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RESEARCH

Assessment of biomass utilization pathways: a German case study

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Abstract

Currently, biomass utilization is predominantly directed toward bioenergy (BE) production. Yet, alternative pathways such as biochar carbon removal (BCR) and bioenergy with carbon capture and storage (BECCS) are emerging options within negative emission technologies. Given limited biomass resources, determining their most beneficial allocation remains a pressing question. This study addresses the research gap by jointly evaluating the private investment perspective (net private benefit, NPB) and the broader societal perspective (net social benefit, NSB). Through an integrated assessment framework, the analyses compare biomass utilization pathways across a range of technological, regulatory, and market developments. Herein, wheat straw in Germany was selected due to its high theoretical potentials. Under current conditions, BE shows the highest NPB, followed by BECCS, while BCR displays a negative NPB without policy or market adjustments. However, all pathways demonstrate positive NSB when environmental externalities are monetized. Scenario analyses indicate that BECCS can surpass BE in NPB with incentives such as higher carbon removal credit, cost reductions, or improved CO_2 storage infrastructure. BCR becomes NPB-positive under scenarios with either cost reductions or revenue increases. It surpasses BE only when both occur simultaneously but does not exceed BECCS in any scenario. As the energy sector decarbonizes, BCR and BECCS become increasingly competitive. The study emphasizes the need for flexible, context-dependent pathways and robust policy support to ensure that biomass utilization in Germany is viable from both private economic and societal standpoints.

Keywords Industrial ecology · Carbon removal · BECCS · Biochar · Sustainability assessment · Economic assessment

1 Introduction

Despite defossilization efforts, substantial residual greenhouse gas emissions are projected to remain, particularly from hard-to-abate industrial sectors in countries such as Germany (Luderer et al., 2021; Wollnik et al., 2024). To address these residual emissions, carbon removal and storage strategies are essential (Creutzig et al., 2015; Smith et al., 2016). One strategy is biomass carbon removal and storage (BiCRS). Therein, bioenergy with carbon capture and storage (BECCS) and biochar carbon removal (BCR) present key options (Borchers et al., 2022; Hahn et al., 2020). BECCS combines bioenergy production with carbon capture and geological storage. BCR converts biomass via pyrolysis, heating it in an oxygen-limited environment. The process sequesters carbon via producing biochar, usable as soil improver or fertilizer (Xu et al., 2021). Pyrolysis also produces gases that can substitute fossil-based energy (Werner et al., 2018; Woolf et al., 2010).

Although BiCRS options exist, biomass in Germany is predominantly converted into bioenergy (BE) without carbon capture and storage (BMEL, 2022; Woodall & McCormick, 2022). Both BE and BiCRS can replace fossil fuels, while BiCRS additionally sequesters carbon. In the case of BCR, the biochar produced can also enhance soil health. However, while BE is economically established, BiCRS face economic uncertainties and policy barriers (Borchers et al., 2024; Thrän et al., 2020, 2025; Wollnik et al., 2024; Xu et al., 2021). As a result, BiCRS options such as BCR and BECCS remain limited in practice while BE is already widely deployed (Hahn et al., 2020). Given rising demand for carbon removal and limited sustainable biomass availability, determining the most beneficial utilization pathway is essential (Patrizio et al., 2021). Together with ongoing

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discussions on BiCRS's geological storage, certification, deployment subsidies, and integration into emission trading (BMWK, 2024; Deutsche Bundesregierung, 2024), this highlights the need to balance private and societal goals and guide strategic decisions with ex-ante assessments (Campion et al., 2023).

Evaluating biomass utilization pathways regarding the private perspective determines under which conditions they are attractive for investment. Financial outcomes are uncertain due to factors such as process design, scale, location, and co-products, leaving economic viability unclear (Shukla et al., 2022; Smith et al., 2016). To address this, the net private benefit (NPB) captures techno-economic performance, providing a systematic way to assess financial returns (Boardman et al., 2018; Pearce & Turner, 1994).

Yet, considering private benefit alone is insufficient. NPB risks favoring pathways that generate high private returns but impose externalities on society. Thus, the net social benefit (NSB) extends the analysis by monetizing externalities, including environmental impacts, in line with welfare economics and cost–benefit analysis (Arendt et al., 2020; Boardman et al., 2018; Jarvis et al., 2022; Pearce & Turner, 1994). For NSB, including multiple environmental impact categories allows detecting trade-offs and co-benefits, so that decisions account for effects beyond global warming potential (GWP) (Arendt et al., 2020; Borchers et al., 2024; Wollnik et al., 2024). Expressing both NPB and NSB in monetary benefit per unit biomass enables cross-pathway comparison (Lynd & Wang, 2003).

A further prerequisite is credibly quantifying carbon removal credit (CRC), which is vital for biomass utilization pathways' competitiveness (Oh et al., 2025; Ruett et al., 2024; Woodall & McCormick, 2022). Herein, a major challenge is inconsistent accounting, as failing to distinguish avoided and removed emissions, both expressed in CO_2eq, can distort economic and environmental evaluations (Tanzer & Ramírez, 2019; Terlouw et al., 2021). Therefore, it is essential to differentiate two emission reduction categories. First, avoided emissions arise from substituting other processes or products, for example when fossil energy is replaced by biomass-based energy. This constitutes an accounting construct whose magnitude depends on the (region- and time-dependent) emissions of the substituted process or product. Second, permanently stored emissions arise from long-term emission binding, such as CO_2 stored in geological formations or carbon fixed in biochar. Although both categories are termed "negative" emissions, only the second qualifies for emission removal. Thus, the actual removal effect of a biomass utilization pathway equals permanently stored emissions minus all positive pathway emissions (i.e., fore- and background emissions). The result reflects the net CO_2eq emissions removed, the so-called carbon dioxide removal (CDR), and thus the real contribution to permanent emission removal from the atmosphere (ISO, 2006; Tanzer & Ramírez, 2019; Terlouw et al., 2021). The distinction of avoided and removed emissions links directly to private and social benefits: permanent CDR contributes to NPB through removal credits such as CRC, while avoided emissions are reflected in NSB through monetized environmental impacts. Clear accounting of both components ensures that assessments reflect investor and broader societal benefits.

Recent studies assessing biomass utilization pathways in Germany lack this integrated perspective. They target either BE or BiCRS (Borchers et al., 2024; Thrän et al., 2020; Wollnik et al., 2024). Also, results are presented qualitatively (Borchers et al., 2024; Thrän et al., 2020), limiting comparability according to private and social benefits. Other studies neglect social value and impact categories beyond GWP. For example, one study analyzes sector-wide optimal biomass utilization for GWP reduction and cost efficiency (Lubjuhn & Venghaus, 2024). However, this study excludes BiCRS and focuses solely on GWP. Studies analyzing BiCRS disregard CRC revenues, yielding an incomplete representation of NPB (Borchers et al., 2022, 2024; Wollnik et al., 2024).

Against this backdrop, this study compares private and social benefits across different biomass utilization pathways to inform about most beneficial strategic sustainable biomass use. We focus on a German case study using wheat straw as biomass due to its high potential in Germany (DBFZ, 2024). Lignocellulosic residues like straw are regarded sustainable biomasses with significant BE and BiCRS potential (Borchers et al., 2022, 2024; F. Cheng et al., 2020a, 2020b; Fajardy & Dowell, 2017; Thrän et al., 2020). Herein, this study addresses the question: What is the most beneficial use of straw in Germany, comparing BE, BCR, and BECCS, considering both net private and net social benefits?

2 Methods

To address this question, we apply the methodological framework of Ruett et al. (2025) (Fig. 1), which integrates pathway modeling, techno-economic assessment (TEA), life cycle assessment (LCA), and monetization of externalities to derive NPB and NSB. Input data defines the temporal and geographic scope (i.e., year and region) of the assessment. Data is compiled following established hierarchies (SAIC, 2006) and are streamlined for consistency.

Pathway modeling defines system boundaries and the biomass utilization pathways assessed. Herein, marketable products are identified, generating revenues and substituting avoided products. The TEA identifies capital (CAPEX) and operational (OPEX) costs, revenues from energy and physical products as well as CRC prices, all levelized over the pathways' lifetime. The LCA identifies and quantifies

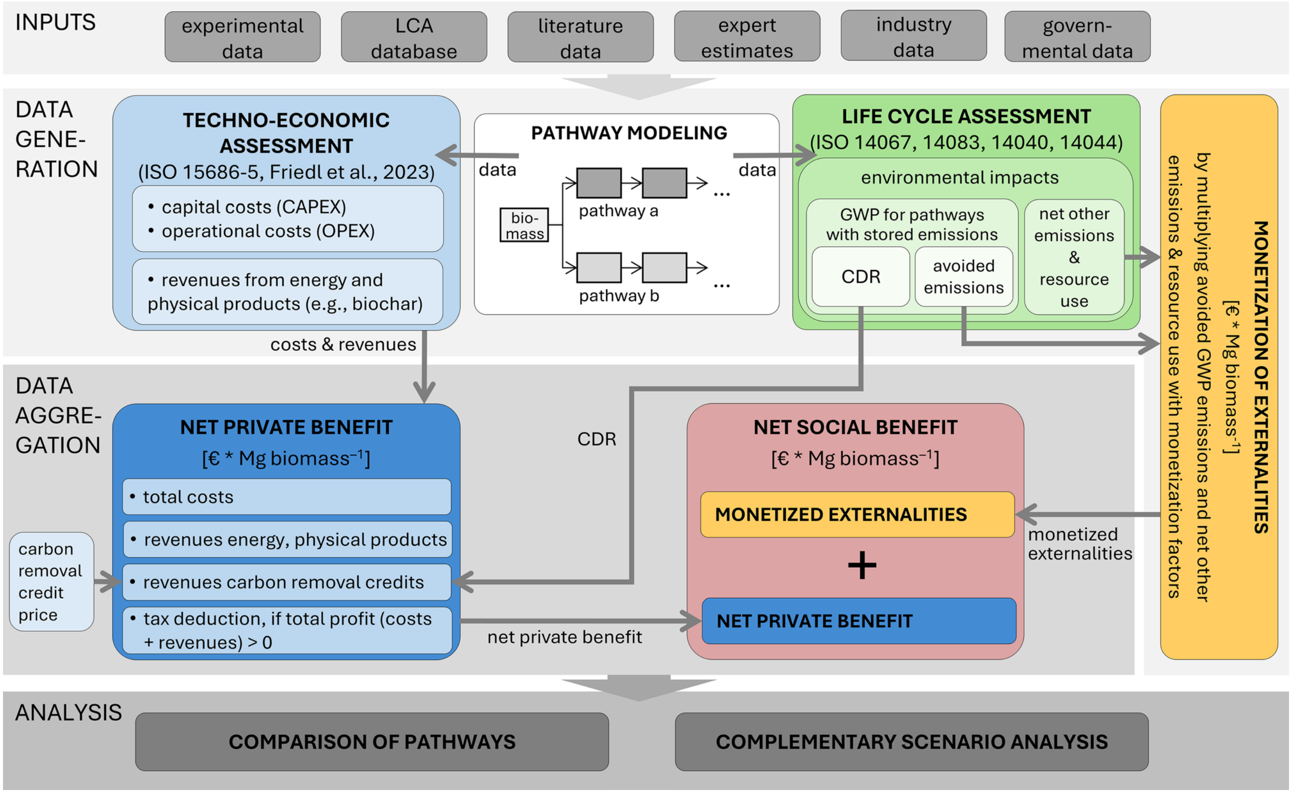


Fig. 1 Methodological framework for assessing biomass utilization pathways, adapted from Ruett et al. (2025). LCA: life cycle assessment, GWP: global warming potential, CDR: carbon dioxide removal

relevant environmental impacts. CDR is derived to calculate CRC revenue (see Eq. 1) which is combined with TEA results to calculate NPB, with taxes deducted if positive.

Monetized externalities are obtained by multiplying avoided GWP emissions for pathways with stored emissions as well as net emissions and resource use (positive plus avoided) of all other impact categories with monetization factors. Adding monetized externalities to NPB yields NSB. Pathways are then compared based on NPB and NSB.

Scenario analyses explore how results vary under different assumptions. A detailed framework description is provided in Ruett et al. (2025). We extend their exemplary miscanthus case to evaluate three straw utilization pathways, BE, BCR, and BECCS, in Germany, generating detailed results and scenario analyses to support decision-making.

2.1 Pathway modeling and data

Figure 2 outlines the system boundaries for BE, BCR, and BECCS pathways, covering straw sourcing, transport, preprocessing, conversion, and carbon storage (where applicable). The identified marketable products generate revenue, while avoiding conventional district heat or electricity (Beiron et al., 2022; Jukka et al., 2022). We employ Mg straw at market (dry mass) as functional unit so that NPB and NSB result in €*Mg straw^{-1}. This unit represents how straw is typically traded and processed, thus generating relevant results for decision-makers. Also, it facilitates a harmonized comparison across pathways with differing output products.

For straw sourcing and transport, we apply the same ecoinvent 3.10 processes for all pathways (Wernet et al., 2016). Consistent with previous assessment of straw-based conversion pathways, economic allocation was chosen for wheat straw to ensure its environmental impacts reflect the market value that drives the material's utilization (ISO, 2006; Parajuli et al., 2017). We then distinguish the value chains for BE (combustion), BCR (slow pyrolysis) and BECCS (gasification with CCS). For BE, we evaluate a heat-producing combustion process in a standard combustion plant (Olabisi et al., 2023), basing the inventory on ecoinvent 3.10 (Wernet et al., 2016). For BCR, straw is first pelletized and then processed in a continuous screw reactor-based plant, producing heat and biochar. Biochar is then transported and tilled into agricultural soils (Ruett et al., 2024).

The BECCS pathway includes straw gasification, pre-combustion carbon capture, CO_2 compression, and transport to long-term geological storage. We assume a gasification process, co-generating both heat and electricity. Gasification-based BECCS is more efficient than alternatives based

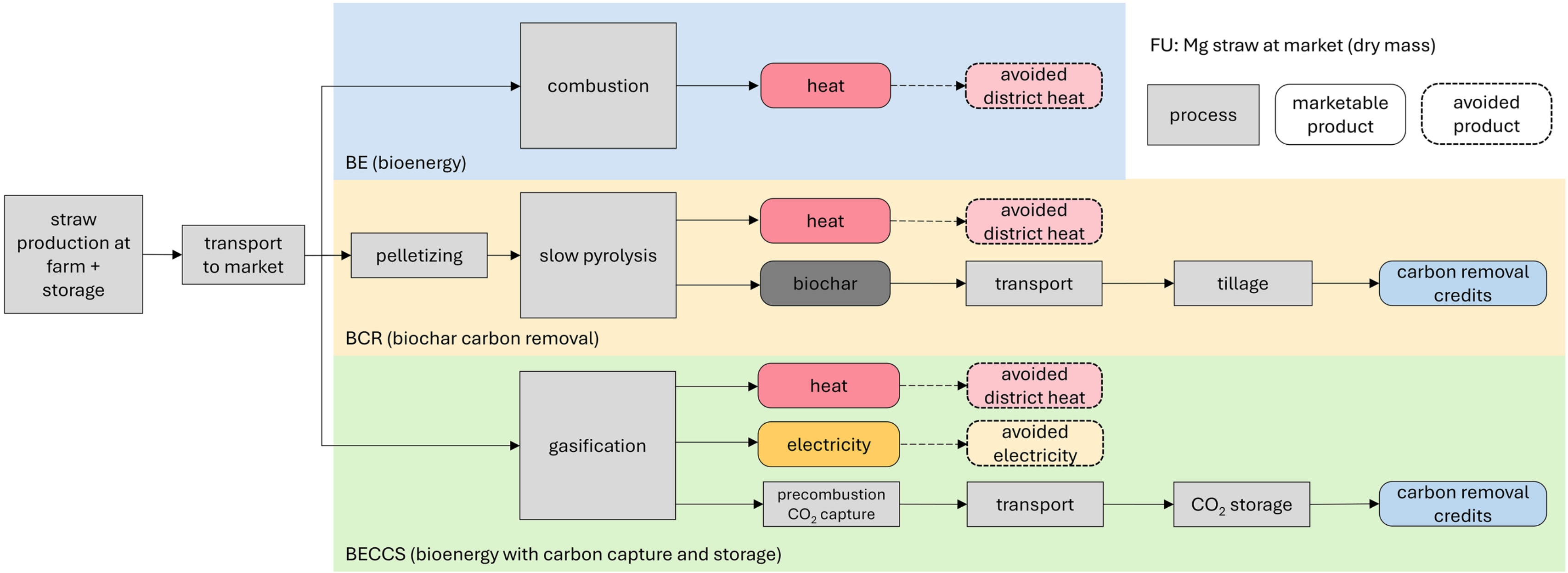


Fig. 2 System boundaries for assessing three straw utilization pathways for a German case study: bioenergy, biochar carbon removal and bioenergy with carbon capture and storage. *FU*: functional unit. Illustration based on Ruett et al. (2025)

on combustion or ethanol production. It also offers lower costs and reduced economic uncertainty (Fuss et al., 2018; Shahbaz et al., 2021).

For carbon capture, we implement a pre-combustion CCS process, the most efficient option for lignocellulosic biomass gasification (Emenike et al., 2020), which outperforms post-combustion capture regarding environmental impact (Oreggioni et al., 2017). We adopt a zeolite-based pressure swing adsorption process, deriving inventory data from Oreggioni et al. (2017). After capture, the CO_2 is compressed and transported to the Northern Lights storage site in Norway. This is the closest site offering large capacities for internationally sourced CO_2 (Burger et al., 2024; Northern Lights JV DA, 2025). Corresponding data is based on Burger et al. (2024). For further input specifications, refer to Supplementary Information SI1.

2.2 Techno-economic and life cycle assessment

For the TEA and LCA, inventories from LCA databases, literature sources and personal communications are compiled (Supplementary Information SI1). All prices are adjusted to € 2024 levels via Producer Price Index (Destatis, 2025; OECD, 2024). Where reported as levelized monetary values, data are converted to present values based on Chan and Tse (2021). Cost and revenue calculations follow procedures outlined by Homagain et al. (2016) and Langhorst et al. (2022). In addition to a 5% discount rate, consistent with Azar et al. (2010) and Homagain et al. (2016), we apply a sensitivity analysis (4–6%, Supplementary Information SI2-4) to assess the effect of alternative rates. Annuity and levelized cost formulas are provided in Supplementary Information SI1.

In terms of environmental impact categories for the LCA, we select GWP over a 100-year time horizon, aligning with studies focusing on BE, BECCS, and BCR technologies (Arfan et al., 2023; Azzi et al., 2022; Cooper et al., 2022). Herein, direct biogenic CO_2 emissions from straw (e.g., due to combustion) are treated as emission-neutral (Guest et al., 2013). CDR is calculated according to Eqs. 2 and 3. Overall, we evaluate GWP, acidification, eutrophication, water use, and ozone depletion, which are commonly applied in BiCRS studies and capture trade-offs, helping to identify burden shifting (Terlouw et al., 2021). The environmental impacts are assessed using the ReCiPe Midpoint (H) method, in accordance with (Esquiaqui et al., 2023). Land use change is excluded, as land occupation is constant across pathways due to identical straw input (Tanzer & Ramírez, 2019).

2.3 Net private benefit

NPB is calculated by combining costs and revenues from the TEA with CRC revenues. If positive, a 25% tax deduction applies (Fawzy et al., 2022; Haeldermans et al., 2020). CRC revenues (€*Mg straw^{-1}) are calculated based on Puro.earth (2023) and Ruett et al. (2025) and draw on both TEA and LCA inputs:

$$CRC_i = P_i \times E_{i,GWP,removed}\ \forall_i \in \{BCR, BECCS\} \tag{1}$$

Here, P_i represents the average market price for CDR via BCR or BECCS (Höglund & Niparko, 2024) given in €*MgCO$_2$eq^{-1}. $E_{i,GWP,removed}$ (Mg CO$_2$eq*Mg straw^{-1}) refers to the total amount of CDR. While BE is excluded as its CDR is zero, the term is calculated differently for BCR and BECCS. For BCR, it is defined as:

$$E_{BCR,GWP,removed} = m_{BCR} \times k_{BCR} \times C_{BCR} \times 3.67 - E_{BCR,GWP,positive} \tag{2}$$

with m_{BCR}denoting the mass of biochar produced (Mg biochar*Mg straw^{-1}) and k_{BCR} is the fraction of carbon considered permanently stored. We assume a permanent fraction of 0.75, in line with long-term stability estimates of biochar under typical soil conditions (Azzi et al., 2024). In the absence of detailed temporal leakage data, we apply a conservative approach by accounting for all potential biochar carbon losses in soils as immediate emissions. C_{BCR} is the biochar's carbon content (Mg C*Mg biochar^{-1}), and 3.67 is the stoichiometric conversion factor from carbon to CO_2. $E_{BCR,GWP,positive}$ denotes positive GWP pathway emissions along the value chain (Mg CO$_2$eq*Mg straw^{-1}). For BECCS, $E_{BECCS,GWP,removed}$ is given by:

$$E_{BECCS,GWP,removed} = m_{CO2} \times k_{BECCS} - E_{BECCS,GWP,positive} \tag{3}$$

with m_{CO2} being the mass of CO_2 injected into geological storage (Mg CO$_2$*Mg straw^{-1}), and k_{BECCS} representing the share of injected CO_2 that is considered permanently stored. We assume full permanence of geological storage, as observed leakage rates remain below 0.01%*a^{-1} (Hepple & Benson, 2005; Miocic et al., 2019). $E_{BECCS,GWP,positive}$ refers to positive GWP emitted along the pathway's value chain (Mg CO$_2$eq*Mg straw^{-1}).

2.4 Monetization of externalities and net social benefit

While NPB matters for private actors, societal decision-making also depends on the social value, quantified by the NSB as the sum of NPB and monetized externalities (Boardman et al., 2018; Pearce & Turner, 1994). Monetized externalities are calculated using discounted midpoint damage cost factors (de Vries et al., 2024), chosen because they are established in cost–benefit analyses and provide estimates for future impacts (Dong et al., 2019). They are applied to avoided GWP emissions for pathways with stored emissions and net other emissions and resource use (Ruett et al., 2025), representing social costs caused by environmental impacts: negative values indicate damage costs, while positive values denote benefits from avoided damage (de Vries et al., 2024). Monetization enables consistent comparison across impact categories and accounts for (avoided) social costs (Arendt et al., 2020; Boardman et al., 2014; Campion et al., 2023). To prevent double counting, CRC revenues, calculated from removed emissions (positive pathway plus stored emissions, Eq. 1–3), are kept separate from damage costs, which are based only on avoided emissions (Fig. 1) (see Ruett et al., 2025).

2.5 Scenario analysis

Building on these methodologies, we assess how key parameter variations affect each pathway (Table 1). NPB and NSB are analyzed separately for clarity. First, we analyze scenarios that test the sensitivity of NPB to cost and revenue parameters. Since these do not affect environmental impacts, monetized externalities remain unchanged. Second, scenarios altering energy system emissions, damage cost assumptions, or allocation affect damage valuations and are evaluated only for NSB. Third, given its decisive role, we analyze CRC pricing under alternative pathway viability and competitiveness assumptions, examining how they translate into varying CRC prices.

Table 1 Scenario analyses description.

Scenario	Description
Net private benefit (NPB) scenarios	
Geological carbon storage in Germany	Transport to a fictional German geological storage close to the German North Sea coast, reducing transport distance by about 80% for BECCS. Domestic storage can significantly reduce costs (Yeates et al., 2024)
BiCRS technological progress	Assuming a 20% reduction in total costs for BECCS (and BCR), based on literature (Heimann et al., 2025)
Lower and higher CRC prices	Lower and higher CRC market prices, according to (Höglund & Niparko, 2024)
Lower and higher district heat prices	District heat price ranges, according to Dominković et al. (2018)
Innovative future	Combination of scenarios: geological carbon storage in Germany, BiCRS technological progress, higher CRC prices, and absence of taxes on BCR and BECCS revenues
Lower and higher biochar carbon permanence	Lower (0.6) and higher (0.9) fractions for carbon permanence in biochar (Azzi et al., 2024)
Net social benefit (NSB) scenarios	
Renewable energy avoided	Electricity and district heat are substituted using projected energy mixes for a climate-neutral Germany in 2045, based on Delpierre et al. (2021) and Prognos et al. (2021). Background processes are not adjusted as their contribution is small relative to the effect of heat and electricity substitution. This approach enables isolating and clearly interpreting the impact of substituting more renewable energy. Does not impact net private benefit as prices for energy mixes remain unchanged. See Supplementary Information SI1 for further information
Lower and higher damage costs	Damage cost ranges according to de Vries et al. (2024). Does not impact net private benefit as changes in damage costs only impact net social benefit
Mass allocation	Environmental impacts of wheat grain production are allocated to straw on a mass base. Does not impact net private benefit as changes in environmental impacts only affect net social benefit
Carbon removal credit prices under alternative assumptions	
Break-even	CRC price at which NPB for the BiCRS technology breaks even (levelized cost of negative CO_2 emissions, according to F. Cheng et al., (2021))
Lower and higher CRC prices	CRC price ranges identified by Höglund and Niparko (2024), regardless of NPB and NSB
Representing (base case/lower/higher) damage costs	CRC prices that reflect the avoided damage costs a technology provides, according to NSB base case damage costs and damage cost ranges provided by de Vries et al. (2024)
Net private benefit higher than BE	CRC price at which the BiCRS pathway's NPB exceeds that of BE (Aines principle (Sandalow et al., 2021), see Woodall and McCormick (2022))

BiCRS: biomass carbon removal and storage, *CRC*: carbon removal credit, *BE*: bioenergy, *BCR*: biochar carbon removal, *BECCS*: bioenergy with carbon capture and storage

3 Results

In the following, we present the results for GWP (3.1), NPB and NSB (3.2), and scenario analyses (3.3) of the straw utilization pathways assessed.

3.1 Global warming potential

Figure 3 reports positive and permanently stored CO_2eq emissions, (a) including or (b) excluding avoided emissions, along with their total for each pathway. Avoiding emissions through substitution (Fig. 3a) improves the total balance for all pathways, with BE showing the strongest substitution effect due to its high district heat generation. The CDR performance (Fig. 3b) varies significantly across pathways. BECCS achieves the highest amount of permanent emission removal per Mg straw, followed by BCR, while BE results in net-positive emissions. Regarding removal efficiencies, BECCS converts a larger share of the straw's theoretical CO_2 potential into stored emissions than BCR (Supplementary Information SI5). However, positive pathway emissions reduce net removal, highlighting their importance and that of conversion efficiency.

3.2 Net private benefit, net social benefit, and damage costs

Figure 4 reports (a) NPB and (b) NSB for the base case. Both negative and positive contributions are displayed and summed to give respective totals. BE and BECCS show positive NPBs under the base case, with BE yielding the highest value. This is largely due to the low process CAPEX and OPEX, as well as the stable revenue stream from district heat. While BECCS displays a lower NPB than BE, it benefits from electricity and CRC revenues, compensating for the higher costs driven by gasification and capture technologies. BCR is not economically viable in the base case, as revenues from biochar and CRC remain insufficient to cover elevated process OPEX. Regarding cost structure, straw feedstock represents a large cost factor across all pathways. BECCS and BCR incur higher processing costs, with BECCS additionally burdened by CO_2 transport expenses. In terms of revenue streams, the three pathways differ considerably: BE depends solely on heat, BCR primarily on biochar and heat, and BECCS on electricity, CRC, and heat. Although BE has an economic advantage, it lacks permanent CDR and cannot benefit from CRC revenues.

Regarding NSB, BE scores highest, followed by BECCS and BCR. All pathways achieve a positive NSB, driven mainly by GWP-related benefits. Other emissions and resource use have a minor contribution to damage costs, despite high environmental prices (Supplementary Information SI5). Figure 5 disaggregates damage costs (a) including (default) or (b) excluding avoided emissions and resource use while adding CRC, and their total for each pathway. Negative costs denote damage costs occurring to society while positive values mean avoided damage costs. All pathways yield net benefits chiefly from avoided GWP. Excluding avoided emissions and resource use while adding CRC, lowers all totals, most for BE, while BECCS still shows net gains due to high CDR and CRC prices. Acidification and water use contribute the most to residual damage costs, whereas other impacts are minimal.

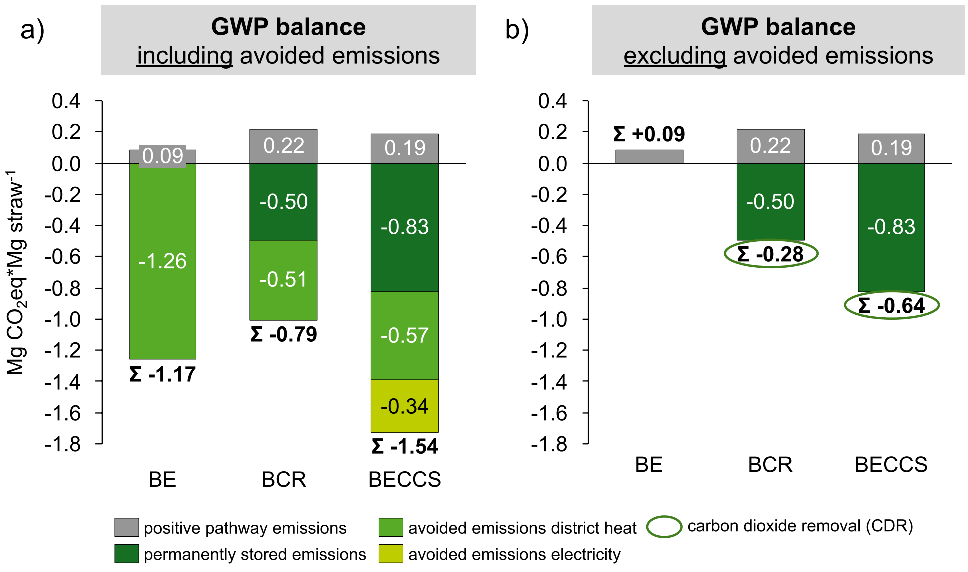


Fig. 3 Global warming potential balance for straw utilization pathways including positive pathway emissions, permanently stored emissions, and (a) including or (b) excluding avoided emissions. *GWP*: global warming potential, *BE*: bioenergy, *BCR*: biochar carbon removal, *BECCS*: bioenergy with carbon capture and storage. Results are presented according to the categorization of Ruett et al. (2025). The data for Fig. 3 can be found in Supplementary Information SI5

Fig. 4 (a) Net private benefit and (b) net social benefit for straw utilization pathways. *BE*: bioenergy, BCR: biochar carbon removal, *BECCS*: bioenergy with carbon capture and storage, *CDR*: carbon dioxide removal, *CAPEX*: capital costs, *OPEX*: operational costs. Results are presented according to the categorization of Ruett et al. (2025). The data for Fig. 4 can be found in Supplementary Information SI5

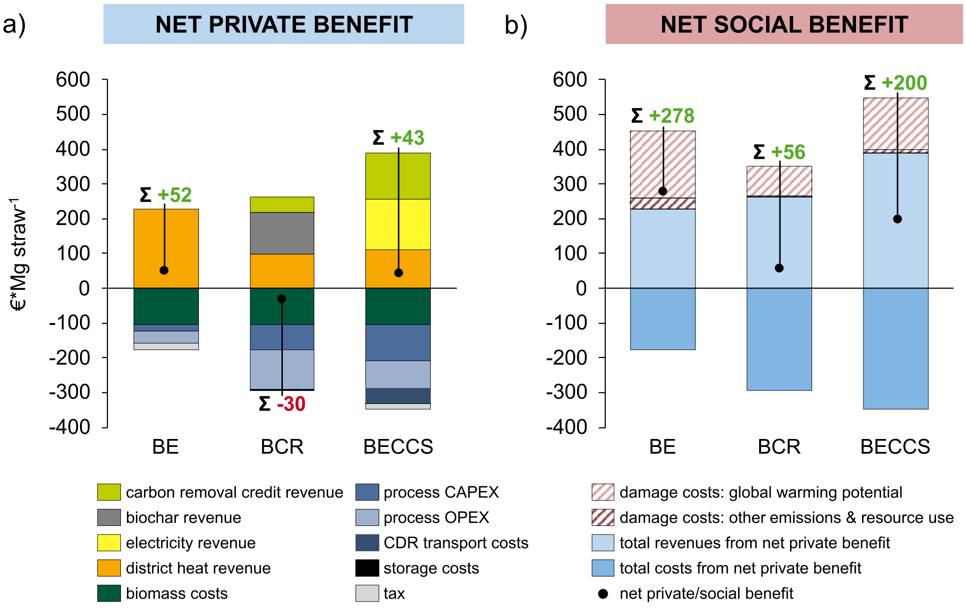
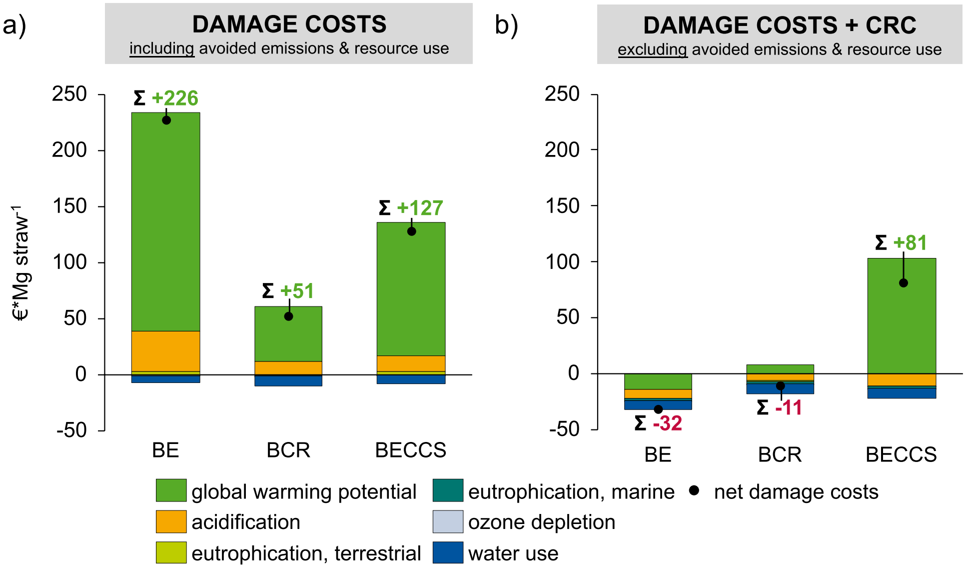


Fig. 5 Disaggregated damage costs for straw utilization pathways (a) including (default for damage cost calculation) or (b) excluding avoided emissions & resource use and adding carbon removal credit. Negative costs denote damage costs that occur to society. Positive values mean avoided damage costs. *CRC*: carbon removal credit, *BE*: bioenergy, *BCR*: biochar carbon removal, *BECCS*: bioenergy with carbon capture and storage. The data for Fig. 5 can be found in Supplementary Information SI5



3.3 Scenario analysis

Table 2 displays results for the scenario analyses, covering scenarios targeted at NPB, NSB, and CRC pricing. For NPB and NSB, results are given as absolute and percentual change compared to the base case. Colors indicate whether a scenario yields a negative (grey) or positive (light green) NPB/NSB and whether BiCRS outperforms BE (dark green). The results of the scenario analyses confirm the overall pathway ranking while also revealing conditions under which less favorable pathways may become viable. NPB and NSB remain positive for BE across all scenarios, though it is sensitive to heat prices. BCR and BECCS are less sensitive to fluctuations in individual revenue streams due to diversified income sources.

BECCS benefits strongly from policy support, technological progress, and domestic CO_2 storage infrastructure while being less sensitive to heat price changes. Herein, BECCS surpasses BE in several scenarios. BCR only becomes NPB-positive under conditions such as higher CRC prices, higher biochar carbon permanence, or technological progress. It is consistently the lowest NPB option, except in the innovative future scenario, where combined technological progress and higher CRC prices enable BCR to outperform BE.

NSB is positive for BE and BECCS across all scenarios. All pathways show lower NSB in the mass allocation scenario since higher environmental impacts are allocated

Table 2. Scenario analyses results for straw utilization pathways. Colors indicate whether a scenario yields negative (grey) or positive (light green) net private or net social benefit, and whether BiCRS outperforms BE (dark green). *BiCRS*: biomass carbon removal and storage, *BE*: bioenergy, *BCR*: biochar carbon removal, *BECCS*: bioenergy with carbon capture and storage, *CRC*: carbon removal credit. For detailed figures, including adoption of NPB scenarios for NSB, see SI5

	BE		**BCR**		**BECCS**	
Net private benefit scenarios: absolute and percentual change compared to the base case						
Base case	0 €	0 %	0 €	0 %	0 €	0 %
Geological carbon storage in Germany	0 €	0 %	0 €	0 %	+18 €	+43 %
BiCRS technological progress	0 €	0 %	+54 €	+178 %	+50 €	+117 %
Lower CRC prices	0 €	0 %	-14 €	-47 %	-6 €	-13 %
Higher CRC prices	0 €	0 %	+35 €	+115 %	+55 €	+127 %
Lower district heat prices	-44 €	-84 %	-25 €	-84 %	-21 €	-49 %
Higher district heat prices	44 €	+84 %	+25 €	+84 %	+21 €	+49 %
Innovative future	0 €	0 %	+98 €	+324 %	+173 €	+405 %
Lower biochar carbon permanence	0 €	0 %	-15 €	-51 %	0 €	0 %
Higher biochar carbon permanence	0 €	0 %	+15 €	+51 %	0 €	0 %
Net social benefit scenarios. absolute and percentual change compared to the base case						
Base Case	0 €	0 %	0 €	0 %	0 €	0 %
Renewable energy avoided	-192 €	-69 %	-75 €	-140 %	-162 €	-71 %
Lower damage costs	-131 €	-47 %	-46 €	-86 %	-120 €	-52 %
Higher damage costs	+69 €	+25 %	+22 €	+41 %	+13 €	+6 %
Mass allocation	-69 €	-25 %	-66 €	-116 %	-97 €	-48 %
Carbon removal credit prices under alternative scenarios						
Base case	N/A		155 €		210 €	
Break-even	N/A		283 €		121 €	
Lower CRC prices	N/A		104 €		198 €	
Higher CRC prices	N/A		286 €		323 €	
Representing base case damage costs	N/A		166 €		166 €	
Representing lower damage costs	N/A		64 €		64 €	
Representing higher damage costs	N/A		204 €		204 €	
Net private benefit higher than BE	N/A		532 €		230 €	

to straw, increasing damage costs. This leads to a negative NSB for BCR. NSB also becomes negative in the renewable energy scenario. In this case, all pathways show lower benefits from fewer avoided fossil emissions and, consequently, reduced avoided damage costs from substituting heat and electricity. BE, which relies heavily on these substitutes, is most affected, underscoring its dependence on the impact magnitude of the substituted energy mix. In contrast, BCR and BECCS are less impacted. Their avoided emissions from heat (Fig. 3), and thus avoided damage costs, are lower. Across all scenarios, BECCS emerges as a robust alternative, particularly under supportive regulatory conditions and market mechanisms.

Variation in CRC prices further highlights BiCRS's sensitivity to them. While BECCS already breaks even well below current CRC levels, BCR requires significantly higher prices for viability. To outperform BE in terms of NPB, BCR would need CRC prices of more than three times current levels, suggesting that cost reductions and policy support beyond carbon pricing are needed. Lower damage costs estimates are lower than current CRC. Base case damage costs align with current CRC for BCR whereas higher damage cost estimates represent CRC for BECCS.

4 Discussion

Based on the preceding analyses, this section reflects key findings of GWP (4.1), NPB, and NSB (4.2), and interprets the results considering policy implications, while identifying levers affecting BiCRS viability (4.2 and 4.3).

4.1 Global warming potential

Net CDR varies with system boundaries and positive pathway emissions (Tanzer & Ramírez, 2019). The latter reduce the removal capacity by approximately 12% for both BECCS and BCR (Supplementary Information SI5). BECCS removes 0.64 Mg CO_2*Mg straw^{-1}, aligning with Salas et al. (2024), and over twice as much as BCR, reflecting higher conversion efficiency and CO_2 capture (F. Cheng et al., 2021). Geological storage provides more durable CDR than biochar application to soils (Dees et al., 2023). For biochar, 1.22 Mg CO_2*Mg biochar^{-1} are removed, one-third less than other studies (Azzi et al., 2022; Fawzy et al., 2022), reflecting conservative assumptions on permanence and positive pathway emissions.

BE achieves the highest avoided emissions under current energy mixes by substituting GWP-intensive heat production, whereas BCR and BECCS avoid similar amounts, consistent with Sanchez et al. (2025). In a low-carbon future, BE's avoided emissions decline. Results support Patrizio et al. (2021), showing BE suits short-term fossil fuel substitution, while most BiCRS pathways are better for long-term emission removal. In our case, BECCS serves both purposes, achieving substitution and removal simultaneously. If large biochar shares are needed (e.g., for agriculture), BCR may be suitable.

4.2 Net private benefit

The NPB analyses also align with previous studies. Costs and revenues depend on scale, co-products, regional conditions, and infrastructure (Smith et al., 2016). For BE, our costs are comparable to the study of Huang et al. (2013), which evaluated break-even prices for miscanthus and wood chips. BCR costs of 1,281 €*t biochar^{-1} match the results (1,050–1,600 €*t biochar^{-1}) of Lenk et al. (2024). Biochar production costs lie within ranges provided by Nematian et al. (2021) and Groot et al. (2018). Unlike our study, F. Cheng et al. (2021) find pyrolysis systems profitable at biochar prices of approximately 960 €*t biochar^{-1} (converted from USD), nearly twice as high as in our base case (500 €*t biochar^{-1}). BECCS capture costs fall within ranges reported by Sher et al. (2025) and below Beiron et al. (2022), likely due to shorter CO_2 transport distances. The findings for the entire BECCS value chain align with F. Cheng et al. (2021).

Under current German conditions, BE is most profitable, followed by BECCS. BCR is not profitable due to higher CAPEX and OPEX as well as lower maturity of BiCRS. Literature confirms that BE typically incurs half the cost of BECCS (Fajardy et al., 2021). Despite delivering both energy and CDR, BiCRS produce less energy, limiting energy revenue streams (Peters et al., 2015; Woodall & McCormick, 2022). Compared to BECCS, BCR offers one third the CDR potential and a 55 € lower CRC price. Although BCR benefits from its decentralized value chain, small-scale deployment, and lower process CAPEX (CDRfyi, 2025), its OPEX is higher due to missing economies of scale. This leads to proportionally higher costs for labor, service, and maintenance.

Most cost drivers vary across pathways, but feedstock cost is consistently a significant factor. While increased land demand may rise costs, technological progress could also counteract cost increases (Fuss et al., 2018). For BECCS, gasification dominates process costs, followed by CO_2-capture and conditioning. Although the assessed pre-combustion BECCS setup is competitive with post-combustion and oxy-fuel BECCS, it demands high energy input (Minx et al., 2018; Sher et al., 2025). Considering its early development stage, the assumed technological improvements are reasonable (Oh et al., 2025; Sher et al., 2025). Its high CAPEX but lower OPEX, compared to post-combustion BECCS (Hekmatmehr et al., 2024), suggests capital subsidies could accelerate deployment (Fridahl et al., 2020). More broadly, reducing costs across the CCS value chain, where technological readiness varies, can yield large gains (Abdelshafy et al., 2022). As CO_2 transport accounts for 13% of total costs, pipeline infrastructure offers potential savings (Becattini et al., 2024; Oeuvray et al., 2024). Domestic geological storage availability would significantly reduce costs (Yeates et al., 2024), as our scenario confirms.

For BCR, process innovation, e.g., cost reductions, scaling, and plant optimization, is key to economic viability (Fuss et al., 2018; Lenk et al., 2024). Transport costs play a smaller role for BCR due to short distances and decentralized setups but could increase if feedstocks or biochar application sites are more distant. Transport distance is particularly critical for low-density products like biomass and biochar (W. Cheng et al., 2020a, 2020b). Competition from other biomass uses, e.g., construction and paper, may further constrain availability (Danielewicz & Surma-Ślusarska, 2019; Moll et al., 2020).

Revenue streams also vary. BE relies solely on heat sales and is thus vulnerable to the fluctuations of heat prices. In contrast, diversified product portfolios in BECCS and BCR enhance revenue stability. For BECCS, electricity revenues dominate, followed by CRC and heat. Even under adverse price scenarios, the pathway remains profitable. For BCR, biochar is the main revenue source, followed by heat and CRC. Nonetheless, this hierarchy may change if biochar prices respond to willingness-to-pay, rise for specialized applications, or decrease as supply grows (F. Cheng et al., 2021; Haeldermans et al., 2020). BCR is also sensitive to heat prices, but less than BE due to its lower revenue reliance on heat. Sensitivity to CRC prices and biochar carbon permanence necessitates regulatory clarity and market development. Options could include conservative default values or producer audits. Initiatives like the EU's CDR certification framework (European Council, 2024) and biochar standards (Bier et al., 2020) are steps in this direction.

The scenario analysis also demonstrates the importance of considering market conditions and volatility. While BE is currently the most profitable, BECCS outperforms it in several future-oriented scenarios, particularly when domestic geological storage becomes available, technological progress is achieved, heat prices fall, or CRC prices rise. Single policy levers, such as enabling geological storage or boosting CRC prices, can make BECCS more profitable than BE. BCR becomes profitable with incentives fostering technological progress and higher CRC prices. In multiple scenarios, BCR approaches or exceeds break-even. Thus, modest combined cost or revenue changes could ensure positive NPB. BCR surpasses BE only in more ambitious combined scenarios requiring both innovation and policy support, though BECCS remains superior. This reflects BECCS's stronger CRC and electricity income, and its higher responsiveness to supportive technological and regulative conditions, as specified above. BE remains profitable, but less competitive. As a mature technology, it is expected to continue contributing in Germany's future decarbonized energy mix (Prognos et al., 2021).

In summary, our outcomes align with the findings of Patrizio et al. (2021): the most beneficial pathway depends on strategic goals. For energy generation and fossil displacement, BE is most cost-effective. For CDR, BECCS is preferable. BCR may complement both if biochar demand and regulatory support increase. Future policy instruments, such as CRC price thresholds, technology-specific subsidies, or infrastructure investments, should align with the desired balance between energy generation and durable CDR.

4.3 Net social benefit

NPB reflects financial outcomes for private actors, but assessing the full value of biomass pathways requires NSB, which accounts for environmental externalities and their social costs. All pathways show positive social benefits when damage costs are included. For BCR, CRC prices reflect avoided damage costs of GWP. BECCS's CRC revenues exceed GWP damage costs by roughly 20%, owing to high CRC market prices. BECCS's CRC prices fall within damage cost ranges of our scenario analysis. Herein, BECCS's CRC prices remain within the range of estimated GWP damage costs, supporting potential future damage cost increases due to improved knowledge (de Vries et al., 2024). Non-GWP categories contribute less to NSB. Overall, avoided impacts dominate most categories when they are included, highlighting the relevance of monetization mechanisms such as environmental premiums or CRC to support BiCRS adoption (Pourhashem et al., 2019).

These findings align with literature. Faragò et al. (2022) find negative BCR private benefits in the base case, which turn positive when damage costs are monetized, consistent with our results. For BECCS, Almena et al. (2025) find positive NSB, mirroring our findings, even though they report negative NPB due to lower CRC prices. Other studies emphasize co-benefits enhancing overall value: Cobo et al. (2022) highlight climate and health benefits using endpoint indicators, Donnison et al. (2020) demonstrate increased welfare from ecosystem services, and Oreggioni et al. (2017) report non-GWP impacts in BECCS, partly reflected in our results. Across all pathways, water use and acidification remain notable burdens when avoided emissions and resource use are excluded, consistent with Borchers et al. (2024), although GWP damage costs dominate overall outcome. This balance could shift with higher fertilizer use, increasing acidification and eutrophication, or revisions to damage cost estimates.

Comparing pathways, BE consistently shows the highest social benefit, driven by energy substitution. Scenario analysis shows that its advantage declines in a renewable-dominated energy mix. Avoided damage from energy substitution remains uncompensated, as only permanent emission removal earns CRC. BE-specific feed-in tariffs could address this gap by reflecting avoided damage costs of substituting fossil energy, adjusted as the grid defossilizes. BECCS and BCR have deployment potential in Germany (Borchers et al., 2024), but trade-offs may vary locally (Campion et al., 2023; Donnison et al., 2020; Oh et al., 2025). For example, biochar can enhance soil health, yields, and nutrient retention, depending on local conditions (Kern et al., 2025; Xue et al., 2019; Yang et al., 2017). However, biochar market saturation could constrain long-term credit generation, as soils approach capacity, storage costs rise, and biomass competition intensifies, reducing BCR viability (CDRfyi, 2025).

For all pathways and benefit considerations, unsustainable biomass use can reverse benefits and harm biodiversity, soil, water quality, or food security (Borchers et al., 2022;

Fuss et al., 2018; Salas et al., 2024; Sandalow et al., 2021). In countries such as Germany, potentials lie in sustainably sourced residues and waste, as well as in energy crops grown on marginal or residual land, like miscanthus. Straw availability is limited, as a large share must remain on fields to decompose and restore soil humus. Special attention is also required for long-rotation feedstocks like timber as their biogenic emissions may not necessarily be zero (Guest et al., 2013). General resource competition can also be expected due to increasing demand and dense population (Borchers et al., 2024; Thrän et al., 2020). These conditions can impact the suitable pathway. For example, centralized BECCS may suit regions with high availability, while BE and BCR are better suited to decentralized or resource-constrained settings. In Germany, some feedstocks may also face restrictions due to contamination (Lenk et al., 2024). To secure supply, sustainable procurement must be incentivized. Farmers could receive premiums for waste biomass provision under sustainability criteria. Future supply may also include novel feedstocks like algae (Sandalow et al., 2021; Schmidt et al., 2015; Thrän et al., 2020).

Additionally, collaboration and knowledge transfer could prove beneficial. Germany lacks established CO_2 transport and geological storage infrastructure, despite geophysical potential and cost reduction needs (Borchers et al., 2024; Thrän et al., 2025). Therefore, learning from countries like Canada could accelerate development. Existing CO_2 separation in biogas plants could be leveraged to support infrastructure development (Thrän et al., 2025). Technologies combining CDR and BE, like BECCS and BCR, are particularly relevant as renewable energy demand remains high (Gielen et al., 2019; Holechek et al., 2022). Yet, BiCRS is still weakly embedded in German policy (Thrän et al., 2025). A phased strategy could mirror Swedish proposals for BECCS (Zetterberg et al., 2021): First, guarantee products offtake, then integrate CRC into EU's emission trading and/or mandate purchase quotas for certain sectors.

Despite our rigorous analyses, several limitations must be acknowledged. First, damage costs estimate the social welfare loss caused or prevented by each unit of emissions or resource use (Dong et al., 2019). However, these estimates are inherently uncertain and context-dependent, varying with local conditions, emission sources, and uncertain long-term effects, and may not fully capture ethical considerations or intergenerational values (de Vries et al., 2024). Second, monetary valuation itself represents a normative weighting step, as differing value judgements can yield diverging estimates across impact categories and contexts (Amadei et al., 2021; Bantje et al., 2025). Finally, monetization of novel technologies such as BECCS is further constrained by uncertainties in technology deployment, biomass availability, and climate-effective long-term net removals, as well as the need for accurate monitoring and verification (Heimann et al., 2025; Tanzer et al., 2025). Within these limitations, damage costs can guide the relative comparison of biomass utilization pathways but remain uncertain in estimating absolute future damages, despite the ranges applied in our scenario analysis.

This study faces further constraints. The analyses relied on current market data and cost assumptions and considered only a single configuration and feedstock per technology. Long-term soil effects and agricultural co-benefits of biochar require further study, as its potential to reduce nutrient leaching (Bekchanova et al., 2024) could lower eutrophication and associated damage costs. Moreover, access to primary facility-level data would improve accuracy and future research should dynamically examine how biomass utilization pathways adapt to changing markets and policies.

5 Conclusion

This study assesses the most beneficial use of wheat straw in Germany by comparing BE, BCR, and BECCS, regarding private economic and social benefits. Applying a methodological assessment framework, we find that BE is currently the most economically beneficial pathway due to low costs and high district heat revenues. BECCS is moderately viable, benefiting from energy and CRC revenues. BCR remains unprofitable in the base case, limited by high process OPEX and lower CRC revenues. When externalities are monetized, all pathways show positive social benefits. BE performs best under current energy mixes, but its advantage declines in future low-emission scenarios. BECCS generates benefits even without avoided impacts, due to its permanent CDR. BECCS outperforms BCR in CDR and social benefit due to higher capture rates, CRC prices, and permanence. BCR provides fewer removals, but holds potential as a decentralized option, particularly if biochar demand increases.

Scenario analyses reveal that BECCS can become more economically attractive than BE under favorable conditions, such as higher CRC prices, domestic storage infrastructure, or technological progress. BCR reaches economic viability in selected cases and never outperforms BECCS. These findings support a strategic biomass allocation: BE serves near-term fossil displacement while BECCS and BCR gain relevance as CDR becomes a stronger focus. Overall, as biomass remains scarce, the most beneficial use depends not only on economic returns but also on where biomass delivers the greatest value to society. In this regard, we recommend (1) enabling CO_2 storage infrastructure, (2) establishing CRC price thresholds reflecting avoided damage costs, (3) defining permanence criteria for biochar, (4) incentivizing sustainable biomass sourcing, and (5) adjusting energy feed-in tariffs to reflect shifting decarbonization priorities.

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Data availability The data that supports the findings of this study are available in the Supplementary Information of this article. Further inventory data are available from the third parties specified in Supplementary Information SI1. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the author with the permission of the third parties or directly from the third party.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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Summaries: Supplementary Information SI1: This supporting information provides assumptions and data inventories for the life cycle assessment and techno-economic assessment.

Supplementary Information SI2a: This supplementary information provides calculations and results of the techno-economic assessment for bioenergy (BE).

Supplementary Information SI2b: This supplementary information provides calculations and results of the techno-economic assessment for biochar carbon removal (BCR).

Supplementary Information SI2c: This supplementary information provides calculations and results of the techno-economic assessment for bioenergy with carbon capture and storage (BECCS).

Supplementary Information SI3: This supplementary information provides detailed, numerical results of the net private benefit, net social benefit, life cycle assessment, and damage cost calculations that inform Figures 3 to 5.