *Min 1* biomass scenario always leads to the smallest GHG mitigation potentials, irrespective of variations in any other assumptions (Tables 48-50 and A.94-A.102). Thus, while the finding for the *Max 1* scenario coincides with its position in the technical biomass potentials, the *Min 1* scenario ranks last despite its greater biomass potential compared to the *Min 2* scenario – due to the just-mentioned influence of the net avoided GHG emissions per dry tonne of feedstock.

Independent of the respective biomass scenario and year, it is always found that the total technical GHG mitigation potentials are highest for small-scale pyrolysis units and lowest for large-scale pyrolysis units, caused by the lower mean transport distances for the smaller technology scales. However, the variations across the pyrolysis-unit scales are very tiny due to the generally low transport emissions. Moreover, based on the more favorable energy balance, process heat recovery is associated with greater GHG mitigation potentials than no process heat recovery. Furthermore, the use of lignite as fossil fuel leads to the greatest total GHG mitigation potentials; the use of natural gas to the lowest. This is mainly driven by the net avoided GHG emissions per tonne of dry-matter feedstock in the group of solid biomass residues (cp. Section 4.5) and the dominating role of solid feedstocks in the total biomass potentials for biochar (Tables 35-36). Thus, for each given biomass scenario and year, the maximum total technical GHG mitigation potential of biochar is always obtained for small-scale pyrolysis units in combination with process heat recovery and the choice of lignite as fossil fuel. Likewise, the minimum total technical GHG mitigation potential is always achieved for large-scale pyrolysis units, where no process heat is recovered and where natural gas is used as fossil fuel.

To summarize, the maximum total technical GHG mitigation potential in 2015 is reached with the *Max 2* (= *Med 2* = *Min 2*) biomass scenario where biochar is produced in small-scale pyrolysis units with process heat recovery and where lignite is used as fossil fuel; the smallest total technical GHG mitigation potential, in turn, is associated with the *Max 2* (= *Med 2* = *Min 2*) biomass scenario where biochar is produced in large-scale pyrolysis units with no process heat recovery and where natural gas is used as fossil fuel. The total technical GHG mitigation potential in 2015, thus, ranges from 2,136-3,169 kt CO₂e/a (Tables 46-47). In both 2030 and 2050, the total technical GHG mitigation potential is highest for the *Max 1* biomass scenario in combination with the same assumptions concerning technology scale, process heat and fossil-fuel type as for the maximum GHG mitigation potential in 2015; likewise, it is lowest for the *Min 1* biomass scenario and the same remaining assumptions as for the minimum GHG mitigation potential in 2015. Consequently, the total annual technical GHG mitigation potential ranges from 2,804-10,157 kt CO₂e/a in 2030 (Tables 48-50 and A.94-A.96) and from 2,920-10,587 kt CO₂e/a in 2050 (Tables A.97-A.102). This is equivalent to about 0.4-1.5% of the annual GHG reduction target of 688 Mt CO₂e to be achieved by 2030 and 0.3-1.1% of the annual reduction target of 1,001 Mt CO₂e envisaged for 2050.¹¹⁰

¹⁰⁹ While the technical biomass potentials in the 2015 *Max 1* (= *Med 1* = *Min 1*) scenario are always larger than those in the *Max 2* (= *Med 2* = *Min 2*) scenario (Section 5.1), the *Max 2* scenario can lead to greater GHG mitigation potentials since the biomass potentials of the solid biomass residues in the *Max 2* scenario exceed those from *Max 1* (Tables 35 and 36) and since greater net avoided GHG emissions per dry tonne of feedstock tend to be associated with solid biomass residues than with digestible biomass residues (Table 31). Within the group of digestible biomass residues, in turn, the net avoided GHG emissions for the feedstocks that dominate quantitatively – solid cattle manure, solid swine manure and organic municipal solid waste (Table 35) – are greatest when natural gas is used as fossil fuel (Table 31).

¹¹⁰ Note that slightly different GWPs for CH₄ and N₂O were used in the calculation of the GHG reduction targets (see above). Adjusting the GHG reduction targets for the GWPs used in this study, however, does not give rise to significant changes in the percentages. The adjusted GHG reduction targets amount to 697 Mt CO₂e in 2030 and

Comparisons of the total technical GHG mitigation potentials of biochar with those from other mitigation measures lead to mixed results. Against the GHG abatement that could be potentially achieved with CCS in Germany, for example, the GHG mitigation potentials of biochar seem modest. For 2030, for example, McKinsey (2007) arrived at annual GHG mitigation potentials from CCS of 66 Mt CO₂e in the energy sector and of 38 Mt CO₂e in the industrial sectors.¹¹¹ At the same time, however, the study by McKinsey (2007) also reveals that many other mitigation measures might lead to net GHG emissions reductions well below the 10-11 Mt CO₂e/a that can be reached with biochar. These include many industry-specific measures – like clinker substitution in the cement industry or reductions of N₂O emissions from the chemicals industry – or measures to be taken in the transport sector – such as the introduction of hybrid engines or vehicle optimizations.

6.2) Technical GHG Mitigation Potentials per Type of Feedstock

Finally, taking a closer look at the contributions of the single feedstocks to the technical GHG mitigation potentials of biochar, Tables 46-50 and A.94-A.102 reveal that by far the greatest GHG mitigation potentials – across all biomass scenarios and remaining assumptions – are derived from forestry residues, with 868-1,824 kt CO₂e/a in 2015, 981-4,632 kt CO₂e/a in 2030 and 1,060-5,004 kt CO₂e/a in 2050. As illustrated in Figures 4-5, this result is mainly driven by the huge biomass potentials considered for forestry residues (see also Section 5.1).

At least in 2030 and 2050, the next-largest GHG mitigation potentials are associated with biochar from cereal straw, green waste from extensive grassland and solid cattle manure, however, with huge gaps to biochar from forestry residues and closely followed by biochar from some other solid feedstocks (Tables 46-50 and A.94-A.102; Figures 4-5). Thereby, the contribution of cereal straw follows from the combination of relatively substantial biomass potentials (Tables 35-36) with relatively favorable net avoided GHG emissions per dry tonne of feedstock (Tables 44-45 and A.82-A.93). The GHG mitigation potential of biochar from green waste from extensive grassland, in turn, is obtained despite a moderate biomass potential – due to considerable net avoided GHG emissions (Tables 35-36, 44-45 and A.82-A.93). The opposite holds for solid cattle manure, where the feedstock's high biomass potential – which is amongst the highest (see Section 5.1) – cannot be transferred to a similar GHG mitigation potential due to the low net avoided GHG emissions (e.g., Figures 4-5).

Among the feedstocks associated with the lowest GHG mitigation potentials of biochar are industrial wood waste and short-rotation coppice (Tables 46-50 and A.94-A.102), for which positive net avoided GHG emissions are only obtained under certain circumstances (Tables 44-45 and A.82-A.93). This is due to the assumption that these feedstocks are used energetically in the baseline scenario and substitute for fossil fuels (see Section 4.5). As illustrated in Figure 5, for short-rotation coppice, the tiny net avoided GHG emissions mean that hardly any GHG mitigation can be achieved from this feedstock despite its considerable technical biomass potential – one of the greatest from 2030 onwards (see Section 5.1).^{112, 113}

1,014 Mt CO₂e in 2050. They are based on the 1990 CH₄ emissions of 109,950 Gg CO₂e at a GWP of 21, the 1990 N₂O emissions of 86,804 Gg CO₂e at a GWP of 310, and the corresponding total CO₂e emissions (without LULUCF) of 1,250, 529 Gg CO₂e (UBA 2013: Table 1) – which change to 1,268,112 Gg CO₂e when using the GWPs of 25 for CH₄ and 298 for N₂O. Note that 1,000 Gg = 1 Mt.

¹¹¹ While the timing for the implementation of CCS assumed by McKinsey (2007) seems outdated (cp. von Hirschhausen et al. 2012), the orders of magnitude of the GHG mitigation potentials can still be compared.

¹¹² Before 2030, the technical biomass potential of short-rotation coppice was assumed to be zero (Tables 35-36).

¹¹³ As discussed above, the same could happen to the other feedstocks if their baseline scenario would be changed to an energetic use of the biomass.

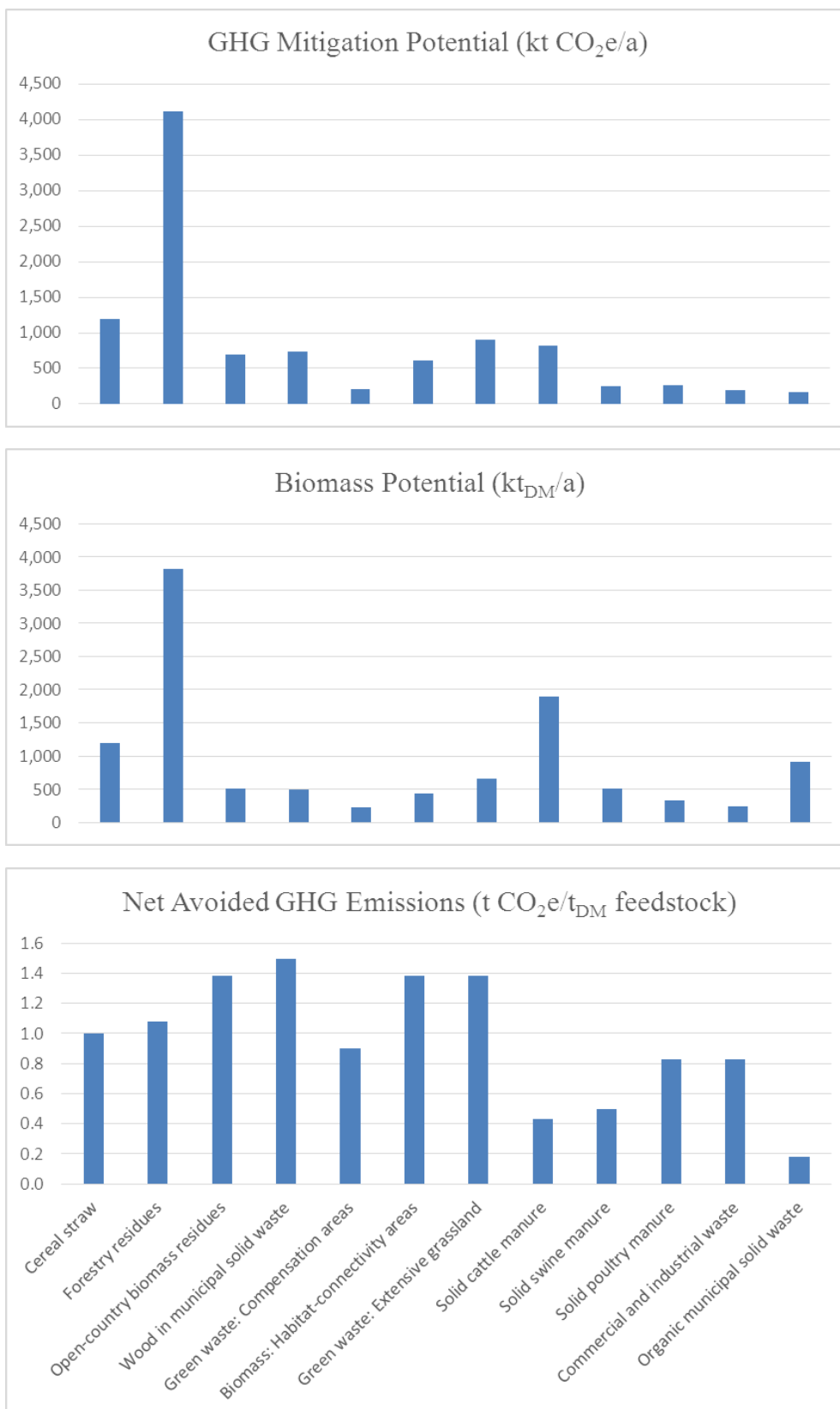


Figure 4: Breakdown of the 2030 *Max 1* scenario for small-scale pyrolysis units, process heat recovery and lignite

Sources: Table 48 (column 4), Table 35 (column 3), Table 32 (column 4).

Notes: Without industrial wood waste and short-rotation coppice due to their negative contribution to GHG mitigation with biochar under the given assumptions.

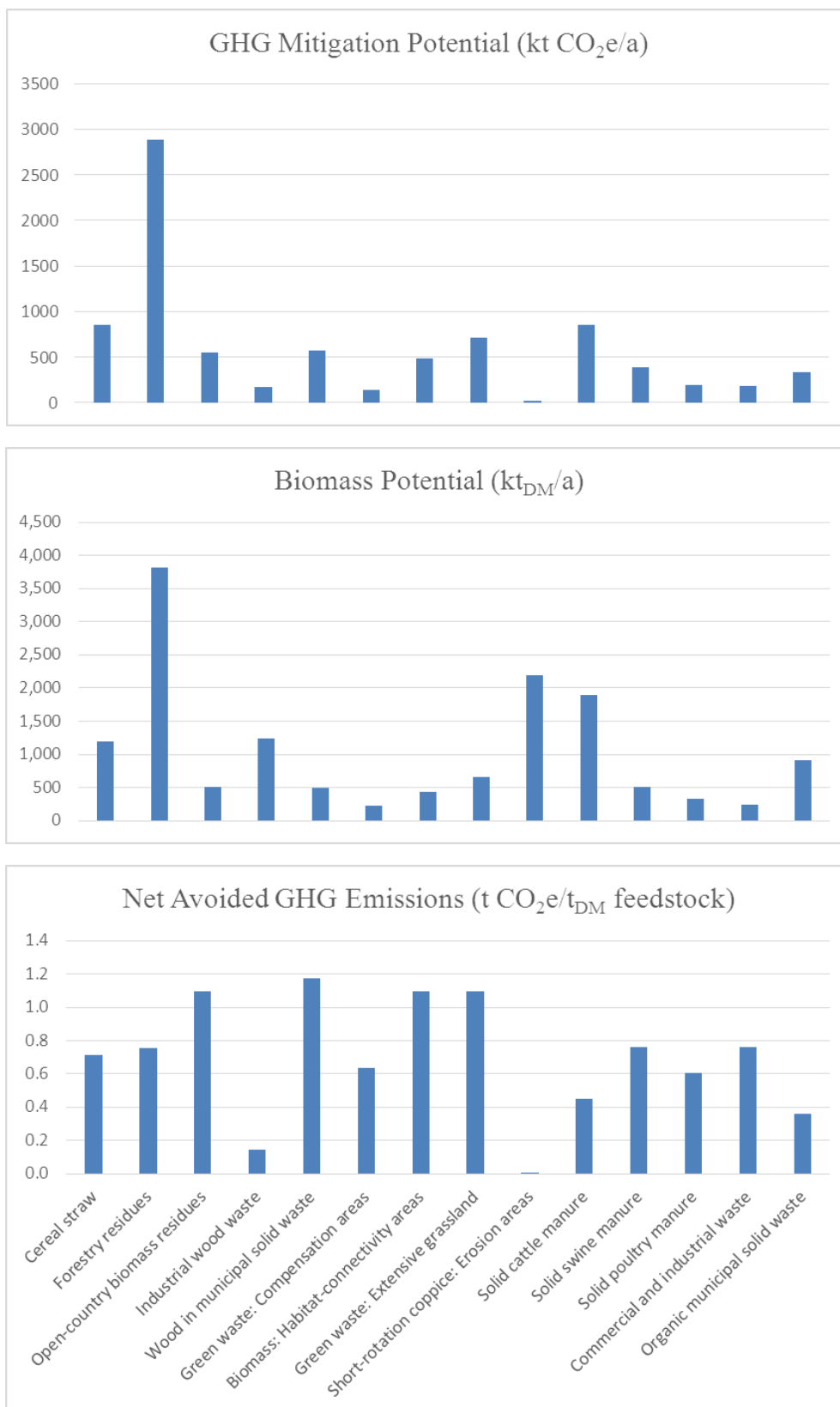


Figure 5: Breakdown of the 2030 *Max 1* scenario for small-scale pyrolysis units, process heat recovery and natural gas

Sources: Table 48 (column 6), Table 35 (column 3), Table 32 (column 6).

7) Conclusion

For the time horizons 2015, 2030 and 2050, we have analyzed the technical GHG mitigation potentials of slow-pyrolysis biochar from a broad range of biomass residues relevant in Germany. In addition to carbon sequestration via biochar soil incorporation, we have included the energetic use of the pyrolysis by-products to offset GHG emissions from fossil fuels. However, due to the huge uncertainties about biochar-soil interactions, we have abstracted from possible agricultural benefits of biochar soil incorporation.

The wide variety of feedstocks included in our study has allowed us to draw a comprehensive picture of biochar in Germany. Compared to the literature, our analysis is more dynamic in that we provide for GHG mitigation potentials of biochar until mid-century. Moreover, we account for feedstock-specific biochar yields, carbon contents and other biochar properties from an extensive literature survey.

In addition to the amount of biochar carbon expected to remain stable in soil in the long-term, the total technical GHG mitigation potentials of biochar hinge on assumptions about the type and amount of biomass potentially available for biochar production, about the baseline scenario, the type of fossil fuel used in biochar production and replaced by the pyrolysis by-products, and whether process heat from pyrolysis is recovered or not. Of less importance, however, are the scales of the pyrolysis plants and, thus, the mean transport distances for biomass and biochar. Moreover, while the amount of biochar carbon sequestered in soil is an important factor for the technical GHG mitigation potentials of biochar, the contribution of the pyrolysis by-products offsetting GHG emissions from fossil fuels might often be equally or even more important than that of biochar soil incorporation.

Regarding the type of feedstock and associated baseline scenario, wet biomass residues tend to abate less GHGs per tonne of dry-matter feedstock than dry biomass feedstocks. The main reason for this observation is the energy required to dry the wet feedstocks. For some feedstocks (sewage sludge, liquid cattle and swine manure, sugar-beet leaf and potato haulm, and digestates), this has even led to a negative GHG mitigation balance. Moreover, an energetic use of biomass – as assumed for industrial wood waste and short-rotation coppice – seems more favorable than the biochar strategy, at least if lignite and hard coal are used as fossil fuels. Even for the case of natural gas, however, where the GHG mitigation balance for biochar from industrial wood waste and short-rotation coppice has often become positive, the net avoided GHG emissions tended to be very small.

Just focusing on feedstocks associated with a positive GHG mitigation balance, the total technical GHG mitigation potentials of biochar range from 2,136-3,169 kt CO₂e/a in 2015, from 2,804-10,157 kt CO₂e/a in 2030 and from 2,920-10,587 kt CO₂e/a in 2050. A considerable amount thereof is contributed by biochar from forestry residues. Assessed against the respective GHG reduction targets established by the German government, the total technical GHG mitigation potentials translate into 0.4-1.5% of the annual reduction target that can be achieved with the help of biochar in 2030 and 0.3-1.1% in 2050. While these shares seem modest when compared to the GHG mitigation potential that could be obtained with CCS – if implemented –, the technical GHG mitigation potentials of biochar compare well with many other abatement measures in the industry and transport sectors, for example.

While the available acreage in Germany for biochar soil incorporation does not tend to be a constraint, the technical GHG mitigation potential of biochar is ultimately restricted by the quantity of biomass that can be provided for biochar production. The competition for biomass is high and likely to increase in the future, in particular for biomass residues. The technical biomass potentials assumed available for biochar production were chosen to reflect varying degrees of competition for biomass with bioenergy generation. A detailed analysis of the competing biomass uses, however, was beyond the scope of this paper.

The GHG mitigation potentials calculated in this study reflect technical mitigation potentials. In their own, they do not give insights about the economic efficiency of carbon sequestration with biochar. A forthcoming analysis of the GHG abatement costs of biochar will provide an economic assessment of biochar and reveal to what extent the just-derived technical GHG mitigation potentials are economically viable.

Moreover, the selection of assumptions and parameters was guided by our emphasis on biochar carbon sequestration, i.e. on the maximization of stable biochar carbon, which resulted in the choice of the slow-pyrolysis process. Other conclusions about the technical GHG mitigation potential of biochar might be drawn when focusing on the use of biochar for energetic purposes, on pyrolysis oils and gases (for energetic use) rather than on biochar, or on the nutrient value of biochar to optimize its use in agriculture. The trade-offs between the choice of feedstock, conversion process, highest heating temperature, biochar (carbon) yield, and biochar carbon stability call for more detailed analyses of the optimal feedstock-specific GHG mitigation strategies with biochar. In particular, the findings obtained for wet biomass residues, such as sewage sludge, liquid cattle and swine manure, sugar-beet leaf and potato haulm or digestates, might change tremendously when transforming these feedstocks in the HTC process and using the resulting hydrochar as a source of renewable energy.

Finally, future research should reveal whether the results obtained for industrial wood waste and short-rotation coppice, i.e. for the baseline scenario of direct biomass combustion, can be generalized for other solid feedstocks, and how biochar soil incorporation compares to biogas production from the digestable feedstocks. Another interesting question is how far possible agricultural benefits could further improve the GHG mitigation potential of biochar. Profound analyses of the agricultural benefits, however, still require more research into the long-term effects of biochar in agriculture.

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Appendix

Table 5: Biomass Potentials for Biochar Production, Germany, 2015-2050, Scenarios *Max 1*, *Med 1* and *Min 1*

Feedstocks	Scenario <i>Max 1</i>					Scenario <i>Med 1</i>					Scenario <i>Min 1</i>				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	kt _{DM} /a					kt _{DM} /a					kt _{DM} /a				
Cereal straw	304	630	1,040	1,078	1,078	304	630	594	616	616	304	315	297	308	308
Forestry residues	845	1,783	3,337	3,466	3,605	845	1,783	1,907	1,980	2,060	845	891	953	990	1,030
Open-country biomass residues	126	253	442	442	442	126	253	253	253	253	126	126	126	126	126
Industrial wood waste	310	620	1,084	1,084	1,084	310	620	620	620	620	310	310	310	310	310
Wood in municipal solid waste	129	254	429	438	438	129	254	245	250	250	129	127	123	125	125
Green waste: Compensation areas	0	114	200	200	200	0	114	114	114	114	0	57	57	57	57
Biomass: Habitat-connectivity areas	0	92	385	385	385	0	92	220	220	220	0	46	110	110	110
Green waste: Extensive grassland	0	142	571	571	571	0	142	326	326	326	0	71	163	163	163
Short-rotation coppice: Erosion areas	0	0	1,925	1,925	1,925	0	0	1,100	1,100	1,100	0	0	550	550	550
Solid biomass residues	1,714	3,887	9,412	9,588	9,728	1,714	3,887	5,378	5,479	5,559	1,714	1,943	2,689	2,740	2,779
Sewage sludge	82	184	338	338	338	82	184	193	193	193	82	92	97	97	97
Solid cattle manure	478	969	1,664	1,693	1,693	478	969	951	967	967	478	485	475	484	484
Solid swine manure	132	266	447	454	454	132	266	255	259	259	132	133	128	130	130
Solid poultry manure	69	151	285	285	285	69	151	163	163	163	69	76	81	81	81
Liquid cattle and swine manure	906	1,835	3,138	3,193	3,193	906	1,835	1,793	1,825	1,825	906	918	897	912	912
Sugar-beet leaf and potato haulm	90	180	309	309	309	90	180	177	177	177	90	90	88	88	88
Commercial and industrial waste	60	119	208	208	208	60	119	119	119	119	60	60	60	60	60
Organic municipal solid waste	191	439	804	864	907	191	439	459	494	518	191	220	230	247	259
Digestable biomass residues	2,007	4,144	7,193	7,344	7,387	2,007	4,144	4,110	4,197	4,221	2,007	2,072	2,055	2,098	2,111
Corn-silage digestates	2,692	2,692	2,692	2,978	2,978	1,795	1,795	1,795	1,986	1,986	897	897	897	993	993
Digestates (energy crops)	2,692	2,692	2,692	2,978	2,978	1,795	1,795	1,795	1,986	1,986	897	897	897	993	993
TOTAL	6,413	10,723	19,296	19,911	20,093	5,516	9,826	11,283	11,661	11,765	4,618	4,913	5,641	5,831	5,883

Sources: Own calculations, based on Tables 1, 3 and 4 (values rounded).

Notes: DM = dry mass. a = year. kt = kiloton.

Table 6: Biomass Potentials for Biochar Production, Germany, 2015-2050, Scenarios *Max 2*, *Med 2* and *Min 2*

Feedstocks	Scenario <i>Max 2</i>					Scenario <i>Med 2</i>					Scenario <i>Min 2</i>				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	kt _{DM} /a					kt _{DM} /a					kt _{DM} /a				
Cereal straw	607	945	1,337	1,386	1,386	607	945	891	924	924	607	630	594	616	616
Forestry residues	1,690	2,674	4,290	4,456	4,635	1,690	2,674	2,860	2,971	3,090	1,690	1,783	1,907	1,980	2,060
Open-country biomass residues	253	379	569	569	569	253	379	379	379	379	253	253	253	253	253
Industrial wood waste	620	929	1,394	1,394	1,394	620	929	929	929	929	620	620	620	620	620
Wood in municipal solid waste	259	381	551	563	563	259	381	368	375	375	259	254	245	250	250
Green waste: Compensation areas	0	171	257	257	257	0	171	171	171	171	0	114	114	114	114
Biomass: Habitat-connectivity areas	0	138	495	495	495	0	138	330	330	330	0	92	220	220	220
Green waste: Extensive grassland	0	213	734	734	734	0	213	489	489	489	0	142	326	326	326
Short-rotation coppice: Erosion areas	0	0	2,475	2,475	2,475	0	0	1,650	1,650	1,650	0	0	1,100	1,100	1,100
Solid biomass residues	3,428	5,830	12,101	12,328	12,507	3,428	5,830	8,068	8,219	8,338	3,428	3,887	5,378	5,479	5,559
Sewage sludge (D)	392	432	446	446	446	261	288	298	298	298	131	144	149	149	149
Solid cattle manure (D)	2,942	2,985	2,928	2,981	2,981	1,962	1,990	1,952	1,987	1,987	981	995	976	994	994
Solid swine manure (D)	763	767	736	748	748	509	511	491	499	499	254	256	245	249	249
Solid poultry manure (D)	339	374	403	403	403	226	250	269	269	269	113	125	134	134	134
Liquid cattle and swine manure (D)	4,676	4,738	4,633	4,714	4,714	3,118	3,159	3,089	3,143	3,143	1,559	1,579	1,544	1,571	1,571
Sugar-beet leaf and potato haulm (D)	367	368	362	362	362	245	245	241	241	241	122	123	121	121	121
Commercial and industrial waste (D)	220	220	220	220	220	147	147	147	147	147	73	73	73	73	73
Organic municipal solid waste (D)	870	999	1,044	1,123	1,179	580	666	696	749	786	290	333	348	374	393
Digestates (biomass residues)	10,568	10,882	10,771	10,995	11,051	7,046	7,255	7,181	7,330	7,368	3,523	3,627	3,590	3,665	3,684
Corn-silage digestates	2,692	2,692	2,692	2,978	2,978	1,795	1,795	1,795	1,986	1,986	897	897	897	993	993
Digestates (energy crops)	2,692	2,692	2,692	2,978	2,978	1,795	1,795	1,795	1,986	1,986	897	897	897	993	993
TOTAL	16,688	19,404	25,564	26,301	26,536	12,268	14,879	17,043	17,534	17,691	7,848	8,411	9,866	10,137	10,235

Sources: Own calculations, based on Tables 1 to 4 (values rounded).

Notes: DM = dry mass. a = year. kt = kiloton. For feedstocks indicated by (D), the biomass potentials refer to the digestates obtained from these feedstocks.

Table 8: Feedstock Properties and Associated Slow-Pyrolysis Biochar Yields and Characteristics

Feedstocks	Feedstock characteristics					Product distribution			Biochar characteristics							
	Elements		Ash	Water	HHV	Char	Li- quid	Gas	Fixed C	Ash	Elements				HHV	C reco- very ²
	C	N									C	N	P	K		
	wt% _{db}		wt% [§]	MJ/kg _{db}	wt% _{db} ^{§§, §§§}						wt% ^{§§§}				MJ/kg ^{§§§}	% _{db} ^{§§§}
	(1)	(2)									(11)	(12)	(13)	(14)		
Cereal straw	47	0.47	6.9	7.9	17.9	34	21	39	n.a.	13.8	70	0.65	n.a.	2.17	24.7	50
Forestry residues ¹	49	0.17	0.9	10.8	19.7	30	46	23	69	2.1	81	0.36	0.002	0.13	29.8	46
Open-country biomass residues	46	0.74	4.6	7.8	18.7	31	47	23	66	12.4	69	0.68	0.002 [¶]	0.13 [¶]	29.8	46
Industrial wood waste	49	0.13	0.8	8.1	19.3	29	46	24	69	2.0	82	0.16	0.002	0.13	30.3	46
Wood in municipal solid waste	49	0.16	0.9	10.9	19.7	30	47	23	69	2.2	81	0.37	0.002	0.13	29.8	47
Green waste: Compensation areas	45	1.03	6.5	6.3	18.2	32	n.a.	n.a.	65 ^{¶¶}	17.5	63 ^{¶¶}	0.83	n.a.	n.a.	29.8 ^{**}	45
Biomass: Habitat-connectivity areas	46	0.74	4.6	7.8	18.7	31	47	23	66	12.4	69	0.68	0.002 [¶]	0.13 [¶]	29.8	46
Green waste: Extensive grassland	46	0.74	4.6	7.8	18.7	31	47	23	66	12.4	69	0.68	0.002 [¶]	0.13 [¶]	29.8	46
Short-rotation coppice: Erosion areas	47	0.38	1.3	17.9	19.3	25	n.a.	n.a.	n.a.	5.3	72	0.93	n.a.	n.a.	29.8	47
Sewage sludge	36	3.97	33.7	79.5	17.0	49	32	10	24	40.3	35	4.40	5.60	n.a.	17.5	46
Solid cattle manure	40	2.42	16.9	63.6	17.3	47	n.a.	n.a.	34	34.7	51	1.82	0.87	3.58	18.8	55
Solid swine manure	47	4.35	19.7	78.5	19.4	47	n.a.	n.a.	33	43.7	49	3.17	6.02	2.37	18.2	49
Solid poultry manure	36	3.59	21.9	13.4	14.5	44	39	19	24	42.9	46	3.12	2.76	5.85	15.4	57
Liquid cattle and swine manure	46	3.13	14.8	90.2	17.6	45	n.a.	n.a.	28	41.6	44	2.31	0.89	2.26	19.9	54
Sugar-beet leaf and potato haulm	43	1.33	25.0	84.0	16.9 [*]	45 [*]	n.a.	n.a.	n.a.	n.a.	51 [*]	3.02 [*]	n.a.	n.a.	18.0 [*]	n.a.
Commercial and industrial waste	50	3.07	6.3	61.3	16.9 [*]	37	20	29	48	17.6	66	4.18	n.a.	2.05	18.0 [*]	41
Organic municipal solid waste	31	1.67	23.1	70.9	15.2	45 [*]	n.a.	n.a.	45	23.0	63	2.14	0.53	2.36	18.0 [*]	n.a.
Digestates	37	5.59	28.6	85.3	16.8	49	33	10	28	38.8	42	2.57	0.68	1.04	11.6	29

Sources: Own calculations; averages over suitable reference feedstocks as calculated in Table A.7 (values rounded). Tables numbered with the leading “A.” refer to Teichmann (2014).

Notes: Due to missing data, the specific feedstocks entering the means of a given feedstock category might differ across the single characteristics. C = carbon. N = nitrogen. P = phosphorus. K = potassium. HHV = higher heating value. wt% = weight percent. db = dry base. kg = kilogram. MJ = megajoule. n.a. = not available. § = Based on as-received fresh weight. §§ = Based on feedstock dry weight. Note that it was not always entirely clear from the literature cited in Table A.7 whether the char, liquid and gas yields were indeed based on the feedstock dry weights. Still, the values have been assigned to this measurement unit. The reason is that, if the char yields were truly given on the basis of feedstock fresh weights, the direction of bias would be an underestimation of the char yields, leading to conservative measures, not overstating the impact of biochar. §§§ = Note that we do not differentiate between biochar fresh weight and biochar dry weight since the water contents of biochar tend to be below 4% (e.g., Kern et al. 2012b; Inguanzo et al. 2002; Hossain et al. 2011; Spokas et al. 2011) and are, thus, considered to be negligible. For further details, see Table A.7.

* Due to the lack of feedstock-specific data, calculated as average over the respective values for digestable biomass residues.

** Due to the lack of feedstock-specific data, the same value as for *Green waste: Extensive grassland* was assigned.

¶ Driven by the share of woody biochar due to the lack of P and K data for biochar from herbaceous biomass (see Table A.7).

¶¶ Note that the value for biochar fixed carbon (column 9) exceeds the total biochar carbon of column 11 since the respective means are not based on the same feedstocks due to data availability (see Table A.7).

1) Weighted average of the means for forestry residues (95%) and additional forestry residues from historical-forest formation (5%) (see Table A.7), based on the dry-mass values from Table A.1.

2) Own calculation, (16) = (6) · (11)/(1).

Table 9: Slow-Pyrolysis Biochar Potentials, Germany, 2015-2050, Scenarios *Max 1*, *Med 1* and *Min 1*

Feedstocks	Scenario <i>Max 1</i>					Scenario <i>Med 1</i>					Scenario <i>Min 1</i>				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	kt/a					kt/a					kt/a				
Cereal straw	103	214	354	367	367	103	214	202	210	210	103	107	101	105	105
Forestry residues	254	535	1,001	1,040	1,082	254	535	572	594	618	254	267	286	297	309
Open-country biomass residues	39	78	137	137	137	39	78	78	78	78	39	39	39	39	39
Industrial wood waste	90	180	314	314	314	90	180	180	180	180	90	90	90	90	90
Wood in municipal solid waste	39	76	129	131	131	39	76	74	75	75	39	38	37	38	38
Green waste: Compensation areas	0	36	64	64	64	0	36	36	36	36	0	18	18	18	18
Biomass: Habitat-connectivity areas	0	28	119	119	119	0	28	68	68	68	0	14	34	34	34
Green waste: Extensive grassland	0	44	177	177	177	0	44	101	101	101	0	22	51	51	51
Short-rotation coppice: Erosion areas	0	0	481	481	481	0	0	275	275	275	0	0	138	138	138
Solid biomass residues	525	1,192	2,776	2,830	2,872	525	1,192	1,586	1,617	1,641	525	596	793	809	821
Sewage sludge	40	90	165	165	165	40	90	95	95	95	40	45	47	47	47
Solid cattle manure	224	455	782	796	796	224	455	447	455	455	224	228	223	227	227
Solid swine manure	62	125	210	213	213	62	125	120	122	122	62	62	60	61	61
Solid poultry manure	30	67	125	125	125	30	67	72	72	72	30	33	36	36	36
Liquid cattle and swine manure	408	826	1,412	1,437	1,437	408	826	807	821	821	408	413	404	411	411
Sugar-beet leaf and potato haulm	41	81	139	139	139	41	81	80	80	80	41	41	40	40	40
Commercial and industrial waste	22	44	77	77	77	22	44	44	44	44	22	22	22	22	22
Organic municipal solid waste	86	198	362	389	408	86	198	207	222	233	86	99	103	111	117
Digestable biomass residues	913	1,886	3,273	3,342	3,361	913	1,886	1,870	1,910	1,921	913	943	935	955	960
Corn-silage digestates	1,319	1,319	1,319	1,459	1,459	879	879	879	973	973	440	440	440	486	486
Digestates (energy crops)	1,319	1,319	1,319	1,459	1,459	879	879	879	973	973	440	440	440	486	486
TOTAL	2,757	4,397	7,368	7,632	7,693	2,317	3,957	4,336	4,500	4,535	1,877	1,979	2,168	2,250	2,267

Sources: Own calculations, based on Table 5 and the char yields from Table 8, column 6 (values rounded). Notes: a = year. kt = kiloton.

Table 10: Slow-Pyrolysis Biochar Potentials, Germany, 2015-2050, Scenarios *Max 2*, *Med 2* and *Min 2*

Feedstocks	Scenario <i>Max 2</i>					Scenario <i>Med 2</i>					Scenario <i>Min 2</i>				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	kt/a					kt/a					kt/a				
Cereal straw	206	321	455	471	471	206	321	303	314	314	206	214	202	210	210
Forestry residues	507	802	1,287	1,337	1,391	507	802	858	891	927	507	535	572	594	618
Open-country biomass residues	78	118	176	176	176	78	118	118	118	118	78	78	78	78	78
Industrial wood waste	180	270	404	404	404	180	270	270	270	270	180	180	180	180	180
Wood in municipal solid waste	78	114	165	169	169	78	114	110	113	113	78	76	74	75	75
Green waste: Compensation areas	0	55	82	82	82	0	55	55	55	55	0	36	36	36	36
Biomass: Habitat-connectivity areas	0	43	153	153	153	0	43	102	102	102	0	28	68	68	68
Green waste: Extensive grassland	0	66	227	227	227	0	66	152	152	152	0	44	101	101	101
Short-rotation coppice: Erosion areas	0	0	619	619	619	0	0	413	413	413	0	0	275	275	275
Solid biomass residues	1,049	1,788	3,569	3,639	3,693	1,049	1,788	2,380	2,426	2,462	1,049	1,192	1,586	1,617	1,641
Sewage sludge (D)	192	212	219	219	219	128	141	146	146	146	64	71	73	73	73
Solid cattle manure (D)	1,442	1,463	1,435	1,460	1,460	961	975	956	974	974	481	488	478	487	487
Solid swine manure (D)	374	376	361	366	366	249	250	240	244	244	125	125	120	122	122
Solid poultry manure (D)	166	183	197	197	197	111	122	132	132	132	55	61	66	66	66
Liquid cattle and swine manure (D)	2,291	2,321	2,270	2,310	2,310	1,528	1,548	1,513	1,540	1,540	764	774	757	770	770
Sugar-beet leaf and potato haulm (D)	180	180	177	177	177	120	120	118	118	118	60	60	59	59	59
Commercial and industrial waste (D)	108	108	108	108	108	72	72	72	72	72	36	36	36	36	36
Organic municipal solid waste (D)	426	490	512	550	578	284	326	341	367	385	142	163	171	183	193
Digestates (biomass residues)	5,178	5,332	5,278	5,388	5,415	3,452	3,555	3,518	3,592	3,610	1,726	1,777	1,759	1,796	1,805
Corn-silage digestates	1,319	1,319	1,319	1,459	1,459	879	879	879	973	973	440	440	440	486	486
Digestates (energy crops)	1,319	1,319	1,319	1,459	1,459	879	879	879	973	973	440	440	440	486	486
TOTAL	7,546	8,439	10,166	10,486	10,567	5,381	6,222	6,777	6,991	7,045	3,215	3,409	3,785	3,900	3,933

Sources: Own calculations, based on Table 5 and the char yields from Table 8, column 6 (values rounded).

Notes: a = year. kt = kiloton. For feedstocks indicated by (D), the relevant char yields are those associated with digestates.

Table 16: N₂O Emissions from Conventional Feedstock Management

Feedstocks	Conventional feedstock management (see Table 12)	N ^a	N ₂ O emissions from manure management ^b		N ₂ O emissions from composting ^e			N ₂ O emissions from energetic use ⁱ	N ^j	N ₂ O emissions from soil ^k			Total N ₂ O emissions	
			Direct ^c	Volatilization ^d	Direct ^f	Volatilization ^g	Leaching/Runoff ^h			Direct ^l	Volatilization ^m	Leaching/Runoff ⁿ		
		wt% _{db}	kg N ₂ O/t _{DM} feedstock						wt% _{db}	kg N ₂ O/t _{DM} feedstock			kg N ₂ O/t _{DM} feedstock ^o	t CO ₂ e/t _{DM} feedstock ^p
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Cereal straw	Decomposition in field	0.47	-	-	-	-	-	-	0.47	0.074	-	0.017	0.090	0.027
Forestry residues	Decomposition in forest	0.17	-	-	-	-	-	-	0.17	0.027	-	0.006	0.033	0.010
Open-country biomass residues	Composting, land spread	0.74	-	-	0.093	0.043	0.002	-	0.44	0.070	0.014	0.016	0.237	0.071
Industrial wood waste	Energetic use	0.13	-	-	-	-	-	0.058	-	-	-	-	0.058	0.017
Wood in municipal solid waste	Composting, land spread	0.16	-	-	0.020	0.009	0.0004	-	0.10	0.015	0.003	0.003	0.051	0.015
Green waste: Compensation areas	Decomposition on site	1.03	-	-	-	-	-	-	1.03	0.162	-	0.036	0.198	0.059
Biomass: Habitat-connectivity areas	Composting, land spread	0.74	-	-	0.093	0.043	0.002	-	0.44	0.070	0.014	0.016	0.237	0.071
Green waste: Extensive grassland	Composting, land spread	0.74	-	-	0.093	0.043	0.002	-	0.44	0.070	0.014	0.016	0.237	0.071
Short-rotation coppice: Erosion areas	Energetic use	0.38	-	-	-	-	-	0.058	-	-	-	-	0.058	0.017
Sewage sludge	Composting, land spread	3.97	-	-	0.187	0.097	0.004	-	3.31	0.519	0.104	0.117	1.028	0.306
Solid cattle manure	Solid storage, land spread	2.42	0.460	0.114	-	-	-	-	1.66	0.261	0.052	0.059	0.946	0.282
Solid swine manure	Solid storage, land spread	4.35	0.822	0.307	-	-	-	-	2.34	0.367	0.073	0.083	1.653	0.493
Solid poultry manure	Solid storage, land spread	3.59	0.057	0.225	-	-	-	-	2.15	0.338	0.068	0.076	0.764	0.228
Liquid cattle and swine manure	Liquid storage, land spread	3.13	0.160	0.201	-	-	-	-	1.84	0.288	0.058	0.065	0.772	0.230
Sugar-beet leaf and potato haulm	Decomposition in field	1.33	-	-	-	-	-	-	1.33	0.209	-	0.047	0.256	0.076
Commercial and industrial waste	Composting, land spread	3.07	-	-	0.386	0.179	0.007	-	1.84	0.289	0.058	0.065	0.985	0.293
Organic municipal solid waste	Composting, land spread	1.67	-	-	0.210	0.098	0.004	-	1.00	0.157	0.031	0.035	0.536	0.160
Digestates	Composting, land spread	5.59	-	-	0.264	0.137	0.005	-	4.66	0.731	0.146	0.165	1.448	0.431

Sources:

- Table 8, column 2.
- Own calculations, based on Dong et al. (2006), UBA (2013) and the N contents in column 1. Note that we follow UBA (2013) in that we take account of the amount of N introduced into solid-manure management via bedding material (straw). Based on UBA (2013), we further assume that indirect N₂O emissions from manure management due to leaching/runoff are zero.
- Direct N₂O emissions from manure management are calculated with the emission factors (EF) given in Table A.15, column 3, i.e. (2) = (1)/100 · EF · 1,000.
- Indirect N₂O emissions from volatilization of N from manure management are calculated with the default emission factor of 0.01 kg N₂O-N (kg NH₃-N + NO_x-N volatilized)⁻¹ from Dong et al. (2006) and De Klein et al. (2006) – which is equivalent to 0.0157 kg N₂O (kg NH₃-N + NO_x-N volatilized)⁻¹ using the relation N₂O = N₂O-N · 44/28 (De Klein et al. 2006) – as well as the default fractions (FRAC) of manure N volatilizing as NH₃ and NO_x given in Table A.16. Thus, (3) = (1)/100 · FRAC/100 · 0.0157 · 1,000.

- e) Own calculations, based on the values in Detzel et al. (2003) and differentiating between direct and indirect N₂O emissions analogously to De Klein et al. (2006) due to the lack of differentiation of N₂O emissions in Pipatti et al. (2006). Note that the default emission factor from Pipatti et al. (2006: Table 4.1) is 0.6 g N₂O/kg_{DM} waste treated.
- f) Direct N₂O emissions from composting are based on the assumptions that 0.3% of the N contents of digestates and sewage sludge and 0.8% of the N contents of the other feedstocks are emitted as N₂O-N during composting (Detzel et al. 2003). Thus, the emission factors are derived as (4) = (1/100 · 0.3/100 · 44/28 · 1,000 and (4) = (1/100 · 0.8/100 · 44/28 · 1,000, respectively. Note that the 0.3% (0.8%) used by Detzel et al. (2003) referred to digestates (biowaste and green waste) only.
- g) Indirect N₂O emissions from volatilization of N from composting are calculated analogously to De Klein et al. (2006), i.e. with the default emission factor of 0.01 kg N₂O-N (kg NH₃-N + NO_x-N volatilized)⁻¹ – which is equivalent to 0.0157 kg N₂O (kg NH₃-N + NO_x-N volatilized)⁻¹ using the relation N₂O = N₂O-N · 44/28 (De Klein et al. 2006). The fraction of N that volatilizes as NH₃-N is assumed to be 15.6% (37.2%) for the digestates and sewage sludge (the remaining feedstocks) (Detzel et al. 2003). Thus, the calculations are (5) = (1/100 · 15.6/100 · 0.0157 · 1,000 and (5) = (1/100 · 37.2/100 · 0.0157 · 1,000, respectively. Note that the 15.6% (37.2%) used by Detzel et al. (2003) referred to digestates (biowaste and green waste) only.
- h) Indirect N₂O emissions from leaching/runoff of N from composting are calculated analogously to De Klein et al. (2006), i.e. with the default emission factor of 0.0075 kg N₂O-N (kg N leaching/runoff)⁻¹ – which is equivalent to 0.0118 kg N₂O (kg N leaching/runoff)⁻¹ using the relation N₂O = N₂O-N · 44/28 (De Klein et al. 2006). The fraction of N that is lost through leaching and runoff is assumed to be 0.8% (2%) for the digestates and sewage sludge (the remaining feedstocks), whereby the 0.8% (2%) are calculated as the difference between the total N loss of 16.7% (40%) and the N losses from direct N₂O emissions of 0.3% (0.8%) and NH₃ emissions of 15.6% (37.2%) given in Detzel et al. (2003). Thus, the calculations are (6) = (1/100 · 0.008 · 0.0118 · 1,000 and (6) = (1/100 · 0.02 · 0.0118 · 1,000, respectively.
- i) Own calculation, based on the technological emission factor of 3 kg N₂O/TJ for *boiler firing with biomass* from UBA (2013: Table 30) (originally from Rentz et al. 2002) and the HHV of 19.3 MJ/kg_{db} for both feedstocks from Table 8, column 5. For comparison, the emission factor for *Wood/Wood Waste Boilers* from Gómez et al. (2006: Table 2.6) is 7 kg N₂O/TJ. Note that we use HHVs instead of LHV's due to the lack of consistent data for LHV's. The bias introduced by this procedure is considered negligible due to the generally low emissions. Thus, (7) = 3 · 19.3/1,000,000 · 1,000. Note that we only consider direct N₂O emissions since there is no information on indirect N₂O emissions (volatilization) from combustion-related sources in UBA (2013).
- j) The N contents of the manure feedstocks have been corrected for the N lost due to N₂O emissions from manure management (cp. Dong et al. 2006) based on the loss fractions (LOSS) given in Table A.17, i.e. (8) = (1) · (1 – LOSS/100). Analogously, the N contents of the feedstocks to be composted have been corrected for the respective N losses, i.e. 16.7% (40%) for the digestates and sewage sludge (the remaining feedstocks) (Detzel et al. 2003), leading to the calculations of (8) = (1) · (1 – 0.167) for digestates and sewage sludge and (8) = (1) · (1 – 0.4) for the remaining feedstocks. Note that the 16.7% (40%) used by Detzel et al. (2003) referred to digestates (biowaste and green waste) only. Furthermore, due to the lack of data, it is assumed that the biomass that is assumed to decompose on site enters the soil without prior N losses.
- k) Own calculations, based on De Klein et al. (2006) and the N contents in column 8. Note that we include inputs of forestry residues as N₂O sources from soil although they are not explicitly mentioned in De Klein et al. (2006), but since De Klein et al. (2006) explicitly cover managed forest land.
- l) Direct N₂O emissions from N inputs to soil are calculated with the default emission factor of 0.01 kg N₂O-N (kg N input)⁻¹ from De Klein et al. (2006) – which is equivalent to 0.0157 kg N₂O (kg N input)⁻¹ using the relation N₂O = N₂O-N · 44/28 (De Klein et al. 2006). Thus, (9) = (8)/100 · 0.0157 · 1,000.
- m) Indirect N₂O emissions from volatilization are calculated with the default emission factor of 0.01 kg N₂O-N (kg NH₃-N + NO_x-N volatilized)⁻¹ from De Klein et al. (2006) – which is equivalent to 0.0157 kg N₂O (kg NH₃-N + NO_x-N volatilized)⁻¹ using the relation N₂O = N₂O-N · 44/28 (De Klein et al. 2006) – as well as the default fraction of applied organic N fertilizer materials volatilizing as NH₃ and NO_x of 0.2 kg NH₃-N + NO_x-N (kg N applied)⁻¹ from De Klein et al. (2006). Thus, (10) = (8)/100 · 0.2 · 0.0157 · 1,000. Note that UBA (2013) uses a different methodology than De Klein et al. (2006) and arrives at ca. 0.3 kg NH₃-N + NO_x-N (kg N)⁻¹, including N volatilization from manure management and grazing.
- n) Indirect N₂O emissions from leaching/runoff are calculated with the default emission factor of 0.0075 kg N₂O-N (kg N leaching/runoff)⁻¹ from De Klein et al. (2006) – which is equivalent to 0.0118 kg N₂O (kg N leaching/runoff)⁻¹ using the relation N₂O = N₂O-N · 44/28 (De Klein et al. 2006) – as well as the default fraction of all N added that is lost through leaching and runoff of 0.3 kg N (kg N additions)⁻¹ from De Klein et al. (2006). Thus, (11) = (8)/100 · 0.3 · 0.0118 · 1,000.
- o) Own calculation, (12) = (2) + (3) + (4) + (5) + (6) + (7) + (9) + (10) + (11).
- p) The CO₂e are calculated by multiplying the N₂O emissions from column 12 by their 100-year GWP of 298 as given in Forster et al. (2007). That is, (13) = (12) · 298/1,000.

Notes: Values rounded. DM = dry mass. db = dry base. wt% = weight percent. g = gram. kg = kilogram. t = tonne. MJ = megajoule. TJ = terajoule. HHV = higher heating value. NH₃ = ammonia. NO_x = nitric oxides. - = not applicable. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 17: N₂O Emissions from Biochar Soil Application and from SOC Losses

Feedstocks	Conventional feedstock management (see Table 12)	N ^a	Char yield ^a	N ₂ O emissions from soil due to biochar application			N ₂ O emissions from soil due to SOC loss		Total N ₂ O emissions	
				Direct ^b	Volatilization ^c	Leaching/Runoff ^d	Direct ^e	Leaching/Runoff ^f		
		wt%	wt% _{db}	kg N ₂ O/t _{DM} feedstock			kg N ₂ O/t _{DM} feedstock		kg N ₂ O/t _{DM} feedstock ^g	t CO ₂ e/t _{DM} feedstock ^h
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Cereal straw	Decomposition in field	0.65	34	0.035	0.007	0.008	0.074	0.017	0.140	0.042
Forestry residues	Decomposition in forest	0.36	30	0.017	0.003	0.004	0.051	0.012	0.087	0.026
Open-country biomass residues	Composting, land spread	0.68	31	0.033	0.007	0.007	0.029	0.007	0.083	0.025
Industrial wood waste	Energetic use	0.16	29	0.007	0.001	0.002	-	-	0.010	0.003
Wood in municipal solid waste	Composting, land spread	0.37	30	0.017	0.003	0.004	0.031	0.007	0.063	0.019
Green waste: Compensation areas	Decomposition on site	0.83	32	0.042	0.008	0.009	0.071	0.016	0.146	0.044
Biomass: Habitat-connectivity areas	Composting, land spread	0.68	31	0.033	0.007	0.007	0.029	0.007	0.083	0.025
Green waste: Extensive grassland	Composting, land spread	0.68	31	0.033	0.007	0.007	0.029	0.007	0.083	0.025
Short-rotation coppice: Erosion areas	Energetic use	0.93	25	0.037	0.007	0.008	-	-	0.052	0.016
Sewage sludge	Composting, land spread	4.40	49	0.338	0.068	0.076	0.042	0.010	0.534	0.159
Solid cattle manure	Solid storage, land spread	1.82	47	0.134	0.027	0.030	0.048	0.011	0.250	0.075
Solid swine manure	Solid storage, land spread	3.17	47	0.234	0.047	0.053	0.057	0.013	0.403	0.120
Solid poultry manure	Solid storage, land spread	3.12	44	0.216	0.043	0.049	0.042	0.009	0.358	0.107
Liquid cattle and swine manure	Liquid storage, land spread	2.31	45	0.163	0.033	0.037	0.058	0.013	0.303	0.090
Sugar-beet leaf and potato haulm	Decomposition in field	3.02	45	0.213	0.043	0.048	0.068	0.015	0.387	0.115
Commercial and industrial waste	Composting, land spread	4.18	37	0.243	0.049	0.055	0.031	0.007	0.385	0.115
Organic municipal solid waste	Composting, land spread	2.14	45	0.151	0.030	0.034	0.019	0.004	0.239	0.071
Digestates	Composting, land spread	2.57	49	0.198	0.040	0.045	0.044	0.010	0.335	0.100

Sources:

- Table 8, column 12 (N) and column 6 (char yield).
- See footnote l) in Table 16. Thus, the calculations are based on the formula (3) = (1)/100 · (2)/100 · 0.0157 · 1,000.
- See footnote m) in Table 16. Thus, the calculations are based on the formula (4) = (1)/100 · (2)/100 · 0.2 · 0.0157 · 1,000.
- See footnote n) in Table 16. Thus, the calculations are based on the formula (5) = (1)/100 · (2)/100 · 0.3 · 0.0118 · 1,000.
- Direct N₂O emissions from SOC loss are calculated with the default emission factor of 0.01 kg N₂O-N (kg N mineralized)⁻¹ from De Klein et al. (2006) – which is equivalent to 0.0157 kg N₂O (kg N mineralized)⁻¹ using the relation N₂O = N₂O-N · 44/28 (De Klein et al. 2006). The amount of N mineralized from SOC loss is based on equation 11.8 in De Klein et al. (2006), where the SOC loss is given by the values in Table 15, column 2 and where the default C:N ratios of SOM from De Klein et al. (2006) are used, such that the C:N ratio of 15 (*Forest Land to Cropland*) is associated with forestry residues and that of 10 (*Cropland Remaining Cropland*) is assumed for the remaining feedstocks. Thus, the respective calculations are (6) = SOC loss (Table 15, column 2) · 1/15 · 0.0157 · 1,000 and (6) = SOC loss (Table 15, column 2) · 1/10 · 0.0157 · 1,000.
- Following De Klein et al. (2006), indirect N₂O emissions from SOC loss are based on the emission factor and fraction of N lost through leaching and runoff given in footnote n) in Table 16. The amount of N mineralized is the same as used in column 6. Thus, the calculations are (7) = SOC loss (Table 15, column 2) · 1/15 · 0.3 · 0.0118 · 1,000 and (7) = SOC loss (Table 15, column 2) · 1/10 · 0.3 · 0.0118 · 1,000.
- Own calculation, (8) = (3) + (4) + (5) + (6) + (7).
- The CO₂e are calculated by multiplying the N₂O emissions from column 8 by their 100-year GWP of 298 as given in Forster et al. (2007). That is, (9) = (8) · 298/1,000.

Notes: Values rounded. DM = dry mass. db = dry base. wt% = weight percent. kg = kilogram. t = tonne. SOC = soil organic carbon. SOM = soil organic matter. - = not applicable.

Table 18: GHG Emissions from Fossil Fuels that Are Offset by the Energetic Use of Biomass

			Lignite	Hard coal					Natural gas					
CO ₂ emission factor ^a	t CO ₂ /TJ	(A)	107.5	94.2					56.0					
CH ₄ emission factor ^b	kg CH ₄ /TJ	(B)	226.5	3.35					0.02					
N ₂ O emission factor ^c	kg N ₂ O/TJ	(C)	10.7	10.0					0.6					
Electrical efficiency ^d	%	(D)	43	43					40					
Feedstocks			CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	Total CO ₂ e ^h	CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	Total CO ₂ e ^h	CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	Total CO ₂ e ^h
			t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock	t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock	t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Industrial wood waste			1.448	3.050	0.144	1.567	1.268	0.045	0.135	1.310	0.811	0.0003	0.009	0.813
Short-rotation coppice: Erosion areas			1.448	3.050	0.144	1.567	1.268	0.045	0.135	1.310	0.811	0.0003	0.009	0.813

Sources:

- a) UBA (2013: Table 347, pp. 740-741), 2009-2011 averages; the value for lignite refers to *raw lignite in public power stations* and is a simple average of 4 districts, i.e. $(114 + 99 + 113 + 104)/4 = 107.5$.
- b) UBA (2013: Table 352), i.e. CH₄ emission factors from systems *<50 MW furnace thermal output*; originally from Rentz et al. (2002). Note that simple averages were used when several emission factors were displayed for the same fuel, i.e. $(3.4 + 3.3)/2 = 3.35$ for hard coal and $(269 + 184)/2 = 226.5$ for lignite. Also note that these emission factors have not yet been completely adopted by UBA (2013).
- c) UBA (2013: Table 30), i.e. N₂O emission factors from systems *<50 MW furnace thermal output: boiler firing*; originally from Rentz et al. (2002).
- d) The efficiencies refer to the conversion of the biomass/fossil fuel to electricity only, i.e. not considering combined heat and power (CHP) due to the lack of consistent data for CHP efficiencies. For the biomass feedstocks, we apply electrical efficiencies of 30%, as reached in dedicated bio-power plants (IEA 2007: 2). The electrical efficiencies for the fossil fuels are taken from Traber and Kemfert (2011: Table 1), whereby the value for lignite refers to *“new brown coal” (BC New)*, i.e. to lignite-fired power plants with optimized plant engineering (Schröder et al. 2013), the value for hard coal to *“new hard coal” (HC New)*, i.e. to supercritical pulverized-coal-fired power plants (Schröder et al. 2013), and the one for natural gas (*NG ST*) to steam turbines.
- e) Own calculation, using the HHV* of 19.3 MJ/kg_{db} for both biomass feedstocks (Table 8, column 5) and the electrical efficiency of 30% for both biomasses (see d)), e.g. $(1) = (A) \cdot 30/(D) \cdot 19.3/1,000,000 \cdot 1,000$.
- f) Own calculation, using the HHV* of 19.3 MJ/kg_{db} for both biomass feedstocks (Table 8, column 5) and the electrical efficiency of 30% for both biomasses (see d)), e.g. $(2) = (B) \cdot 30/(D) \cdot 19.3/1,000,000 \cdot 1,000$.
- g) Own calculation, using the HHV* of 19.3 MJ/kg_{db} for both biomass feedstocks (Table 8, column 5) and the electrical efficiency of 30% for both biomasses (see d)), e.g. $(3) = (C) \cdot 30/(D) \cdot 19.3/1,000,000 \cdot 1,000$.
- h) Own calculation, multiplying the CH₄ (N₂O) emissions by their respective 100-year GWP of 25 (298) as given in Forster et al. (2007) and summing up all emissions, e.g., $(4) = (1) + (2) \cdot 25/1,000 + (3) \cdot 298/1,000$.

Notes: Values rounded. DM = dry mass. db = dry base. kg = kilogram. t = tonne. MW = megawatt. MJ = megajoule. TJ = terajoule. HHV = higher heating value. LHV = lower heating value. * = Note that we use HHVs instead of LHVs due to the lack of consistent data for LHVs.

Table 20: GHG Emissions from Fossil Fuels that Are Offset by the Energetic Use of the Pyrolysis By-Products

			Lignite				Hard coal				Natural gas			
CO ₂ emission factor ^a	t CO ₂ /TJ	(A)	107.5				94.2				56.0			
CH ₄ emission factor ^b	kg CH ₄ /TJ	(B)	226.5				3.35				0.02			
N ₂ O emission factor ^c	kg N ₂ O/TJ	(C)	10.7				10.0				0.6			
Electrical efficiency ^d	%	(D)	43				43				40			
Feedstocks			CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	CO ₂ e ^h	CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	CO ₂ e ^h	CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	CO ₂ e ^h
			t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock	t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock	t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Cereal straw			0.608	1.281	0.061	0.658	0.533	0.019	0.057	0.550	0.341	0.0001	0.004	0.342
Forestry residues			0.689	1.451	0.069	0.745	0.603	0.021	0.064	0.623	0.386	0.0001	0.004	0.387
Open-country biomass residues			0.606	1.276	0.060	0.655	0.531	0.019	0.056	0.548	0.339	0.0001	0.004	0.340
Industrial wood waste			0.673	1.418	0.067	0.728	0.590	0.021	0.063	0.609	0.377	0.0001	0.004	0.378
Wood in municipal solid waste			0.689	1.451	0.069	0.745	0.603	0.021	0.064	0.623	0.386	0.0001	0.004	0.387
Green waste: Compensation areas			0.554	1.168	0.055	0.600	0.486	0.017	0.052	0.502	0.311	0.0001	0.003	0.312
Biomass: Habitat-connectivity areas			0.606	1.276	0.060	0.655	0.531	0.019	0.056	0.548	0.339	0.0001	0.004	0.340
Green waste: Extensive grassland			0.606	1.276	0.060	0.655	0.531	0.019	0.056	0.548	0.339	0.0001	0.004	0.340
Short-rotation coppice: Erosion areas			0.758	1.598	0.075	0.821	0.665	0.024	0.071	0.686	0.425	0.0002	0.005	0.426
Sewage sludge			0.539	1.136	0.054	0.584	0.472	0.017	0.050	0.488	0.302	0.0001	0.003	0.303
Solid cattle manure			0.542	1.141	0.054	0.586	0.475	0.017	0.050	0.490	0.303	0.0001	0.003	0.304
Solid swine manure			0.694	1.463	0.069	0.751	0.608	0.022	0.065	0.628	0.389	0.0001	0.004	0.390
Solid poultry manure			0.494	1.042	0.049	0.535	0.433	0.015	0.046	0.447	0.277	0.0001	0.003	0.278
Liquid cattle and swine manure			0.553	1.166	0.055	0.599	0.485	0.017	0.051	0.501	0.310	0.0001	0.003	0.311
Sugar-beet leaf and potato haulm			0.563	1.187	0.056	0.610	0.494	0.018	0.052	0.510	0.315	0.0001	0.003	0.316
Commercial and industrial waste			0.655	1.381	0.065	0.709	0.574	0.020	0.061	0.593	0.367	0.0001	0.004	0.368
Organic municipal solid waste			0.454	0.957	0.045	0.492	0.398	0.014	0.042	0.411	0.254	0.0001	0.003	0.255
Digestates			0.711	1.499	0.071	0.770	0.623	0.022	0.066	0.644	0.398	0.0001	0.004	0.400

Sources:

- See footnote a) in Table 18.
- See footnote b) in Table 18.
- See footnote c) in Table 18.
- The efficiencies refer to the conversion of the pyrolysis by-products/fossil fuel to electricity only, i.e. not considering CHP due to the lack of consistent data for CHP efficiencies. For the pyrolysis by-products, we apply electrical efficiencies of 32% as done by Woolf et al. (2010b). The electrical efficiencies for the fossil fuels are taken from Traber and Kemfert (2011: Table 1); for the details, see footnote d) in Table 18.
- Own calculation, using the energy contents E_{out} from Table 19, column 5 and the electrical efficiency of 32% for the pyrolysis by-products (see d)), e.g. (1) = (A) · 32/(D) · $E_{out}/1,000,000$ · 1,000.
- Own calculation, using the energy contents E_{out} from Table 19, column 5 and the electrical efficiency of 32% for the pyrolysis by-products (see d)), e.g. (2) = (B) · 32/(D) · $E_{out}/1,000,000$ · 1,000.
- Own calculation, using the energy contents E_{out} from Table 19, column 5 and the electrical efficiency of 32% for the pyrolysis by-products (see d)), e.g. (3) = (C) · 32/(D) · $E_{out}/1,000,000$ · 1,000.
- Own calculation, multiplying the CH₄ (N₂O) emissions by their respective 100-year GWP of 25 (298) as given in Forster et al. (2007) and summing up all emissions, e.g., (4) = (1) + (2) · 25/1,000 + (3) · 298/1,000.

Notes: Values rounded. DM = dry mass. kg = kilogram. t = tonne. TJ = terajoule. CHP = combined heat and power.

Table 22: GHG Emissions from Fossil Fuels that Provide the Energy Input for Biochar Production When Process Heat is Not Recovered

			Lignite				Hard coal				Natural gas			
CO ₂ emission factor ^a	t CO ₂ /TJ	(A)	107.5				94.2				56.0			
CH ₄ emission factor ^b	kg CH ₄ /TJ	(B)	226.5				3.35				0.02			
N ₂ O emission factor ^c	kg N ₂ O/TJ	(C)	10.7				10.0				0.6			
Thermal efficiency ^d	%	(D)	80				80				72.5			
Feedstocks			CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	CO ₂ e ^h	CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	CO ₂ e ^h	CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	CO ₂ e ^h
			t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock	t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock	t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Cereal straw			0.171	0.360	0.017	0.185	0.150	0.005	0.016	0.155	0.098	0.0000	0.001	0.099
Forestry residues			0.187	0.395	0.019	0.203	0.164	0.006	0.017	0.170	0.108	0.0000	0.001	0.108
Open-country biomass residues			0.172	0.363	0.017	0.187	0.151	0.005	0.016	0.156	0.099	0.0000	0.001	0.099
Industrial wood waste			0.177	0.372	0.018	0.191	0.155	0.006	0.016	0.160	0.102	0.0000	0.001	0.102
Wood in municipal solid waste			0.188	0.396	0.019	0.203	0.165	0.006	0.017	0.170	0.108	0.0000	0.001	0.108
Green waste: Compensation areas			0.165	0.348	0.016	0.179	0.145	0.005	0.015	0.149	0.095	0.0000	0.001	0.095
Biomass: Habitat-connectivity areas			0.172	0.363	0.017	0.187	0.151	0.005	0.016	0.156	0.099	0.0000	0.001	0.099
Green waste: Extensive grassland			0.172	0.363	0.017	0.187	0.151	0.005	0.016	0.156	0.099	0.0000	0.001	0.099
Short-rotation coppice: Erosion areas			0.219	0.461	0.022	0.237	0.192	0.007	0.020	0.198	0.126	0.0000	0.001	0.126
Sewage sludge			1.395	2.940	0.139	1.510	1.223	0.043	0.130	1.263	0.802	0.0003	0.009	0.805
Solid cattle manure			0.709	1.494	0.071	0.767	0.621	0.022	0.066	0.641	0.407	0.0001	0.004	0.409
Solid swine manure			1.332	2.807	0.133	1.442	1.167	0.042	0.124	1.205	0.766	0.0003	0.008	0.768
Solid poultry manure			0.182	0.382	0.018	0.196	0.159	0.006	0.017	0.164	0.104	0.0000	0.001	0.105
Liquid cattle and swine manure			3.161	6.660	0.315	3.421	2.770	0.098	0.294	2.860	1.817	0.0006	0.019	1.823
Sugar-beet leaf and potato haulm			1.853	3.905	0.184	2.006	1.624	0.058	0.172	1.677	1.065	0.0004	0.011	1.069
Commercial and industrial waste			0.664	1.399	0.066	0.718	0.582	0.021	0.062	0.601	0.382	0.0001	0.004	0.383
Organic municipal solid waste			0.930	1.960	0.093	1.007	0.815	0.029	0.087	0.842	0.535	0.0002	0.006	0.536
Digestates			2.032	4.281	0.202	2.199	1.781	0.063	0.189	1.839	1.168	0.0004	0.013	1.172

Sources:

- See footnote a) in Table 18.
- See footnote b) in Table 18.
- See footnote c) in Table 18.
- The thermal efficiencies refer to the conversion of the fossil fuels to heat. They are calculated as simple averages of the *new boiler efficiencies* of industrial boilers displayed in Vatopoulos et al. (2012: Table 2-2), whereby the efficiency for “coal” is applied to both hard coal and lignite, and the efficiency for “gas” to natural gas.
- Own calculation, using the energy contents E_{in} from Table 21, column 6, e.g. (1) = (A) · 100/(D) · $E_{in}/1,000,000$ · 1,000.
- Own calculation, using the energy contents E_{in} from Table 21, column 6, e.g. (2) = (B) · 100/(D) · $E_{in}/1,000,000$ · 1,000.
- Own calculation, using the energy contents E_{in} from Table 21, column 6, e.g. (3) = (C) · 100/(D) · $E_{in}/1,000,000$ · 1,000.
- Own calculation, multiplying the CH₄ (N₂O) emissions by their respective 100-year GWP of 25 (298) as given in Forster et al. (2007) and summing up all emissions, e.g., (4) = (1) + (2) · 25/1,000 + (3) · 298/1,000.

Notes: Values rounded. DM = dry mass. kg = kilogram. t = tonne. TJ = terajoule.

Table 23: GHG Emissions From Fossil Fuels that Provide the Energy Input for Biochar Production When Process Heat is Recovered

			Lignite				Hard coal				Natural gas			
CO ₂ emission factor ^a	t CO ₂ /TJ	(A)	107.5				94.2				56.0			
CH ₄ emission factor ^b	kg CH ₄ /TJ	(B)	226.5				3.35				0.02			
N ₂ O emission factor ^c	kg N ₂ O/TJ	(C)	10.7				10.0				0.6			
Thermal efficiency ^d	%	(D)	80				80				72.5			
Feedstocks			CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	CO ₂ e ^h	CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	CO ₂ e ^h	CO ₂ ^e	CH ₄ ^f	N ₂ O ^g	CO ₂ e ^h
			t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock	t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock	t CO ₂ /t _{DM} feedstock	kg CH ₄ /t _{DM} feedstock	kg N ₂ O/t _{DM} feedstock	t CO ₂ e/t _{DM} feedstock
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Cereal straw			0.057	0.120	0.006	0.061	0.050	0.002	0.005	0.051	0.033	0.00001	0.0003	0.033
Forestry residues			0.069	0.146	0.007	0.075	0.061	0.002	0.006	0.063	0.040	0.00001	0.0004	0.040
Open-country biomass residues			0.057	0.120	0.006	0.061	0.050	0.002	0.005	0.051	0.033	0.00001	0.0003	0.033
Industrial wood waste			0.059	0.123	0.006	0.063	0.051	0.002	0.005	0.053	0.034	0.00001	0.0004	0.034
Wood in municipal solid waste			0.070	0.147	0.007	0.075	0.061	0.002	0.006	0.063	0.040	0.00001	0.0004	0.040
Green waste: Compensation areas			0.051	0.107	0.005	0.055	0.044	0.002	0.005	0.046	0.029	0.00001	0.0003	0.029
Biomass: Habitat-connectivity areas			0.057	0.120	0.006	0.061	0.050	0.002	0.005	0.051	0.033	0.00001	0.0003	0.033
Green waste: Extensive grassland			0.057	0.120	0.006	0.061	0.050	0.002	0.005	0.051	0.033	0.00001	0.0003	0.033
Short-rotation coppice: Erosion areas			0.101	0.213	0.010	0.109	0.089	0.003	0.009	0.091	0.058	0.00002	0.0006	0.058
Sewage sludge			1.299	2.736	0.129	1.405	1.138	0.040	0.121	1.175	0.746	0.00027	0.0080	0.749
Solid cattle manure			0.601	1.266	0.060	0.651	0.527	0.019	0.056	0.544	0.346	0.00012	0.0037	0.347
Solid swine manure			1.226	2.584	0.122	1.327	1.075	0.038	0.114	1.109	0.705	0.00025	0.0076	0.707
Solid poultry manure			0.077	0.162	0.008	0.083	0.067	0.002	0.007	0.070	0.044	0.00002	0.0005	0.044
Liquid cattle and swine manure			3.052	6.430	0.304	3.303	2.674	0.095	0.284	2.761	1.754	0.00063	0.0188	1.760
Sugar-beet leaf and potato haulm			1.751	3.689	0.174	1.895	1.534	0.055	0.163	1.584	1.006	0.00036	0.0108	1.010
Commercial and industrial waste			0.549	1.157	0.055	0.594	0.481	0.017	0.051	0.497	0.316	0.00011	0.0034	0.317
Organic municipal solid waste			0.827	1.741	0.082	0.895	0.724	0.026	0.077	0.748	0.475	0.00017	0.0051	0.477
Digestates			1.932	4.070	0.192	2.091	1.693	0.060	0.180	1.748	1.110	0.00040	0.0119	1.114

Sources:

a) See footnote a) in Table 18.

b) See footnote b) in Table 18.

c) See footnote c) in Table 18.

d) See footnote d) in Table 22.

e) Own calculation, using the energy contents E'_{in} from Table 21, column 10, e.g. (1) = (A) · 100/(D) · $E'_{in}/1,000,000$ · 1,000.

f) Own calculation, using the energy contents E'_{in} from Table 21, column 10, e.g. (2) = (B) · 100/(D) · $E'_{in}/1,000,000$ · 1,000.

g) Own calculation, using the energy contents E'_{in} from Table 21, column 10, e.g. (3) = (C) · 100/(D) · $E'_{in}/1,000,000$ · 1,000.

h) Own calculation, multiplying the CH₄ (N₂O) emissions by their respective 100-year GWP of 25 (298) as given in Forster et al. (2007) and summing up all emissions, e.g., (4) = (1) + (2) · 25/1,000 + (3) · 298/1,000.

Notes: Values rounded. DM = dry mass. kg = kilogram. t = tonne. TJ = terajoule.

Table 24: CO₂ Emissions from the Transportation of Biomass to the Pyrolysis Units, Germany, 2015-2050, Scenario *Max 1*

Feedstocks	Small-scale pyrolysis units (à 2,000 t _{DM} feedstock/a)					Medium-scale pyrolysis units (à 16,000 t _{DM} feedstock/a)					Large-scale pyrolysis units (à 184,800 t _{DM} feedstock/a)				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Cereal straw	0.00023	0.00017	0.00011	0.00010	0.00009	0.00065	0.00048	0.00030	0.00028	0.00026	0.00220	0.00162	0.00103	0.00096	0.00090
Forestry residues	0.00024	0.00017	0.00011	0.00010	0.00010	0.00067	0.00049	0.00031	0.00029	0.00027	0.00227	0.00168	0.00107	0.00099	0.00093
Open-country biomass residues	0.00023	0.00017	0.00011	0.00010	0.00009	0.00065	0.00048	0.00030	0.00028	0.00026	0.00220	0.00162	0.00103	0.00096	0.00090
Industrial wood waste	0.00023	0.00017	0.00011	0.00010	0.00009	0.00065	0.00048	0.00031	0.00028	0.00027	0.00220	0.00163	0.00104	0.00096	0.00090
Wood in municipal solid waste	0.00024	0.00017	0.00011	0.00010	0.00010	0.00067	0.00049	0.00031	0.00029	0.00027	0.00227	0.00168	0.00107	0.00099	0.00093
Green waste: Compensation areas	0.00022	0.00017	0.00011	0.00010	0.00009	0.00064	0.00047	0.00030	0.00028	0.00026	0.00216	0.00159	0.00102	0.00094	0.00088
Biomass: Habitat-connectivity areas	0.00023	0.00017	0.00011	0.00010	0.00009	0.00065	0.00048	0.00030	0.00028	0.00026	0.00220	0.00162	0.00103	0.00096	0.00090
Green waste: Extensive grassland	0.00023	0.00017	0.00011	0.00010	0.00009	0.00065	0.00048	0.00030	0.00028	0.00026	0.00220	0.00162	0.00103	0.00096	0.00090
Short-rotation coppice: Erosion areas	0.00026	0.00019	0.00012	0.00011	0.00011	0.00073	0.00054	0.00034	0.00032	0.00030	0.00247	0.00182	0.00116	0.00108	0.00101
Sewage sludge	0.00103	0.00076	0.00048	0.00045	0.00042	0.00291	0.00215	0.00137	0.00127	0.00119	0.00988	0.00729	0.00465	0.00432	0.00404
Solid cattle manure	0.00058	0.00043	0.00027	0.00025	0.00024	0.00164	0.00121	0.00077	0.00072	0.00067	0.00556	0.00411	0.00262	0.00243	0.00228
Solid swine manure	0.00098	0.00072	0.00046	0.00043	0.00040	0.00277	0.00205	0.00130	0.00121	0.00113	0.00942	0.00695	0.00443	0.00412	0.00385
Solid poultry manure	0.00024	0.00018	0.00011	0.00011	0.00010	0.00069	0.00051	0.00032	0.00030	0.00028	0.00234	0.00173	0.00110	0.00102	0.00096
Liquid cattle and swine manure	0.00215	0.00159	0.00101	0.00094	0.00088	0.00608	0.00449	0.00286	0.00266	0.00249	0.02067	0.01525	0.00972	0.00903	0.00846
Sugar-beet leaf and potato haulm	0.00132	0.00097	0.00062	0.00058	0.00054	0.00373	0.00275	0.00175	0.00163	0.00152	0.01266	0.00934	0.00596	0.00553	0.00518
Commercial and industrial waste	0.00054	0.00040	0.00026	0.00024	0.00022	0.00154	0.00114	0.00072	0.00067	0.00063	0.00523	0.00386	0.00246	0.00229	0.00214
Organic municipal solid waste	0.00072	0.00053	0.00034	0.00032	0.00030	0.00205	0.00151	0.00096	0.00090	0.00084	0.00696	0.00514	0.00327	0.00304	0.00285
Digestates (energy crops)	0.00143	0.00106	0.00067	0.00063	0.00059	0.00405	0.00299	0.00191	0.00177	0.00166	0.01378	0.01017	0.00648	0.00602	0.00564

Sources: Own calculation, multiplying the biomass transport emissions from Table A.20 by the respective mean transport distance from Table A.18, row A (values rounded).

Notes: DM = dry mass. a = year. t = tonne. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 25: CO₂ Emissions from the Transportation of Biomass to the Pyrolysis Units, Germany, 2015-2050, Scenario *Max 2*

Feedstocks	Small-scale pyrolysis units (à 2,000 t _{DM} feedstock/a)					Medium-scale pyrolysis units (à 16,000 t _{DM} feedstock/a)					Large-scale pyrolysis units (à 184,800 t _{DM} feedstock/a)				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Cereal straw	0.00014	0.00013	0.00009	0.00009	0.00008	0.00040	0.00035	0.00026	0.00025	0.00023	0.00136	0.00121	0.00090	0.00084	0.00078
Forestry residues	0.00015	0.00013	0.00010	0.00009	0.00008	0.00041	0.00037	0.00027	0.00025	0.00024	0.00141	0.00125	0.00093	0.00086	0.00081
Open-country biomass residues	0.00014	0.00013	0.00009	0.00009	0.00008	0.00040	0.00035	0.00026	0.00025	0.00023	0.00136	0.00120	0.00090	0.00084	0.00078
Industrial wood waste	0.00014	0.00013	0.00009	0.00009	0.00008	0.00040	0.00036	0.00027	0.00025	0.00023	0.00137	0.00121	0.00090	0.00084	0.00078
Wood in municipal solid waste	0.00015	0.00013	0.00010	0.00009	0.00008	0.00041	0.00037	0.00027	0.00025	0.00024	0.00141	0.00125	0.00093	0.00086	0.00081
Green waste: Compensation areas	0.00014	0.00012	0.00009	0.00009	0.00008	0.00039	0.00035	0.00026	0.00024	0.00023	0.00134	0.00119	0.00088	0.00082	0.00077
Biomass: Habitat-connectivity areas	0.00014	0.00013	0.00009	0.00009	0.00008	0.00040	0.00035	0.00026	0.00025	0.00023	0.00136	0.00120	0.00090	0.00084	0.00078
Green waste: Extensive grassland	0.00014	0.00013	0.00009	0.00009	0.00008	0.00040	0.00035	0.00026	0.00025	0.00023	0.00136	0.00120	0.00090	0.00084	0.00078
Short-rotation coppice: Erosion areas	0.00016	0.00014	0.00010	0.00010	0.00009	0.00045	0.00040	0.00030	0.00028	0.00026	0.00153	0.00135	0.00101	0.00094	0.00088
Sewage sludge (D)	0.00089	0.00079	0.00059	0.00055	0.00051	0.00251	0.00222	0.00166	0.00154	0.00144	0.00854	0.00756	0.00563	0.00524	0.00491
Solid cattle manure (D)	0.00089	0.00079	0.00059	0.00055	0.00051	0.00251	0.00222	0.00166	0.00154	0.00144	0.00854	0.00756	0.00563	0.00524	0.00491
Solid swine manure (D)	0.00089	0.00079	0.00059	0.00055	0.00051	0.00251	0.00222	0.00166	0.00154	0.00144	0.00854	0.00756	0.00563	0.00524	0.00491
Solid poultry manure (D)	0.00089	0.00079	0.00059	0.00055	0.00051	0.00251	0.00222	0.00166	0.00154	0.00144	0.00854	0.00756	0.00563	0.00524	0.00491
Liquid cattle and swine manure (D)	0.00089	0.00079	0.00059	0.00055	0.00051	0.00251	0.00222	0.00166	0.00154	0.00144	0.00854	0.00756	0.00563	0.00524	0.00491
Sugar-beet leaf and potato haulm (D)	0.00089	0.00079	0.00059	0.00055	0.00051	0.00251	0.00222	0.00166	0.00154	0.00144	0.00854	0.00756	0.00563	0.00524	0.00491
Commercial and industrial waste (D)	0.00089	0.00079	0.00059	0.00055	0.00051	0.00251	0.00222	0.00166	0.00154	0.00144	0.00854	0.00756	0.00563	0.00524	0.00491
Organic municipal solid waste (D)	0.00089	0.00079	0.00059	0.00055	0.00051	0.00251	0.00222	0.00166	0.00154	0.00144	0.00854	0.00756	0.00563	0.00524	0.00491
Digestates (energy crops)	0.00089	0.00079	0.00059	0.00055	0.00051	0.00251	0.00222	0.00166	0.00154	0.00144	0.00854	0.00756	0.00563	0.00524	0.00491

Sources: Own calculation, multiplying the biomass transport emissions from Table A.20 by the respective mean transport distance from Table A.18, row D (values rounded).

Notes: DM = dry mass. a = year. t = tonne. For feedstocks indicated by (D), the relevant emissions are those associated with digestates. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 26: CO₂ Emissions from the Transportation of Biochar to the Farms, Germany, 2015-2050, Scenario *Max 1*

Feedstocks	Small-scale pyrolysis units (à 2,000 t _{DM} feedstock/a)					Medium-scale pyrolysis units (à 16,000 t _{DM} feedstock/a)					Large-scale pyrolysis units (à 184,800 t _{DM} feedstock/a)				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Cereal straw	0.00007	0.00005	0.00003	0.00003	0.00003	0.00020	0.00015	0.00010	0.00009	0.00008	0.00069	0.00051	0.00032	0.00030	0.00028
Forestry residues	0.00006	0.00005	0.00003	0.00003	0.00003	0.00018	0.00013	0.00008	0.00008	0.00007	0.00061	0.00045	0.00029	0.00027	0.00025
Open-country biomass residues	0.00007	0.00005	0.00003	0.00003	0.00003	0.00018	0.00014	0.00009	0.00008	0.00008	0.00063	0.00046	0.00030	0.00027	0.00026
Industrial wood waste	0.00006	0.00005	0.00003	0.00003	0.00003	0.00017	0.00013	0.00008	0.00008	0.00007	0.00059	0.00043	0.00028	0.00026	0.00024
Wood in municipal solid waste	0.00006	0.00005	0.00003	0.00003	0.00003	0.00018	0.00013	0.00008	0.00008	0.00007	0.00061	0.00045	0.00029	0.00027	0.00025
Green waste: Compensation areas	0.00007	0.00005	0.00003	0.00003	0.00003	0.00019	0.00014	0.00009	0.00008	0.00008	0.00065	0.00048	0.00030	0.00028	0.00027
Biomass: Habitat-connectivity areas	0.00007	0.00005	0.00003	0.00003	0.00003	0.00018	0.00014	0.00009	0.00008	0.00008	0.00063	0.00046	0.00030	0.00027	0.00026
Green waste: Extensive grassland	0.00007	0.00005	0.00003	0.00003	0.00003	0.00018	0.00014	0.00009	0.00008	0.00008	0.00063	0.00046	0.00030	0.00027	0.00026
Short-rotation coppice: Erosion areas	0.00005	0.00004	0.00002	0.00002	0.00002	0.00015	0.00011	0.00007	0.00007	0.00006	0.00051	0.00037	0.00024	0.00022	0.00021
Sewage sludge	0.00010	0.00008	0.00005	0.00005	0.00004	0.00029	0.00022	0.00014	0.00013	0.00012	0.00099	0.00073	0.00047	0.00043	0.00041
Solid cattle manure	0.00010	0.00007	0.00005	0.00004	0.00004	0.00028	0.00021	0.00013	0.00012	0.00011	0.00095	0.00070	0.00045	0.00042	0.00039
Solid swine manure	0.00010	0.00007	0.00005	0.00004	0.00004	0.00028	0.00021	0.00013	0.00012	0.00011	0.00095	0.00070	0.00045	0.00042	0.00039
Solid poultry manure	0.00009	0.00007	0.00004	0.00004	0.00004	0.00026	0.00019	0.00012	0.00011	0.00011	0.00089	0.00066	0.00042	0.00039	0.00036
Liquid cattle and swine manure	0.00009	0.00007	0.00004	0.00004	0.00004	0.00027	0.00020	0.00013	0.00012	0.00011	0.00091	0.00067	0.00043	0.00040	0.00037
Sugar-beet leaf and potato haulm	0.00009	0.00007	0.00004	0.00004	0.00004	0.00027	0.00020	0.00013	0.00012	0.00011	0.00091	0.00067	0.00043	0.00040	0.00037
Commercial and industrial waste	0.00008	0.00006	0.00004	0.00003	0.00003	0.00022	0.00016	0.00010	0.00010	0.00009	0.00075	0.00055	0.00035	0.00033	0.00031
Organic municipal solid waste	0.00009	0.00007	0.00004	0.00004	0.00004	0.00027	0.00020	0.00013	0.00012	0.00011	0.00091	0.00067	0.00043	0.00040	0.00037
Digestates (energy crops)	0.00010	0.00008	0.00005	0.00005	0.00004	0.00029	0.00022	0.00014	0.00013	0.00012	0.00099	0.00073	0.00047	0.00043	0.00041

Sources: Own calculation, multiplying the biochar transport emissions from Table A.21 by the respective mean transport distance from Table A.18, row A (values rounded).

Notes: DM = dry mass. a = year. t = tonne. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 27: CO₂ Emissions from the Transportation of Biochar to the Farms, Germany, 2015-2050, Scenario *Max 2*

Feedstocks	Small-scale pyrolysis units (à 2,000 t _{DM} feedstock/a)					Medium-scale pyrolysis units (à 16,000 t _{DM} feedstock/a)					Large-scale pyrolysis units (à 184,800 t _{DM} feedstock/a)				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Cereal straw	0.00004	0.00004	0.00003	0.00003	0.00003	0.00013	0.00011	0.00008	0.00008	0.00007	0.00043	0.00038	0.00028	0.00026	0.00025
Forestry residues	0.00004	0.00003	0.00003	0.00002	0.00002	0.00011	0.00010	0.00007	0.00007	0.00006	0.00038	0.00033	0.00025	0.00023	0.00022
Open-country biomass residues	0.00004	0.00004	0.00003	0.00002	0.00002	0.00011	0.00010	0.00008	0.00007	0.00007	0.00039	0.00034	0.00026	0.00024	0.00022
Industrial wood waste	0.00004	0.00003	0.00002	0.00002	0.00002	0.00011	0.00009	0.00007	0.00007	0.00006	0.00036	0.00032	0.00024	0.00022	0.00021
Wood in municipal solid waste	0.00004	0.00003	0.00003	0.00002	0.00002	0.00011	0.00010	0.00007	0.00007	0.00006	0.00038	0.00033	0.00025	0.00023	0.00022
Green waste: Compensation areas	0.00004	0.00004	0.00003	0.00003	0.00002	0.00012	0.00010	0.00008	0.00007	0.00007	0.00040	0.00036	0.00026	0.00025	0.00023
Biomass: Habitat-connectivity areas	0.00004	0.00004	0.00003	0.00002	0.00002	0.00011	0.00010	0.00008	0.00007	0.00007	0.00039	0.00034	0.00026	0.00024	0.00022
Green waste: Extensive grassland	0.00004	0.00004	0.00003	0.00002	0.00002	0.00011	0.00010	0.00008	0.00007	0.00007	0.00039	0.00034	0.00026	0.00024	0.00022
Short-rotation coppice: Erosion areas	0.00003	0.00003	0.00002	0.00002	0.00002	0.00009	0.00008	0.00006	0.00006	0.00005	0.00031	0.00028	0.00021	0.00019	0.00018
Sewage sludge (D)	0.00006	0.00006	0.00004	0.00004	0.00004	0.00018	0.00016	0.00012	0.00011	0.00010	0.00062	0.00054	0.00041	0.00038	0.00035
Solid cattle manure (D)	0.00006	0.00006	0.00004	0.00004	0.00004	0.00018	0.00016	0.00012	0.00011	0.00010	0.00062	0.00054	0.00041	0.00038	0.00035
Solid swine manure (D)	0.00006	0.00006	0.00004	0.00004	0.00004	0.00018	0.00016	0.00012	0.00011	0.00010	0.00062	0.00054	0.00041	0.00038	0.00035
Solid poultry manure (D)	0.00006	0.00006	0.00004	0.00004	0.00004	0.00018	0.00016	0.00012	0.00011	0.00010	0.00062	0.00054	0.00041	0.00038	0.00035
Liquid cattle and swine manure (D)	0.00006	0.00006	0.00004	0.00004	0.00004	0.00018	0.00016	0.00012	0.00011	0.00010	0.00062	0.00054	0.00041	0.00038	0.00035
Sugar-beet leaf and potato haulm (D)	0.00006	0.00006	0.00004	0.00004	0.00004	0.00018	0.00016	0.00012	0.00011	0.00010	0.00062	0.00054	0.00041	0.00038	0.00035
Commercial and industrial waste (D)	0.00006	0.00006	0.00004	0.00004	0.00004	0.00018	0.00016	0.00012	0.00011	0.00010	0.00062	0.00054	0.00041	0.00038	0.00035
Organic municipal solid waste (D)	0.00006	0.00006	0.00004	0.00004	0.00004	0.00018	0.00016	0.00012	0.00011	0.00010	0.00062	0.00054	0.00041	0.00038	0.00035
Digestates (energy crops)	0.00006	0.00006	0.00004	0.00004	0.00004	0.00018	0.00016	0.00012	0.00011	0.00010	0.00062	0.00054	0.00041	0.00038	0.00035

Sources: Own calculation, multiplying the biochar transport emissions from Table A.21 by the respective mean transport distance from Table A.18, row D (values rounded).

Notes: DM = dry mass. a = year. t = tonne. For feedstocks indicated by (D), the relevant emissions are those associated with digestates. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 28: CO₂ Emissions from the Transportation of Biomass under Conventional Feedstock Management

Feedstocks	Conventional feedstock management (see Table 12)	CO ₂ emissions from the transportation of biomass under conventional feedstock management ^a					CO ₂ emissions from the transportation of composts ^b				
		2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
		t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock				
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Cereal straw	Decomposition in field	-	-	-	-	-	-	-	-	-	-
Forestry residues	Decomposition in forest	-	-	-	-	-	-	-	-	-	-
Open-country biomass residues	Composting, land spread	0.000441	0.000421	0.000360	0.000340	0.000319	0.000434	0.000414	0.000354	0.000334	0.000314
Industrial wood waste	Energetic use	0.000443	0.000422	0.000361	0.000341	0.000320	-	-	-	-	-
Wood in municipal solid waste	Composting, land spread	0.000456	0.000435	0.000372	0.000352	0.000331	0.000434	0.000414	0.000354	0.000334	0.000314
Green waste: Compensation areas	Decomposition on site	-	-	-	-	-	-	-	-	-	-
Biomass: Habitat-connectivity areas	Composting, land spread	0.000441	0.000421	0.000360	0.000340	0.000319	0.000434	0.000414	0.000354	0.000334	0.000314
Green waste: Extensive grassland	Composting, land spread	0.000441	0.000421	0.000360	0.000340	0.000319	0.000434	0.000414	0.000354	0.000334	0.000314
Short-rotation coppice: Erosion areas	Energetic use	0.000495	0.000473	0.000404	0.000381	0.000359	-	-	-	-	-
Sewage sludge	Composting, land spread	0.001984	0.001893	0.001619	0.001528	0.001437	0.000434	0.000414	0.000354	0.000334	0.000314
Solid cattle manure	Solid storage, land spread	-	-	-	-	-	-	-	-	-	-
Solid swine manure	Solid storage, land spread	-	-	-	-	-	-	-	-	-	-
Solid poultry manure	Solid storage, land spread	-	-	-	-	-	-	-	-	-	-
Liquid cattle and swine manure	Liquid storage, land spread	-	-	-	-	-	-	-	-	-	-
Sugar-beet leaf and potato haulm	Decomposition in field	-	-	-	-	-	-	-	-	-	-
Commercial and industrial waste	Composting, land spread	0.001051	0.001003	0.000858	0.000809	0.000761	0.000434	0.000414	0.000354	0.000334	0.000314
Organic municipal solid waste	Composting, land spread	0.001398	0.001333	0.001141	0.001076	0.001012	0.000434	0.000414	0.000354	0.000334	0.000314
Digestates	Composting, land spread	0.002767	0.002639	0.002258	0.002131	0.002003	0.000434	0.000414	0.000354	0.000334	0.000314

Sources:

- Own calculation, multiplying the semi-trailer-related diesel consumption per tonne of freight and kilometer (Table A.19, row D) by the assumed mean transport distance of 9 km, the assumed share of fossil diesel of 93%, the diesel heating value of 35.87 MJ/l (FNR 2012c: 28) and the CO₂ emission factor for diesel fuel of 74.0 t CO₂/TJ (UBA 2013: Table 347, p. 741), and by accounting for the fact that fresh biomass is transported instead of dry biomass, i.e. = semi-trailer diesel consumption (Table A.19, row D) · 9 · 0.93 · 100/(100 – water content (Table 8, column 4)) · 35.87 · 74.0/1,000,000.
- Own calculation, based on the assumption that 64% of the biomass (dry mass) to be composted is transformed into compost (dry mass) and that composts (fresh weight) have an average water content of 40% (derived from Knappe et al. 2012: Figures D-2 and D-5, referring to finished compost from household biowaste and from greenwaste). Due to the lack of more specific data, the respective values were applied to all the composts. Thus, the CO₂ emissions were calculated by multiplying the semi-trailer-related diesel consumption per tonne of freight and kilometer (Table A.19, row D) by the assumed mean transport distance of 9 km, the assumed share of fossil diesel of 93%, the diesel heating value of 35.87 MJ/l (FNR 2012c: 28) and the CO₂ emission factor for diesel fuel of 74.0 t CO₂/TJ (UBA 2013: Table 347, p. 741), and by accounting for the fact that composts are transported undry, i.e. = semi-trailer diesel consumption (Table A.19, row D) · 9 · 0.93 · 64/(100 – 40) · 35.87 · 74.0/1,000,000.

Notes: Values rounded. DM = dry mass. t = tonne. km = kilometer. l = liter. MJ = megajoule. TJ = terajoule. - = not applicable. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 31: Total Net Avoided GHG Emissions from Sections 4.1 to 4.3

Feedstocks	Emissions from biochar		Emissions from conventional feedstock management						Combustion of pyrolysis by-products				Energy input for biochar production					
	Stable C ^a	N ₂ O ^b	CH ₄ ^c	N ₂ O ^d	Stable C ^e	Fossil-fuel substitution			CH ₄ , N ₂ O ⁱ	Fossil-fuel substitution			No process heat recovery			Process heat recovery		
	t CO ₂ e/t _{DM} feedstock		t CO ₂ e/t _{DM} feedstock						t CO ₂ e/t _{DM} feedstock				t CO ₂ e/t _{DM} feedstock					
	(1)	(2)	(3)	(4)	(5)	(6a) ^f	(6b) ^g	(6c) ^h	(7)	(8a) ^j	(8b) ^k	(8c) ^l	(9a) ^m	(9b) ⁿ	(9c) ^o	(10a) ^p	(10b) ^q	(10c) ^r
Cereal straw	0.59	-0.042	-	0.027	-0.172	-	-	-	-0.0004	0.658	0.550	0.342	-0.185	-0.155	-0.099	-0.061	-0.051	-0.033
Forestry residues	0.61	-0.026	-	0.010	-0.180	-	-	-	-0.0005	0.745	0.623	0.387	-0.203	-0.170	-0.108	-0.075	-0.063	-0.040
Open-country biomass residues	0.53	-0.025	0.276	0.071	-0.067	-	-	-	-0.0004	0.655	0.548	0.340	-0.187	-0.156	-0.099	-0.061	-0.051	-0.033
Industrial wood waste	0.59	-0.003	0.005	0.017	-	-1.567	-1.310	-0.813	-0.0005	0.728	0.609	0.378	-0.191	-0.160	-0.102	-0.063	-0.053	-0.034
Wood in municipal solid waste	0.61	-0.019	0.294	0.015	-0.072	-	-	-	-0.0005	0.745	0.623	0.387	-0.203	-0.170	-0.108	-0.075	-0.063	-0.040
Green waste: Compensation areas	0.50	-0.044	-	0.059	-0.165	-	-	-	-0.0004	0.600	0.502	0.312	-0.179	-0.149	-0.095	-0.055	-0.046	-0.029
Biomass: Habitat-connectivity areas	0.53	-0.025	0.276	0.071	-0.067	-	-	-	-0.0004	0.655	0.548	0.340	-0.187	-0.156	-0.099	-0.061	-0.051	-0.033
Green waste: Extensive grassland	0.53	-0.025	0.276	0.071	-0.067	-	-	-	-0.0004	0.655	0.548	0.340	-0.187	-0.156	-0.099	-0.061	-0.051	-0.033
Short-rotation coppice: Erosion areas	0.45	-0.016	0.005	0.017	-	-1.567	-1.310	-0.813	-0.0005	0.821	0.686	0.426	-0.237	-0.198	-0.126	-0.109	-0.091	-0.058
Sewage sludge	0.21	-0.159	0.084	0.306	-0.099	-	-	-	-0.0004	0.584	0.488	0.303	-1.510	-1.263	-0.805	-1.405	-1.175	-0.749
Solid cattle manure	0.30	-0.075	0.100	0.282	-0.112	-	-	-	-0.0004	0.586	0.490	0.304	-0.767	-0.641	-0.409	-0.651	-0.544	-0.347
Solid swine manure	0.29	-0.120	0.550	0.493	-0.133	-	-	-	-0.0005	0.751	0.628	0.390	-1.442	-1.205	-0.768	-1.327	-1.109	-0.707
Solid poultry manure	0.25	-0.107	0.100	0.228	-0.098	-	-	-	-0.0003	0.535	0.447	0.278	-0.196	-0.164	-0.105	-0.083	-0.070	-0.044
Liquid cattle and swine manure	0.25	-0.090	0.525	0.230	-0.135	-	-	-	-0.0004	0.599	0.501	0.311	-3.421	-2.860	-1.823	-3.303	-2.761	-1.760
Sugar-beet leaf and potato haulm	0.29	-0.115	-	0.076	-0.158	-	-	-	-0.0004	0.610	0.510	0.316	-2.006	-1.677	-1.069	-1.895	-1.584	-1.010
Commercial and industrial waste	0.30	-0.115	0.300	0.293	-0.073	-	-	-	-0.0004	0.709	0.593	0.368	-0.718	-0.601	-0.383	-0.594	-0.497	-0.317
Organic municipal solid waste	0.35	-0.071	0.186	0.160	-0.045	-	-	-	-0.0003	0.492	0.411	0.255	-1.007	-0.842	-0.536	-0.895	-0.748	-0.477
Digestates	0.26	-0.100	0.086	0.431	-0.102	-	-	-	-0.0005	0.770	0.644	0.400	-2.199	-1.839	-1.172	-2.091	-1.748	-1.114

Table will be continued on the next page.

Table 31 continued

Feedstocks	Total net avoided GHG emissions (Sections 4.1 to 4.3)					
	No process heat recovery			Process heat recovery		
	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas
	t CO ₂ e/t _{DM} feedstock					
	(11) ^s	(12) ⁱ	(13) ^u	(14) ^v	(15) ^w	(16) ^x
Cereal straw	0.879	0.801	0.649	1.003	0.905	0.715
Forestry residues	0.952	0.863	0.688	1.080	0.970	0.756
Open-country biomass residues	1.256	1.179	1.028	1.382	1.284	1.095
Industrial wood waste	-0.418	-0.249	0.075	-0.290	-0.142	0.143
Wood in municipal solid waste	1.366	1.277	1.103	1.494	1.384	1.171
Green waste: Compensation areas	0.774	0.705	0.569	0.898	0.809	0.635
Biomass: Habitat-connectivity areas	1.256	1.179	1.028	1.382	1.284	1.095
Green waste: Extensive grassland	1.256	1.179	1.028	1.382	1.284	1.095
Short-rotation coppice: Erosion areas	-0.527	-0.366	-0.058	-0.400	-0.260	0.010
Sewage sludge	-0.581	-0.429	-0.156	-0.476	-0.341	-0.100
Solid cattle manure	0.313	0.342	0.389	0.429	0.440	0.451
Solid swine manure	0.385	0.499	0.698	0.500	0.595	0.759
Solid poultry manure	0.714	0.658	0.548	0.827	0.753	0.608
Liquid cattle and swine manure	-2.046	-1.583	-0.735	-1.928	-1.484	-0.673
Sugar-beet leaf and potato haulm	-1.307	-1.078	-0.663	-1.196	-0.985	-0.604
Commercial and industrial waste	0.700	0.702	0.695	0.824	0.806	0.761
Organic municipal solid waste	0.067	0.151	0.301	0.179	0.245	0.361
Digestates	-0.857	-0.623	-0.200	-0.749	-0.532	-0.142

Sources:

- | | | |
|---|---|---|
| a) Table 13, column 4 | i) Table 19, column 8; shown as a negative value | q) Table 23, column 8; shown as a negative value |
| b) Table 17, column 9; shown as a negative value | j) Table 20, column 4 | r) Table 23, column 12; shown as a negative value |
| c) Table 14, column 5 | k) Table 20, column 8 | s) (11) = (1) + (2) + (3) + (4) + (5) + (6a) + (7) + (8a) + (9a) |
| d) Table 16, column 13 | l) Table 20, column 12 | t) (12) = (1) + (2) + (3) + (4) + (5) + (6b) + (7) + (8b) + (9b) |
| e) Table 15, column 3; shown as a negative value | m) Table 22, column 4; shown as a negative value | u) (13) = (1) + (2) + (3) + (4) + (5) + (6c) + (7) + (8c) + (9c) |
| f) Table 18, column 4; shown as a negative value | n) Table 22, column 8; shown as a negative value | v) (14) = (1) + (2) + (3) + (4) + (5) + (6a) + (7) + (8a) + (10a) |
| g) Table 18, column 8; shown as a negative value | o) Table 22, column 12; shown as a negative value | w) (15) = (1) + (2) + (3) + (4) + (5) + (6b) + (7) + (8b) + (10b) |
| h) Table 18, column 12; shown as a negative value | p) Table 23, column 4; shown as a negative value | x) (16) = (1) + (2) + (3) + (4) + (5) + (6c) + (7) + (8c) + (10c) |

Notes: Values rounded. DM = dry mass. t = tonne. Any GHG emissions are entered with a negative sign, any C removals or avoided emissions are entered with a positive sign. Negative total net avoided GHG emissions are highlighted by grey color.

Table 32: Total Net Avoided GHG Emissions, 2030, Scenario *Max 1*

Feedstocks	Small-scale pyrolysis units						Medium-scale pyrolysis units						Large-scale pyrolysis units					
	No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery		
	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas
	t CO ₂ e/t _{DM} feedstock						t CO ₂ e/t _{DM} feedstock						t CO ₂ e/t _{DM} feedstock					
	(1) ^a	(2) ^b	(3) ^c	(4) ^d	(5) ^e	(6) ^f	(7) ^g	(8) ^h	(9) ⁱ	(10) ^j	(11) ^k	(12) ^l	(13) ^m	(14) ⁿ	(15) ^o	(16) ^p	(17) ^q	(18) ^r
Cereal straw	0.879	0.801	0.649	1.002	0.905	0.715	0.879	0.801	0.648	1.002	0.904	0.714	0.878	0.800	0.648	1.001	0.903	0.713
Forestry residues	0.952	0.863	0.688	1.080	0.970	0.756	0.952	0.863	0.688	1.079	0.969	0.756	0.951	0.862	0.687	1.078	0.968	0.755
Open-country biomass residues	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.096	1.256	1.179	1.028	1.381	1.284	1.095
Industrial wood waste	-0.418	-0.249	0.075	-0.290	-0.142	0.143	-0.418	-0.249	0.075	-0.290	-0.142	0.143	-0.419	-0.250	0.074	-0.291	-0.143	0.142
Wood in municipal solid waste	1.367	1.278	1.104	1.495	1.385	1.172	1.367	1.278	1.103	1.495	1.385	1.171	1.366	1.277	1.102	1.494	1.384	1.170
Green waste: Compensation areas	0.774	0.705	0.569	0.898	0.808	0.635	0.774	0.705	0.569	0.898	0.808	0.635	0.773	0.704	0.568	0.897	0.807	0.634
Biomass: Habitat-connectivity areas	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.096	1.256	1.179	1.028	1.381	1.284	1.095
Green waste: Extensive grassland	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.096	1.256	1.179	1.028	1.381	1.284	1.095
Short-rotation coppice: Erosion areas	-0.527	-0.366	-0.058	-0.400	-0.259	0.010	-0.528	-0.366	-0.058	-0.400	-0.260	0.010	-0.529	-0.367	-0.059	-0.401	-0.261	0.009
Sewage sludge	-0.580	-0.428	-0.155	-0.475	-0.340	-0.099	-0.581	-0.429	-0.156	-0.476	-0.341	-0.100	-0.584	-0.432	-0.159	-0.479	-0.344	-0.103
Solid cattle manure	0.313	0.342	0.389	0.429	0.440	0.451	0.312	0.342	0.389	0.429	0.439	0.451	0.310	0.340	0.386	0.427	0.437	0.449
Solid swine manure	0.386	0.499	0.698	0.500	0.595	0.759	0.385	0.498	0.697	0.500	0.594	0.758	0.381	0.495	0.694	0.496	0.591	0.755
Solid poultry manure	0.714	0.658	0.548	0.827	0.753	0.608	0.713	0.658	0.548	0.827	0.752	0.608	0.712	0.657	0.547	0.825	0.751	0.607
Liquid cattle and swine manure	-2.045	-1.582	-0.735	-1.927	-1.483	-0.672	-2.047	-1.584	-0.737	-1.929	-1.485	-0.674	-2.054	-1.591	-0.744	-1.936	-1.492	-0.681
Sugar-beet leaf and potato haulm	-1.308	-1.079	-0.664	-1.197	-0.986	-0.605	-1.309	-1.080	-0.665	-1.198	-0.987	-0.606	-1.314	-1.085	-0.670	-1.203	-0.992	-0.611
Commercial and industrial waste	0.702	0.703	0.696	0.826	0.807	0.762	0.701	0.702	0.695	0.825	0.806	0.762	0.699	0.700	0.693	0.823	0.804	0.760
Organic municipal solid waste	0.068	0.153	0.302	0.180	0.247	0.362	0.067	0.152	0.301	0.180	0.246	0.361	0.065	0.149	0.299	0.177	0.243	0.359
Digestates (energy crops)	-0.855	-0.621	-0.198	-0.747	-0.530	-0.140	-0.856	-0.622	-0.199	-0.748	-0.531	-0.141	-0.861	-0.627	-0.204	-0.753	-0.536	-0.146

Sources:

- a) (1) = Table 31 (column 11) + Table A.30 (column 3)
b) (2) = Table 31 (column 12) + Table A.30 (column 3)
c) (3) = Table 31 (column 13) + Table A.30 (column 3)
d) (4) = Table 31 (column 14) + Table A.30 (column 3)
e) (5) = Table 31 (column 15) + Table A.30 (column 3)
f) (6) = Table 31 (column 16) + Table A.30 (column 3)

- g) (7) = Table 31 (column 11) + Table A.30 (column 8)
h) (8) = Table 31 (column 12) + Table A.30 (column 8)
i) (9) = Table 31 (column 13) + Table A.30 (column 8)
j) (10) = Table 31 (column 14) + Table A.30 (column 8)
k) (11) = Table 31 (column 15) + Table A.30 (column 8)
l) (12) = Table 31 (column 16) + Table A.30 (column 8)

- m) (13) = Table 31 (column 11) + Table A.30 (column 13)
n) (14) = Table 31 (column 12) + Table A.30 (column 13)
o) (15) = Table 31 (column 13) + Table A.30 (column 13)
p) (16) = Table 31 (column 14) + Table A.30 (column 13)
q) (17) = Table 31 (column 15) + Table A.30 (column 13)
r) (18) = Table 31 (column 16) + Table A.30 (column 13)

Notes: Values rounded. DM = dry mass. t = tonne. GHG emissions are indicated by a negative sign, C removals or avoided emissions are displayed as positive values. Negative total net avoided GHG emissions are highlighted by grey color. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 33: Total Net Avoided GHG Emissions, 2030, Scenario *Max 2*

Feedstocks	Small-scale pyrolysis units						Medium-scale pyrolysis units						Large-scale pyrolysis units					
	No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery		
	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas
	t CO ₂ e/t _{DM} feedstock						t CO ₂ e/t _{DM} feedstock						t CO ₂ e/t _{DM} feedstock					
	(1) ^a	(2) ^b	(3) ^c	(4) ^d	(5) ^e	(6) ^f	(7) ^g	(8) ^h	(9) ⁱ	(10) ^j	(11) ^k	(12) ^l	(13) ^m	(14) ⁿ	(15) ^o	(16) ^p	(17) ^q	(18) ^r
Cereal straw	0.879	0.801	0.649	1.002	0.905	0.715	0.879	0.801	0.649	1.002	0.904	0.714	0.878	0.800	0.648	1.001	0.904	0.714
Forestry residues	0.952	0.863	0.688	1.080	0.970	0.756	0.952	0.863	0.688	1.079	0.969	0.756	0.951	0.862	0.687	1.079	0.969	0.755
Open-country biomass residues	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.096	1.256	1.179	1.028	1.381	1.284	1.095
Industrial wood waste	-0.418	-0.249	0.075	-0.290	-0.142	0.143	-0.418	-0.249	0.075	-0.290	-0.142	0.143	-0.419	-0.250	0.074	-0.291	-0.143	0.142
Wood in municipal solid waste	1.367	1.278	1.104	1.495	1.385	1.172	1.367	1.278	1.103	1.495	1.385	1.171	1.366	1.277	1.103	1.494	1.384	1.171
Green waste: Compensation areas	0.774	0.705	0.569	0.898	0.808	0.635	0.774	0.705	0.569	0.898	0.808	0.635	0.773	0.704	0.568	0.897	0.807	0.634
Biomass: Habitat-connectivity areas	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.096	1.256	1.179	1.028	1.381	1.284	1.095
Green waste: Extensive grassland	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.096	1.256	1.179	1.028	1.381	1.284	1.095
Short-rotation coppice: Erosion areas	-0.527	-0.366	-0.058	-0.400	-0.259	0.010	-0.527	-0.366	-0.058	-0.400	-0.260	0.010	-0.528	-0.367	-0.059	-0.401	-0.261	0.009
Sewage sludge (D)	-0.855	-0.620	-0.198	-0.746	-0.530	-0.140	-0.856	-0.622	-0.199	-0.748	-0.531	-0.141	-0.860	-0.626	-0.203	-0.752	-0.535	-0.145
Solid cattle manure (D)	-0.855	-0.620	-0.198	-0.746	-0.530	-0.140	-0.856	-0.622	-0.199	-0.748	-0.531	-0.141	-0.860	-0.626	-0.203	-0.752	-0.535	-0.145
Solid swine manure (D)	-0.855	-0.620	-0.198	-0.746	-0.530	-0.140	-0.856	-0.622	-0.199	-0.748	-0.531	-0.141	-0.860	-0.626	-0.203	-0.752	-0.535	-0.145
Solid poultry manure (D)	-0.855	-0.620	-0.198	-0.746	-0.530	-0.140	-0.856	-0.622	-0.199	-0.748	-0.531	-0.141	-0.860	-0.626	-0.203	-0.752	-0.535	-0.145
Liquid cattle and swine manure (D)	-0.855	-0.620	-0.198	-0.746	-0.530	-0.140	-0.856	-0.622	-0.199	-0.748	-0.531	-0.141	-0.860	-0.626	-0.203	-0.752	-0.535	-0.145
Sugar-beet leaf and potato haulm (D)	-0.855	-0.620	-0.198	-0.746	-0.530	-0.140	-0.856	-0.622	-0.199	-0.748	-0.531	-0.141	-0.860	-0.626	-0.203	-0.752	-0.535	-0.145
Commercial and industrial waste (D)	-0.855	-0.620	-0.198	-0.746	-0.530	-0.140	-0.856	-0.622	-0.199	-0.748	-0.531	-0.141	-0.860	-0.626	-0.203	-0.752	-0.535	-0.145
Organic municipal solid waste (D)	-0.855	-0.620	-0.198	-0.746	-0.530	-0.140	-0.856	-0.622	-0.199	-0.748	-0.531	-0.141	-0.860	-0.626	-0.203	-0.752	-0.535	-0.145
Digestates (energy crops)	-0.855	-0.620	-0.198	-0.746	-0.530	-0.140	-0.856	-0.622	-0.199	-0.748	-0.531	-0.141	-0.860	-0.626	-0.203	-0.752	-0.535	-0.145

Sources:

- | | | |
|---|--|---|
| a) (1) = Table 31 (column 11) + Table A.33 (column 3) | g) (7) = Table 31 (column 11) + Table A.33 (column 8) | m) (13) = Table 31 (column 11) + Table A.33 (column 13) |
| b) (2) = Table 31 (column 12) + Table A.33 (column 3) | h) (8) = Table 31 (column 12) + Table A.33 (column 8) | n) (14) = Table 31 (column 12) + Table A.33 (column 13) |
| c) (3) = Table 31 (column 13) + Table A.33 (column 3) | i) (9) = Table 31 (column 13) + Table A.33 (column 8) | o) (15) = Table 31 (column 13) + Table A.33 (column 13) |
| d) (4) = Table 31 (column 14) + Table A.33 (column 3) | j) (10) = Table 31 (column 14) + Table A.33 (column 8) | p) (16) = Table 31 (column 14) + Table A.33 (column 13) |
| e) (5) = Table 31 (column 15) + Table A.33 (column 3) | k) (11) = Table 31 (column 15) + Table A.33 (column 8) | q) (17) = Table 31 (column 15) + Table A.33 (column 13) |
| f) (6) = Table 31 (column 16) + Table A.33 (column 3) | l) (12) = Table 31 (column 16) + Table A.33 (column 8) | r) (18) = Table 31 (column 16) + Table A.33 (column 13) |

Notes: Values rounded. DM = dry mass. t = tonne. GHG emissions are indicated by a negative sign, C removals or avoided emissions are displayed as positive values. Negative total net avoided GHG emissions are highlighted by grey color. For feedstocks indicated by (D), the relevant emissions are those associated with digestates. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 35: Revised Biomass Potentials for Biochar Production, Germany, 2015-2050, Scenarios *Max 1*, *Med 1* and *Min 1*

	Scenario <i>Max 1</i>					Scenario <i>Med 1</i>					Scenario <i>Min 1</i>				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	kt _{DM} /a					kt _{DM} /a					kt _{DM} /a				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Feedstocks															
Cereal straw	455	788	1,188	1,232	1,232	455	788	743	770	770	455	473	446	462	462
Forestry residues	1,268	2,228	3,814	3,961	4,120	1,268	2,228	2,384	2,476	2,575	1,268	1,337	1,430	1,485	1,545
Open-country biomass residues	190	316	506	506	506	190	316	316	316	316	190	190	190	190	190
Industrial wood waste	465	775	1,239	1,239	1,239	465	775	775	775	775	465	465	465	465	465
Wood in municipal solid waste	194	317	490	500	500	194	317	306	313	313	194	190	184	188	188
Green waste: Compensation areas	0	143	228	228	228	0	143	143	143	143	0	86	86	86	86
Biomass: Habitat-connectivity areas	0	115	440	440	440	0	115	275	275	275	0	69	165	165	165
Green waste: Extensive grassland	0	178	652	652	652	0	178	408	408	408	0	107	245	245	245
Short-rotation coppice: Erosion areas	0	0	2,200	2,200	2,200	0	0	1,375	1,375	1,375	0	0	825	825	825
Solid biomass residues	2,571	4,859	10,757	10,958	11,117	2,571	4,859	6,723	6,849	6,948	2,571	2,915	4,034	4,109	4,169
Solid cattle manure	716	1,211	1,901	1,935	1,935	716	1,211	1,188	1,209	1,209	716	727	713	726	726
Solid swine manure	198	332	510	518	518	198	332	319	324	324	198	199	191	194	194
Solid poultry manure	103	189	326	326	326	103	189	204	204	204	103	114	122	122	122
Commercial and industrial waste	89	149	238	238	238	89	149	149	149	149	89	89	89	89	89
Organic municipal solid waste	287	549	918	988	1,037	287	549	574	617	648	287	330	344	370	389
Digestable biomass residues	1,394	2,431	3,894	4,004	4,054	1,394	2,431	2,434	2,503	2,534	1,394	1,458	1,460	1,502	1,520
TOTAL	3,965	7,289	14,650	14,962	15,171	3,965	7,289	9,157	9,352	9,482	3,965	4,374	5,494	5,611	5,689

Sources: Own calculations, based on Tables 1 and 34 (values rounded). Notes: DM = dry mass. a = year. kt = kiloton.

Table 36: Revised Biomass Potentials for Biochar Production, Germany, 2015-2050, Scenarios *Max 2*, *Med 2* and *Min 2*

	Scenario <i>Max 2</i>					Scenario <i>Med 2</i>					Scenario <i>Min 2</i>				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	kt _{DM} /a					kt _{DM} /a					kt _{DM} /a				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Feedstocks															
Cereal straw	607	945	1,337	1,386	1,386	607	945	891	924	924	607	630	594	616	616
Forestry residues	1,690	2,674	4,290	4,456	4,635	1,690	2,674	2,860	2,971	3,090	1,690	1,783	1,907	1,980	2,060
Open-country biomass residues	253	379	569	569	569	253	379	379	379	379	253	253	253	253	253
Industrial wood waste	620	929	1,394	1,394	1,394	620	929	929	929	929	620	620	620	620	620
Wood in municipal solid waste	259	381	551	563	563	259	381	368	375	375	259	254	245	250	250
Green waste: Compensation areas	0	171	257	257	257	0	171	171	171	171	0	114	114	114	114
Biomass: Habitat-connectivity areas	0	138	495	495	495	0	138	330	330	330	0	92	220	220	220
Green waste: Extensive grassland	0	213	734	734	734	0	213	489	489	489	0	142	326	326	326
Short-rotation coppice: Erosion areas	0	0	2,475	2,475	2,475	0	0	1,650	1,650	1,650	0	0	1,100	1,100	1,100
Solid biomass residues = TOTAL	3,428	5,830	12,101	12,328	12,507	3,428	5,830	8,068	8,219	8,338	3,428	3,887	5,378	5,479	5,559

Sources: Table 6, without digestates from digestable biomass residues and from energy crops (values rounded). *Notes:* DM = dry mass. a = year. kt = kiloton.

Table 37: Revised Slow-Pyrolysis Biochar Potentials, Germany, 2015-2050, Scenarios *Max 1*, *Med 1* and *Min 1*

Feedstocks	Scenario <i>Max 1</i>					Scenario <i>Med 1</i>					Scenario <i>Min 1</i>				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	kt/a					kt/a					kt/a				
Cereal straw	155	268	404	419	419	155	268	253	262	262	155	161	152	157	157
Forestry residues	380	668	1,144	1,188	1,236	380	668	715	743	773	380	401	429	446	464
Open-country biomass residues	59	98	157	157	157	59	98	98	98	98	59	59	59	59	59
Industrial wood waste	135	225	359	359	359	135	225	225	225	225	135	135	135	135	135
Wood in municipal solid waste	58	95	147	150	150	58	95	92	94	94	58	57	55	56	56
Green waste: Compensation areas	0	46	73	73	73	0	46	46	46	46	0	27	27	27	27
Biomass: Habitat-connectivity areas	0	36	136	136	136	0	36	85	85	85	0	21	51	51	51
Green waste: Extensive grassland	0	55	202	202	202	0	55	126	126	126	0	33	76	76	76
Short-rotation coppice: Erosion areas	0	0	550	550	550	0	0	344	344	344	0	0	206	206	206
Solid biomass residues	787	1,490	3,173	3,235	3,283	787	1,490	1,983	2,022	2,052	787	894	1,190	1,213	1,231
Solid cattle manure	337	569	894	909	909	337	569	558	568	568	337	342	335	341	341
Solid swine manure	93	156	240	244	244	93	156	150	152	152	93	94	90	91	91
Solid poultry manure	45	83	143	143	143	45	83	90	90	90	45	50	54	54	54
Commercial and industrial waste	33	55	88	88	88	33	55	55	55	55	33	33	33	33	33
Organic municipal solid waste	129	247	413	444	467	129	247	258	278	292	129	148	155	167	175
Digestable biomass residues	637	1,111	1,778	1,829	1,851	637	1,111	1,111	1,143	1,157	637	667	667	686	694
TOTAL	1,424	2,601	4,951	5,064	5,133	1,424	2,601	3,094	3,165	3,208	1,424	1,561	1,857	1,899	1,925

Sources: Own calculations, based on Table 35 and the char yields from Table 8, column 6 (values rounded). *Notes:* a = year. kt = kiloton.

Table 38: Revised Slow-Pyrolysis Biochar Potentials, Germany, 2015-2050, Scenarios *Max 2*, *Med 2* and *Min 2*

Feedstocks	Scenario <i>Max 2</i>					Scenario <i>Med 2</i>					Scenario <i>Min 2</i>				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	kt/a					kt/a					kt/a				
Cereal straw	206	321	455	471	471	206	321	303	314	314	206	214	202	210	210
Forestry residues	507	802	1,287	1,337	1,391	507	802	858	891	927	507	535	572	594	618
Open-country biomass residues	78	118	176	176	176	78	118	118	118	118	78	78	78	78	78
Industrial wood waste	180	270	404	404	404	180	270	270	270	270	180	180	180	180	180
Wood in municipal solid waste	78	114	165	169	169	78	114	110	113	113	78	76	74	75	75
Green waste: Compensation areas	0	55	82	82	82	0	55	55	55	55	0	36	36	36	36
Biomass: Habitat-connectivity areas	0	43	153	153	153	0	43	102	102	102	0	28	68	68	68
Green waste: Extensive grassland	0	66	227	227	227	0	66	152	152	152	0	44	101	101	101
Short-rotation coppice: Erosion areas	0	0	619	619	619	0	0	413	413	413	0	0	275	275	275
Solid biomass residues = TOTAL	1,049	1,788	3,569	3,639	3,693	1,049	1,788	2,380	2,426	2,462	1,049	1,192	1,586	1,617	1,641

Sources: Table 10, without digestates from digestable biomass residues and from energy crops (values rounded). *Notes:* a = year. kt = kiloton.

Table 40: Revised CO₂ Emissions from the Transportation of Biomass to the Pyrolysis Units, Germany, 2015-2050, Scenario *Max 1*

Feedstocks	Small-scale pyrolysis units					Medium-scale pyrolysis units					Large-scale pyrolysis units				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Cereal straw	0.00029	0.00020	0.00012	0.00012	0.00011	0.00082	0.00058	0.00035	0.00033	0.00030	0.00280	0.00197	0.00119	0.00111	0.00104
Forestry residues	0.00030	0.00021	0.00013	0.00012	0.00011	0.00085	0.00060	0.00036	0.00034	0.00031	0.00289	0.00203	0.00123	0.00114	0.00107
Open-country biomass residues	0.00029	0.00020	0.00012	0.00012	0.00011	0.00082	0.00058	0.00035	0.00033	0.00030	0.00279	0.00197	0.00119	0.00111	0.00103
Industrial wood waste	0.00029	0.00021	0.00012	0.00012	0.00011	0.00082	0.00058	0.00035	0.00033	0.00031	0.00280	0.00197	0.00119	0.00111	0.00104
Wood in municipal solid waste	0.00030	0.00021	0.00013	0.00012	0.00011	0.00085	0.00060	0.00036	0.00034	0.00031	0.00289	0.00203	0.00123	0.00115	0.00107
Green waste: Compensation areas	0.00029	0.00020	0.00012	0.00011	0.00011	0.00081	0.00057	0.00034	0.00032	0.00030	0.00275	0.00193	0.00117	0.00109	0.00102
Biomass: Habitat-connectivity areas	0.00029	0.00020	0.00012	0.00012	0.00011	0.00082	0.00058	0.00035	0.00033	0.00030	0.00279	0.00197	0.00119	0.00111	0.00103
Green waste: Extensive grassland	0.00029	0.00020	0.00012	0.00012	0.00011	0.00082	0.00058	0.00035	0.00033	0.00030	0.00279	0.00197	0.00119	0.00111	0.00103
Short-rotation coppice: Erosion areas	0.00033	0.00023	0.00014	0.00013	0.00012	0.00092	0.00065	0.00039	0.00037	0.00034	0.00314	0.00221	0.00133	0.00124	0.00116
Solid cattle manure	0.00074	0.00052	0.00031	0.00029	0.00027	0.00208	0.00147	0.00088	0.00083	0.00077	0.00708	0.00498	0.00300	0.00281	0.00262
Solid swine manure	0.00125	0.00088	0.00053	0.00049	0.00046	0.00353	0.00248	0.00150	0.00140	0.00131	0.01198	0.00843	0.00509	0.00475	0.00444
Solid poultry manure	0.00031	0.00022	0.00013	0.00012	0.00011	0.00088	0.00062	0.00037	0.00035	0.00032	0.00297	0.00209	0.00126	0.00118	0.00110
Commercial and industrial waste	0.00069	0.00049	0.00029	0.00027	0.00026	0.00196	0.00138	0.00083	0.00078	0.00073	0.00666	0.00468	0.00283	0.00264	0.00246
Organic municipal solid waste	0.00092	0.00065	0.00039	0.00037	0.00034	0.00260	0.00183	0.00111	0.00103	0.00096	0.00885	0.00623	0.00376	0.00351	0.00328

Sources: Own calculation, multiplying the biomass transport emissions from Table A.20 by the respective mean transport distance from Table A.67, row A (values rounded).

Notes: DM = dry mass. t = tonne. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 41: Revised CO₂ Emissions from the Transportation of Biomass to the Pyrolysis Units, Germany, 2015-2050, Scenario *Max 2*

Feedstocks	Small-scale pyrolysis units					Medium-scale pyrolysis units					Large-scale pyrolysis units				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Cereal straw	0.00031	0.00023	0.00014	0.00013	0.00012	0.00089	0.00065	0.00038	0.00036	0.00034	0.00301	0.00220	0.00131	0.00122	0.00114
Forestry residues	0.00032	0.00024	0.00014	0.00013	0.00012	0.00091	0.00067	0.00040	0.00037	0.00035	0.00311	0.00227	0.00135	0.00126	0.00118
Open-country biomass residues	0.00031	0.00023	0.00014	0.00013	0.00012	0.00088	0.00065	0.00038	0.00036	0.00034	0.00300	0.00220	0.00131	0.00122	0.00114
Industrial wood waste	0.00031	0.00023	0.00014	0.00013	0.00012	0.00089	0.00065	0.00039	0.00036	0.00034	0.00301	0.00221	0.00131	0.00122	0.00114
Wood in municipal solid waste	0.00032	0.00024	0.00014	0.00013	0.00012	0.00091	0.00067	0.00040	0.00037	0.00035	0.00311	0.00227	0.00135	0.00126	0.00118
Green waste: Compensation areas	0.00031	0.00023	0.00013	0.00012	0.00012	0.00087	0.00064	0.00038	0.00035	0.00033	0.00296	0.00216	0.00128	0.00120	0.00112
Biomass: Habitat-connectivity areas	0.00031	0.00023	0.00014	0.00013	0.00012	0.00088	0.00065	0.00038	0.00036	0.00034	0.00300	0.00220	0.00131	0.00122	0.00114
Green waste: Extensive grassland	0.00031	0.00023	0.00014	0.00013	0.00012	0.00088	0.00065	0.00038	0.00036	0.00034	0.00300	0.00220	0.00131	0.00122	0.00114
Short-rotation coppice: Erosion areas	0.00035	0.00026	0.00015	0.00014	0.00013	0.00099	0.00073	0.00043	0.00040	0.00038	0.00337	0.00247	0.00147	0.00137	0.00128

Sources: Own calculation, multiplying the biomass transport emissions from Table A.20 by the respective mean transport distance from Table A.67, row D (values rounded).

Notes: DM = dry mass. t = tonne. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 42: Revised CO₂ Emissions from the Transportation of Biochar to the Farms, Germany, 2015-2050, Scenario *Max 1*

Feedstocks	Small-scale pyrolysis units					Medium-scale pyrolysis units					Large-scale pyrolysis units				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Cereal straw	0.00009	0.00006	0.00004	0.00004	0.00003	0.00026	0.00018	0.00011	0.00010	0.00010	0.00088	0.00062	0.00037	0.00035	0.00032
Forestry residues	0.00008	0.00006	0.00003	0.00003	0.00003	0.00023	0.00016	0.00010	0.00009	0.00008	0.00077	0.00054	0.00033	0.00031	0.00029
Open-country biomass residues	0.00008	0.00006	0.00004	0.00003	0.00003	0.00023	0.00017	0.00010	0.00009	0.00009	0.00080	0.00056	0.00034	0.00032	0.00030
Industrial wood waste	0.00008	0.00005	0.00003	0.00003	0.00003	0.00022	0.00015	0.00009	0.00009	0.00008	0.00075	0.00053	0.00032	0.00030	0.00028
Wood in municipal solid waste	0.00008	0.00006	0.00003	0.00003	0.00003	0.00023	0.00016	0.00010	0.00009	0.00008	0.00077	0.00054	0.00033	0.00031	0.00029
Green waste: Compensation areas	0.00009	0.00006	0.00004	0.00003	0.00003	0.00024	0.00017	0.00010	0.00010	0.00009	0.00082	0.00058	0.00035	0.00033	0.00031
Biomass: Habitat-connectivity areas	0.00008	0.00006	0.00004	0.00003	0.00003	0.00023	0.00017	0.00010	0.00009	0.00009	0.00080	0.00056	0.00034	0.00032	0.00030
Green waste: Extensive grassland	0.00008	0.00006	0.00004	0.00003	0.00003	0.00023	0.00017	0.00010	0.00009	0.00009	0.00080	0.00056	0.00034	0.00032	0.00030
Short-rotation coppice: Erosion areas	0.00007	0.00005	0.00003	0.00003	0.00002	0.00019	0.00013	0.00008	0.00008	0.00007	0.00064	0.00045	0.00027	0.00026	0.00024
Solid cattle manure	0.00013	0.00009	0.00005	0.00005	0.00005	0.00036	0.00025	0.00015	0.00014	0.00013	0.00121	0.00085	0.00051	0.00048	0.00045
Solid swine manure	0.00013	0.00009	0.00005	0.00005	0.00005	0.00036	0.00025	0.00015	0.00014	0.00013	0.00121	0.00085	0.00051	0.00048	0.00045
Solid poultry manure	0.00012	0.00008	0.00005	0.00005	0.00004	0.00033	0.00023	0.00014	0.00013	0.00012	0.00113	0.00080	0.00048	0.00045	0.00042
Commercial and industrial waste	0.00010	0.00007	0.00004	0.00004	0.00004	0.00028	0.00020	0.00012	0.00011	0.00010	0.00095	0.00067	0.00040	0.00038	0.00035
Organic municipal solid waste	0.00012	0.00008	0.00005	0.00005	0.00004	0.00034	0.00024	0.00014	0.00014	0.00013	0.00116	0.00082	0.00049	0.00046	0.00043

Sources: Own calculation, multiplying the biochar transport emissions from Table A.21 by the respective mean transport distance from Table A.67, row A (values rounded).

Notes: DM = dry mass. t = tonne. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 43: Revised CO₂ Emissions from the Transportation of Biochar to the Farms, Germany, 2015-2050, Scenario *Max 2*

Feedstocks	Small-scale pyrolysis units					Medium-scale pyrolysis units					Large-scale pyrolysis units				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
	t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock					t CO ₂ /t _{DM} feedstock				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Cereal straw	0.00010	0.00007	0.00004	0.00004	0.00004	0.00028	0.00020	0.00012	0.00011	0.00011	0.00094	0.00069	0.00041	0.00038	0.00036
Forestry residues	0.00009	0.00006	0.00004	0.00004	0.00003	0.00024	0.00018	0.00011	0.00010	0.00009	0.00083	0.00061	0.00036	0.00034	0.00032
Open-country biomass residues	0.00009	0.00007	0.00004	0.00004	0.00003	0.00025	0.00018	0.00011	0.00010	0.00010	0.00086	0.00063	0.00037	0.00035	0.00033
Industrial wood waste	0.00008	0.00006	0.00004	0.00003	0.00003	0.00024	0.00017	0.00010	0.00010	0.00009	0.00080	0.00059	0.00035	0.00033	0.00030
Wood in municipal solid waste	0.00009	0.00006	0.00004	0.00004	0.00003	0.00024	0.00018	0.00011	0.00010	0.00009	0.00083	0.00061	0.00036	0.00034	0.00032
Green waste: Compensation areas	0.00009	0.00007	0.00004	0.00004	0.00003	0.00026	0.00019	0.00011	0.00011	0.00010	0.00089	0.00065	0.00039	0.00036	0.00034
Biomass: Habitat-connectivity areas	0.00009	0.00007	0.00004	0.00004	0.00003	0.00025	0.00018	0.00011	0.00010	0.00010	0.00086	0.00063	0.00037	0.00035	0.00033
Green waste: Extensive grassland	0.00009	0.00007	0.00004	0.00004	0.00003	0.00025	0.00018	0.00011	0.00010	0.00010	0.00086	0.00063	0.00037	0.00035	0.00033
Short-rotation coppice: Erosion areas	0.00007	0.00005	0.00003	0.00003	0.00003	0.00020	0.00015	0.00009	0.00008	0.00008	0.00069	0.00051	0.00030	0.00028	0.00026

Sources: Own calculation, multiplying the biochar transport emissions from Table A.21 by the respective mean transport distance from Table A.67, row D (values rounded).

Notes: DM = dry mass. t = tonne. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 44: Revised Total Net Avoided GHG Emissions, 2030, Scenario *Max 1*

Feedstocks	Small-scale pyrolysis units						Medium-scale pyrolysis units						Large-scale pyrolysis units					
	No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery		
	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas
	t CO ₂ e/t _{DM} feedstock						t CO ₂ e/t _{DM} feedstock						t CO ₂ e/t _{DM} feedstock					
	(1) ^a	(2) ^b	(3) ^c	(4) ^d	(5) ^e	(6) ^f	(7) ^g	(8) ^h	(9) ⁱ	(10) ^j	(11) ^k	(12) ^l	(13) ^m	(14) ⁿ	(15) ^o	(16) ^p	(17) ^q	(18) ^r
Cereal straw	0.879	0.801	0.649	1.002	0.905	0.715	0.879	0.801	0.648	1.002	0.904	0.714	0.877	0.800	0.647	1.001	0.903	0.713
Forestry residues	0.952	0.863	0.688	1.080	0.970	0.756	0.952	0.863	0.688	1.079	0.969	0.756	0.950	0.861	0.687	1.078	0.968	0.755
Open-country biomass residues	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.096	1.256	1.179	1.028	1.381	1.284	1.094
Industrial wood waste	-0.418	-0.249	0.075	-0.290	-0.142	0.143	-0.418	-0.249	0.075	-0.290	-0.142	0.143	-0.419	-0.250	0.074	-0.291	-0.143	0.142
Wood in municipal solid waste	1.367	1.278	1.104	1.495	1.385	1.172	1.367	1.278	1.103	1.495	1.385	1.171	1.366	1.277	1.102	1.493	1.384	1.170
Green waste: Compensation areas	0.774	0.705	0.569	0.898	0.808	0.635	0.774	0.705	0.569	0.898	0.808	0.635	0.773	0.703	0.567	0.896	0.807	0.633
Biomass: Habitat-connectivity areas	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.096	1.256	1.179	1.028	1.381	1.284	1.094
Green waste: Extensive grassland	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.096	1.256	1.179	1.028	1.381	1.284	1.094
Short-rotation coppice: Erosion areas	-0.527	-0.366	-0.058	-0.400	-0.259	0.010	-0.528	-0.366	-0.058	-0.400	-0.260	0.010	-0.529	-0.368	-0.059	-0.401	-0.261	0.009
Solid cattle manure	0.313	0.342	0.389	0.429	0.440	0.451	0.312	0.342	0.388	0.429	0.439	0.451	0.309	0.339	0.386	0.426	0.437	0.448
Solid swine manure	0.386	0.499	0.698	0.500	0.595	0.759	0.385	0.498	0.697	0.499	0.594	0.758	0.381	0.494	0.693	0.495	0.590	0.754
Solid poultry manure	0.714	0.658	0.548	0.827	0.753	0.608	0.713	0.658	0.548	0.826	0.752	0.608	0.712	0.657	0.547	0.825	0.751	0.607
Commercial and industrial waste	0.701	0.703	0.696	0.826	0.807	0.762	0.701	0.702	0.695	0.825	0.806	0.761	0.699	0.700	0.693	0.823	0.804	0.759
Organic municipal solid waste	0.068	0.153	0.302	0.180	0.246	0.362	0.067	0.152	0.301	0.180	0.246	0.361	0.064	0.149	0.298	0.177	0.243	0.358

Sources:

- | | | |
|---|--|---|
| a) (1) = Table 31 (column 11) + Table A.76 (column 3) | g) (7) = Table 31 (column 11) + Table A.76 (column 8) | m) (13) = Table 31 (column 11) + Table A.76 (column 13) |
| b) (2) = Table 31 (column 12) + Table A.76 (column 3) | h) (8) = Table 31 (column 12) + Table A.76 (column 8) | n) (14) = Table 31 (column 12) + Table A.76 (column 13) |
| c) (3) = Table 31 (column 13) + Table A.76 (column 3) | i) (9) = Table 31 (column 13) + Table A.76 (column 8) | o) (15) = Table 31 (column 13) + Table A.76 (column 13) |
| d) (4) = Table 31 (column 14) + Table A.76 (column 3) | j) (10) = Table 31 (column 14) + Table A.76 (column 8) | p) (16) = Table 31 (column 14) + Table A.76 (column 13) |
| e) (5) = Table 31 (column 15) + Table A.76 (column 3) | k) (11) = Table 31 (column 15) + Table A.76 (column 8) | q) (17) = Table 31 (column 15) + Table A.76 (column 13) |
| f) (6) = Table 31 (column 16) + Table A.76 (column 3) | l) (12) = Table 31 (column 16) + Table A.76 (column 8) | r) (18) = Table 31 (column 16) + Table A.76 (column 13) |

Notes: Values rounded. DM = dry mass. t = tonne. GHG emissions are indicated by a negative sign, C removals or avoided emissions are displayed as positive values. Negative total net avoided GHG emissions are highlighted by grey color. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 45: Revised Total Net Avoided GHG Emissions, 2030, Scenario *Max 2*

Feedstocks	Small-scale pyrolysis units						Medium-scale pyrolysis units						Large-scale pyrolysis units					
	No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery		
	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas
	t CO ₂ e/t _{DM} feedstock						t CO ₂ e/t _{DM} feedstock						t CO ₂ e/t _{DM} feedstock					
	(1) ^a	(2) ^b	(3) ^c	(4) ^d	(5) ^e	(6) ^f	(7) ^g	(8) ^h	(9) ⁱ	(10) ^j	(11) ^k	(12) ^l	(13) ^m	(14) ⁿ	(15) ^o	(16) ^p	(17) ^q	(18) ^r
Cereal straw	0.879	0.801	0.649	1.002	0.905	0.715	0.878	0.801	0.648	1.002	0.904	0.714	0.877	0.800	0.647	1.001	0.903	0.713
Forestry residues	0.952	0.863	0.688	1.080	0.970	0.756	0.951	0.862	0.688	1.079	0.969	0.756	0.950	0.861	0.687	1.078	0.968	0.755
Open-country biomass residues	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.095	1.256	1.179	1.028	1.381	1.283	1.094
Industrial wood waste	-0.418	-0.249	0.075	-0.290	-0.142	0.143	-0.418	-0.249	0.075	-0.290	-0.142	0.143	-0.419	-0.250	0.073	-0.291	-0.143	0.142
Wood in municipal solid waste	1.367	1.278	1.104	1.495	1.385	1.172	1.367	1.278	1.103	1.495	1.385	1.171	1.365	1.277	1.102	1.493	1.383	1.170
Green waste: Compensation areas	0.774	0.705	0.569	0.898	0.808	0.635	0.774	0.704	0.568	0.897	0.808	0.635	0.772	0.703	0.567	0.896	0.807	0.633
Biomass: Habitat-connectivity areas	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.095	1.256	1.179	1.028	1.381	1.283	1.094
Green waste: Extensive grassland	1.257	1.180	1.029	1.382	1.285	1.096	1.257	1.180	1.029	1.382	1.285	1.095	1.256	1.179	1.028	1.381	1.283	1.094
Short-rotation coppice: Erosion areas	-0.527	-0.366	-0.058	-0.400	-0.259	0.010	-0.528	-0.366	-0.058	-0.400	-0.260	0.010	-0.529	-0.368	-0.059	-0.401	-0.261	0.008

Sources:

- a) (1) = Table 31 (column 11) + Table A.79 (column 3)
- b) (2) = Table 31 (column 12) + Table A.79 (column 3)
- c) (3) = Table 31 (column 13) + Table A.79 (column 3)
- d) (4) = Table 31 (column 14) + Table A.79 (column 3)
- e) (5) = Table 31 (column 15) + Table A.79 (column 3)
- f) (6) = Table 31 (column 16) + Table A.79 (column 3)

- g) (7) = Table 31 (column 11) + Table A.79 (column 8)
- h) (8) = Table 31 (column 12) + Table A.79 (column 8)
- i) (9) = Table 31 (column 13) + Table A.79 (column 8)
- j) (10) = Table 31 (column 14) + Table A.79 (column 8)
- k) (11) = Table 31 (column 15) + Table A.79 (column 8)
- l) (12) = Table 31 (column 16) + Table A.79 (column 8)

- m) (13) = Table 31 (column 11) + Table A.79 (column 13)
- n) (14) = Table 31 (column 12) + Table A.79 (column 13)
- o) (15) = Table 31 (column 13) + Table A.79 (column 13)
- p) (16) = Table 31 (column 14) + Table A.79 (column 13)
- q) (17) = Table 31 (column 15) + Table A.79 (column 13)
- r) (18) = Table 31 (column 16) + Table A.79 (column 13)

Notes: Values rounded. DM = dry mass. t = tonne. GHG emissions are indicated by a negative sign, C removals or avoided emissions are displayed as positive values. Negative total net avoided GHG emissions are highlighted by grey color. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 46: GHG Mitigation Potentials, 2015, Scenario *Max 1*, *Med 1*, *Min 1**

Feedstocks	Small-scale pyrolysis units						Medium-scale pyrolysis units						Large-scale pyrolysis units					
	No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery		
	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas
	kt CO ₂ e/a						kt CO ₂ e/a						kt CO ₂ e/a					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Cereal straw	400	365	295	456	412	325	400	364	295	456	411	325	398	363	294	455	410	324
Forestry residues	1,206	1,093	872	1,368	1,229	958	1,205	1,092	871	1,367	1,228	957	1,202	1,089	868	1,364	1,225	954
Open-country biomass residues	238	224	195	262	244	208	238	224	195	262	243	208	238	223	195	261	243	207
Industrial wood waste	-	-	35	-	-	66	-	-	34	-	-	66	-	-	33	-	-	65
Wood in municipal solid waste	265	248	214	290	269	227	265	248	214	290	269	227	265	247	214	290	268	227
Green waste: Compensation areas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biomass: Habitat-connectivity areas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Green waste: Extensive grassland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Short-rotation coppice: Erosion areas	-	-	-	-	-	0	-	-	-	-	-	0	-	-	-	-	-	0
Solid biomass residues	2,110	1,930	1,611	2,377	2,153	1,785	2,108	1,928	1,609	2,375	2,151	1,783	2,103	1,923	1,603	2,370	2,146	1,777
Solid cattle manure	224	245	278	307	315	323	223	244	277	306	314	322	218	240	273	302	309	318
Solid swine manure	76	99	138	99	118	150	76	98	138	99	117	150	74	96	136	97	115	148
Solid poultry manure	73	68	56	85	77	62	73	68	56	85	77	62	73	67	56	85	77	62
Commercial and industrial waste	63	63	62	74	72	68	62	63	62	74	72	68	62	62	61	73	71	67
Organic municipal solid waste	19	44	87	52	71	104	19	43	86	51	70	103	17	41	84	49	68	101
Digestible biomass residues	455	518	622	617	653	708	453	515	619	614	650	705	444	507	611	605	641	696
TOTAL	2,565	2,448	2,233	2,993	2,805	2,493	2,561	2,444	2,229	2,989	2,802	2,489	2,547	2,429	2,213	2,975	2,787	2,473

Sources: Own calculation, multiplying the total net avoided GHG emissions from Table A.86 by the respective feedstock-specific biomass potential from Table 35, column 1 (values rounded).

Notes: a = year. kt = kiloton. - = not applicable. No GHG mitigation potentials were calculated for cases of negative net avoided GHG emissions per tonne of dry-matter feedstock. Tables numbered with the leading “A.” refer to Teichmann (2014).

* Due to the identical biomass potentials in 2015 (Table 35), the same results are obtained for the *Max 1*, *Med 1* and *Min 1* scenarios.

Table 47: GHG Mitigation Potentials, 2015, Scenario *Max 2*, *Med 2*, *Min 2**

Feedstocks	Small-scale pyrolysis units						Medium-scale pyrolysis units						Large-scale pyrolysis units					
	No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery		
	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas
	kt CO ₂ e/a						kt CO ₂ e/a						kt CO ₂ e/a					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Cereal straw	533	486	394	608	549	434	533	486	393	608	548	433	531	484	391	606	547	431
Forestry residues	1,608	1,458	1,162	1,824	1,638	1,278	1,607	1,456	1,161	1,823	1,637	1,276	1,602	1,452	1,156	1,818	1,632	1,272
Open-country biomass residues	318	298	260	349	325	277	318	298	260	349	325	277	317	297	259	349	324	276
Industrial wood waste	-	-	46	-	-	89	-	-	46	-	-	88	-	-	44	-	-	86
Wood in municipal solid waste	354	331	286	387	358	303	354	331	285	387	358	303	353	330	285	386	358	302
Green waste: Compensation areas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biomass: Habitat-connectivity areas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Green waste: Extensive grassland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Short-rotation coppice: Erosion areas	-	-	-	-	-	0	-	-	-	-	-	0	-	-	-	-	-	0
Solid biomass residues = TOTAL	2,813	2,573	2,148	3,169	2,870	2,380	2,811	2,571	2,146	3,167	2,868	2,377	2,803	2,563	2,136	3,159	2,861	2,368

Sources: Own calculation, multiplying the total net avoided GHG emissions from Table A.87 by the respective feedstock-specific biomass potential from Table 36, column 1 (values rounded).

Notes: a = year. kt = kiloton. - = not applicable. No GHG mitigation potentials were calculated for cases of negative net avoided GHG emissions per tonne of dry-matter feedstock. Tables numbered with the leading “A.” refer to Teichmann (2014).

* Due to the identical biomass potentials in 2015 (Table 36), the same results are obtained for the *Max 2*, *Med 2* and *Min 2* scenarios.

Table 48: GHG Mitigation Potentials, 2030, Scenario *Max 1*

Feedstocks	Small-scale pyrolysis units						Medium-scale pyrolysis units						Large-scale pyrolysis units					
	No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery		
	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas
	kt CO ₂ e/a						kt CO ₂ e/a						kt CO ₂ e/a					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Cereal straw	1,044	952	771	1,191	1,075	849	1,044	952	771	1,191	1,075	849	1,043	950	769	1,190	1,073	848
Forestry residues	3,630	3,290	2,624	4,117	3,698	2,884	3,629	3,289	2,623	4,116	3,697	2,883	3,625	3,285	2,619	4,112	3,693	2,879
Open-country biomass residues	636	597	520	699	650	554	635	597	520	699	650	554	635	596	520	698	649	553
Industrial wood waste	-	-	93	-	-	177	-	-	93	-	-	177	-	-	91	-	-	176
Wood in municipal solid waste	670	626	541	732	679	574	670	626	541	732	678	574	669	626	540	732	678	573
Green waste: Compensation areas	176	161	130	205	184	145	176	161	130	205	184	145	176	160	129	204	184	144
Biomass: Habitat-connectivity areas	553	519	453	608	565	482	553	519	453	608	565	482	553	519	452	608	565	482
Green waste: Extensive grassland	820	770	671	901	838	714	819	769	671	901	838	714	819	769	670	900	837	714
Short-rotation coppice: Erosion areas	-	-	-	-	-	22	-	-	-	-	-	21	-	-	-	-	-	19
Solid biomass residues	7,529	6,915	5,803	8,454	7,689	6,402	7,527	6,913	5,800	8,452	7,686	6,399	7,519	6,905	5,791	8,444	7,678	6,387
Solid cattle manure	594	651	740	816	836	858	593	650	738	815	835	857	588	645	734	810	830	852
Solid swine manure	197	255	356	255	304	387	196	254	356	255	303	387	194	252	354	253	301	385
Solid poultry manure	232	214	178	269	245	198	232	214	178	269	245	198	232	214	178	269	245	198
Commercial and industrial waste	167	167	166	196	192	181	167	167	165	196	192	181	166	167	165	196	191	181
Organic municipal solid waste	63	140	277	166	226	332	62	139	277	165	226	332	59	137	274	162	223	329
Digestable biomass residues	1,253	1,427	1,717	1,703	1,803	1,957	1,250	1,424	1,715	1,700	1,800	1,954	1,240	1,414	1,704	1,690	1,790	1,944
TOTAL	8,782	8,342	7,520	10,157	9,492	8,359	8,777	8,337	7,515	10,152	9,487	8,353	8,759	8,319	7,495	10,134	9,468	8,331

Sources: Own calculation, multiplying the total net avoided GHG emissions from Table 44 by the respective feedstock-specific biomass potential from Table 35, column 3 (values rounded).

Notes: a = year. kt = kiloton. - = not applicable. No GHG mitigation potentials were calculated for cases of negative net avoided GHG emissions per tonne of dry-matter feedstock.

Table 49: GHG Mitigation Potentials, 2030, Scenario *Min 1*

Feedstocks	Small-scale pyrolysis units						Medium-scale pyrolysis units						Large-scale pyrolysis units					
	No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery		
	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas
	kt CO ₂ e/a						kt CO ₂ e/a						kt CO ₂ e/a					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Cereal straw	392	357	289	447	403	318	391	357	289	446	403	318	391	356	288	446	402	317
Forestry residues	1,361	1,234	984	1,544	1,387	1,081	1,360	1,233	983	1,543	1,386	1,081	1,358	1,231	981	1,541	1,383	1,078
Open-country biomass residues	238	224	195	262	244	208	238	224	195	262	244	208	238	223	195	262	243	207
Industrial wood waste	-	-	35	-	-	66	-	-	35	-	-	66	-	-	34	-	-	65
Wood in municipal solid waste	251	235	203	275	254	215	251	235	203	275	254	215	251	234	202	274	254	215
Green waste: Compensation areas	66	60	49	77	69	54	66	60	49	77	69	54	66	60	48	77	69	54
Biomass: Habitat-connectivity areas	207	195	170	228	212	181	207	195	170	228	212	181	207	194	169	228	212	180
Green waste: Extensive grassland	307	289	252	338	314	268	307	288	251	338	314	268	307	288	251	337	314	267
Short-rotation coppice: Erosion areas	-	-	-	-	-	8	-	-	-	-	-	8	-	-	-	-	-	6
Solid biomass residues	2,823	2,593	2,176	3,170	2,883	2,400	2,822	2,592	2,174	3,169	2,882	2,398	2,817	2,587	2,168	3,164	2,877	2,391
Solid cattle manure	223	244	277	306	313	322	222	243	276	305	313	321	219	240	274	302	310	318
Solid swine manure	74	95	134	96	114	145	73	95	133	95	113	145	72	94	132	94	112	144
Solid poultry manure	87	80	67	101	92	74	87	80	67	101	92	74	87	80	67	101	92	74
Commercial and industrial waste	63	63	62	74	72	68	62	63	62	74	72	68	62	62	62	73	72	68
Organic municipal solid waste	23	52	104	62	85	125	23	52	103	62	84	124	21	50	102	60	83	122
Digestable biomass residues	470	535	644	638	676	734	468	533	642	636	674	732	461	527	636	630	668	725
TOTAL	3,293	3,128	2,819	3,808	3,559	3,134	3,290	3,125	2,816	3,805	3,556	3,130	3,278	3,113	2,804	3,794	3,544	3,117

Sources: Own calculation, multiplying the total net avoided GHG emissions from Table A.83 by the respective feedstock-specific biomass potential from Table 35, column 13 (values rounded).

Notes: a = year. kt = kiloton. - = not applicable. No GHG mitigation potentials were calculated for cases of negative net avoided GHG emissions per tonne of dry-matter feedstock. Tables numbered with the leading “A.” refer to Teichmann (2014).

Table 50: GHG Mitigation Potentials, 2030, Scenario *Max 2*

Feedstocks	Small-scale pyrolysis units						Medium-scale pyrolysis units						Large-scale pyrolysis units					
	No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery			No process heat recovery			Process heat recovery		
	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas	Lignite	Hard coal	Natural gas
	kt CO ₂ e/a						kt CO ₂ e/a						kt CO ₂ e/a					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Cereal straw	1,175	1,071	867	1,340	1,209	955	1,174	1,071	867	1,340	1,209	955	1,173	1,069	865	1,338	1,207	953
Forestry residues	4,083	3,702	2,952	4,632	4,160	3,244	4,082	3,700	2,951	4,630	4,159	3,243	4,077	3,695	2,946	4,625	4,154	3,238
Open-country biomass residues	715	671	585	786	731	623	715	671	585	786	731	623	714	670	584	785	730	622
Industrial wood waste	-	-	104	-	-	199	-	-	104	-	-	199	-	-	102	-	-	197
Wood in municipal solid waste	754	705	608	824	763	646	753	704	608	824	763	646	753	704	607	823	763	645
Green waste: Compensation areas	199	181	146	230	207	163	198	181	146	230	207	163	198	180	146	230	207	162
Biomass: Habitat-connectivity areas	622	584	509	684	636	542	622	584	509	684	636	542	622	583	509	684	635	542
Green waste: Extensive grassland	922	866	755	1,014	942	804	922	865	755	1,014	942	804	921	865	754	1,013	941	803
Short-rotation coppice: Erosion areas	-	-	-	-	-	25	-	-	-	-	-	24	-	-	-	-	-	21
Solid biomass residues = TOTAL	8,470	7,779	6,528	9,511	8,650	7,202	8,467	7,777	6,525	9,508	8,647	7,198	8,457	7,767	6,513	9,498	8,637	7,184

Sources: Own calculation, multiplying the total net avoided GHG emissions from Table 45 by the respective feedstock-specific biomass potential from Table 36, column 3 (values rounded).

Notes: a = year. kt = kiloton. - = not applicable. No GHG mitigation potentials were calculated for cases of negative net avoided GHG emissions per tonne of dry-matter feedstock.