

Evaluating trade-offs of net private and net social benefit – an integrated assessment framework for biomass utilization pathways

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Abstract

Biomass is a finite yet increasingly demanded renewable energy resource, creating the need to identify utilization pathways that deliver both financial returns and societal benefits. Existing assessments often emphasize economic performance and global warming potential while overlooking environmental externalities and inconsistently accounting for avoided and removed CO₂-equivalent (CO₂eq) emissions. These gaps limit their ability to guide pathway-level trade-off assessment and policy design.

This study presents a novel framework that integrates techno-economic analysis, life cycle assessment, and monetization of environmental externalities to derive two central metrics: net private benefit (NPB) and net social benefit (NSB). Expressing results per unit of biomass input allows consistent comparison across heterogeneous pathways, such as heat, biochar, and carbon removal credits. The framework distinguishes among types of emissions and resource use, incorporates multiple environmental impact categories, and links private and societal perspectives to support investment and policy decisions.

The framework's application to miscanthus utilization in Germany compares bioenergy (BE) and biochar carbon removal (BCR). BE yields positive NPB and avoids emissions and resource use but does not achieve permanent CO₂eq emission removal. BCR removes CO₂eq emissions long-term but results in negative NPB. Both pathways, however, show positive NSB, highlighting synergies and conflicts between private incentives and societal value.

Overall, this framework enables a holistic assessment of biomass utilization pathways. By integrating economic and environmental dimensions, standardizing emissions and resource use accounting, and harmonizing metrics, it provides a structured basis for evaluating trade-offs across biomass utilization pathways regarding their private and social benefits.

Highlights

- The framework quantifies net private and social benefits per unit of biomass input
- The framework allows consistent comparison across heterogeneous biomass pathways
- Monetizing externalities links economic and environmental analyses
- Distinguishing removed and avoided emissions enables accurate carbon crediting
- The framework reveals trade-offs between private investor and societal benefits

Keywords

biomass, bioenergy, carbon removal, assessment framework, environmental externalities, biochar, miscanthus

List of abbreviations/Glossary

BCR: Biochar carbon removal

BE: Bioenergy

BiCRS: Biomass carbon removal and storage

CAPEX: Capital expenses

CDR: Carbon dioxide removal

CHP: Combined heat and power

CRC: Carbon removal credit

FU: Functional unit

GWP: Global warming potential

LCA: Life cycle assessment

NPB: Net private benefit

NSB: Net social benefit

OPEX: Operational expenses

TEA: Techno-economic assessment

CO₂eq: Carbon dioxide equivalents

List of units

€*m³ water⁻¹: Euros per cubic meter water

€*Mg biomass⁻¹: Euros per megagram biomass

€*Mg SO₂eq⁻¹: Euros per megagram sulfur dioxide equivalents

€*MgCO₂eq⁻¹: Euros per megagram carbon dioxide equivalents

m³*Mg biomass⁻¹: Cubic meters per megagram biomass

Mg CO₂eq*Mg biomass⁻¹: Megagram carbon dioxide equivalents per megagram biomass

Mg SO₂eq⁻¹*Mg biomass⁻¹: Megagram sulfur dioxide equivalents per megagram biomass

List of equation nomenclature

$CAPEX_i$: levelized capital expenditures for all pathways i

CRC_i : Carbon removal credits for all pathways i

$EXT_{i,GWP}$: monetization factor of global warming potential per unit of impact for all pathways i

$EXT_{i,o}$: monetization factor of externalities per unit of impact in impact category o for all pathways i

$E_{i,GWP,avoided}$: avoided carbon dioxide equivalent emissions for all pathways i

$E_{i,GWP,positive}$: positive pathway carbon dioxide equivalent emissions for all pathways i

$E_{i,GWP,removed}$: permanently removed carbon dioxide equivalent emissions for all pathways i

$E_{i,GWP,stored}$: permanently stored carbon dioxide equivalent emissions for all pathways i

$E_{i,o,avoided}$: other avoided emissions & resource use for all pathways i

$E_{i,o,net}$: net other emissions & resource use for all pathways i

$E_{i,o,positive}$: positive other emissions & resource use for all pathways i

$NPB_i^{after\ tax}$: Net present benefit after taxes for all pathways i

$NPB_i^{before\ tax}$: Net present benefit before taxes for all pathways i

$OPEX_i$: levelized operational expenditures for all pathways i

P_i : average market price of carbon dioxide removal for all pathways i

$REV_{i,p}$: revenue from product p of pathway i

GWP : Global warming potential expressed in carbon dioxide equivalents

i : biomass utilization pathways

o : impact category

p : product

t : tax rate

1 Introduction

Biomass is a limited resource [1,2] and its demand is expected to increase [3]. Since a substantial share of biomass is reserved for food and feed [4], the remainder available for other purposes is limited, leading to competition among multiple sectors for these scarce resources, wastes and energy crops [5].

Against this backdrop of scarcity, competing uses and crucial role in achieving climate targets, biomass has been extensively addressed in literature in recent years [6–10]. Recent advances in biotechnology and biochemical processing have renewed interest in biomass as a viable alternative to fossil carbon, offering opportunities for its use in energy generation, chemical production, fuel supply, construction, and agricultural production to reduce greenhouse gas emissions [10–14]. Furthermore, biomass carbon removal and storage (BiCRS) technologies are essential to permanently remove carbon dioxide from the atmosphere, thereby compensating for residual and hard-to-abate emissions [1,15–18].

Given the wide range of biomass utilization pathways and the trade-offs they entail, careful evaluation is needed to compare the available options regarding their benefits and drawbacks for private investors and broader society. Herein, several criteria must be addressed to enable such a comprehensive trade-off assessment.

First, applying an input-related functional unit (e.g., per ton biomass or feedstock) is required for a consistent comparison across pathways even if they produce multiple different outputs. This is particularly useful for biomass-derived products, as it reflects how effectively a resource is utilized across various processes [12].

Second, evaluating private benefit is essential because investment decisions largely determine which biomass utilization pathways are implemented. Herein, considering both private costs and revenues allows capturing the returns to investors or operators. Particularly for emerging biomass conversion technologies, private benefit depends on techno-economic factors such as geographical location, scale, process configuration, and co-product streams [17,19]. Only pathways generating positive financial returns under these conditions are likely to be deployed.

Third, assessing social benefit is needed since private benefits typically exclude societal externalities [20,21]. Biomass utilization pathways with a high private benefit do not automatically guarantee sustainability. Financial returns alone may overlook aspects beyond the private

investor perspective that affect societal welfare [21]. Assessing social benefit extends the private perspective by accounting for externalities affecting society, including environmental impacts, public health, and ecosystem services, in line with welfare economics and cost-benefit analysis principles [21–24]. Accounting for such externalities can lead to more sustainable choices [20]. For example, in biofuel production, integrating externalities has been shown to significantly increase benefits compared to analyses focusing only on private economic returns [25].

Fourth, including a broad set of impact categories is essential to identify the full spectrum of trade-offs and co-benefits, which in biomass utilization pathways may arise across climate, biodiversity, soil health, and other sustainability objectives [26–28]. To calculate social benefit, normalization of environmental impacts is required since direct comparison is limited [26,28]. For instance, water use and eutrophication are often reported in different metrics. Expressing environmental impacts in monetary terms that reflect the societal harm or benefit they cause enables normalization and consistent comparison [29]. In this way, monetization supports systematic evaluation of trade-offs and co-benefits between environmental impacts.

Fifth, a clear distinction between avoided and permanently removed emissions is required to ensure robust assessment of global warming potential (GWP), the most commonly considered impact category in biomass cost-benefit analyses and sustainability assessments [20,27]. Permanently removed emissions represent long-term carbon storage, i.e., carbon dioxide removal (CDR), which is eligible for crediting mechanisms such as carbon removal credits (CRC) [30]. In contrast, avoided emissions arise from substitution effects and do not constitute actual removal [27,31]. Rigorous emission accounting ensures that both environmental and economic benefits are accurately captured [13,32,33]. In sum, a framework that jointly assesses private and social benefits, accounts for multiple environmental impacts through monetization, applies rigorous emission accounting, and expresses results per unit of biomass input would enable a comprehensive trade-off assessment across biomass utilization pathways.

2 Literature review

Biomass utilization has been investigated in the literature from different analytical perspectives. For example, energy system optimization models (ESOMs) assess biomass allocation at the system level, identifying cost-optimal solutions under resource constraints [34,35]. To evaluate individual biomass utilization pathways, studies typically apply life cycle assessments (LCA) and techno-economic assessments (TEA). However, these assessments are limited regarding several aspects. Most contributions focus on individual dimensions, typically evaluating either the economic or the environmental performance of a single biomass utilization pathway [36–40]. Even more comprehensive assessments often lack quantitative, normalized metrics that enable consistent comparison across biomass utilization pathways [26,28,41,42].

More detailed literature analysis also demonstrates other key limitations (Table 1). First, variation in functional units constrains comparability. For example, the study of Patrizio et al. [2] adopts multiple functional units, hindering systematic comparisons. Others present results separately across indicators [43], or in graphical plots [44], limiting direct comparison. Output-based functional units (e.g., hydrogen, electricity) further restrict the ability to assess multiple biomass utilization pathways with heterogeneous outputs [2,44,45]. Similarly, referencing results to plant-level performance reduces comparability in terms of biomass input [36].

Second, economic assessments, which are crucial for calculating private benefits, also exhibit certain limitations. While many studies include private costs and revenues, some omit revenues entirely [2,45,46], resulting in an incomplete representation of private benefits.

Third, social benefit, usually covering externalities across multiple impact categories, is rarely included and monetized. Most studies completely omit externalities [2,43,44,46–48]. Analyses of biochar supply chains typically focus on quantifiable GWP-related benefits, such as CRC, while other externalities are largely disregarded [20]. Herein, few exceptions exist. Almena et al. [36] and Arfan et al. [45] incorporate damage costs, although Almena et al. [36] do so only for GWP and Faragò et al. [49] apply benefit transfer. Nonetheless, reviews confirm that monetization practices remain inconsistent and are typically limited to selected categories, particularly GWP [20,22].

Fourth, environmental assessments also reveal gaps. Only a few studies consider multiple environmental impact categories [45,47,49,50]. Reviews indicate that most BiCRS assessments remain focused on GWP, overlooking other impacts and limiting the ability to identify trade-offs [27,51].

Fifth, many studies focus on avoided emissions and neglect permanent emission storage, central to genuine CDR [45,47]. This can lead to suboptimal choices, such as combusting biochar instead of using it for long-term carbon storage [45]. Only a few studies systematically include CRC revenues [36,50], while others test CRC price thresholds rather than using market data [43,48,49]. Most analyses disregard CRC revenues, even studies focusing explicitly on BiCRS [2,44,46], limiting the economic assessment.

Table 1. Literature review for studies assessing private benefit and social benefit (e.g., environmental impacts) for two or more biomass utilization pathways. CCS: carbon capture and storage, CHP: combined heat and power, FU: functional unit, GWP: global warming potential, CRC: carbon removal credits

Study	Type of biomass	Biomass utilization pathways	Input-related FU	Private benefit (costs & revenues) included	Social benefit included and monetized	Multiple env. impact categories assessed	CRC revenues included
Almena et al. [36]	Wheat straw	Diverse configurations for CHP with CCS	X	✓	✓	X	✓
Arfan et al. [45]	Biogenic municipal solid waste, sawdust	Anaerobic digestion-based hydrogen production, fast pyrolysis-based hydrogen production	X	X	✓	✓	X
Beiron et al. [44]	Woody biomass	Diverse configurations for a CHP plant with and without CCS	X	✓	X	X	X
Cheng et al. [43]	Crop residues, woody wastes	Combustion with CCS, gasification with CCS, hydrothermal liquefaction, slow pyrolysis	✓	✓	X	X	✓
Faragò et al. [49]	Sewage sludge	Utilization as fertilizer, incineration, two pyrolysis configurations	✓	✓	✓	✓	X
Kar et al. [46]	Woody and herbaceous biomass	Biochemical conversion, fast pyrolysis, Fischer-Tropsch synthesis, bioelectricity, gasification; CCS included if possible	X	X	X	X	X
Patrizio et al. [2]	Wood chips, crop residues, energy crops, timber	Processing for construction, pyrolysis, fermentation (with/without CCS), gasification (with/without CCS), combustion (with/without CCS)	X	X	X	X	X
Pour et al. [50]	Biogenic municipal solid waste	Conventional landfill, combustion with CCS	✓	✓	X	✓	✓
Sacramento Rivero et al. [57]	Wood, sugarcane bagasse	Fuelwood utilization, charcoal utilization, electricity production in CHP	X	✓	X	✓	X
Woodall and McCormick [48]	Biogenic municipal solid waste; forestry residues	Combustion, combustion with CCS; gasification, wood burial	✓	✓	X	X	✓

In sum, while existing studies provide valuable insights, they remain fragmented, applying diverse functional units and incomplete economic assessments, e.g., by disregarding revenues or CRC, and neglecting environmental indicators as well as their normalization and monetization. This impedes fair comparison across biomass utilization pathways with different outputs. While ESOMs address biomass allocation from a system perspective, they are not designed to evaluate trade-offs between private and societal benefits at the pathway level. Therefore, there is a clear need for an assessment framework that consistently integrates private and societal perspectives within an input-related functional unit, includes all relevant economic parameters, and incorporates multiple monetized environmental impacts to derive private and social benefits. Against this background, this study develops a framework, extending conventional LCA and TEA approaches by incorporating monetized externalities and rigorous emission accounting into a standardized trade-off assessment for comparing biomass utilization pathways. In particular, it helps decision-makers distinguish between pathways that substitute fossil emissions and those that deliver CDR, thereby supporting incentive structures that align private and social benefits.

3 Methods

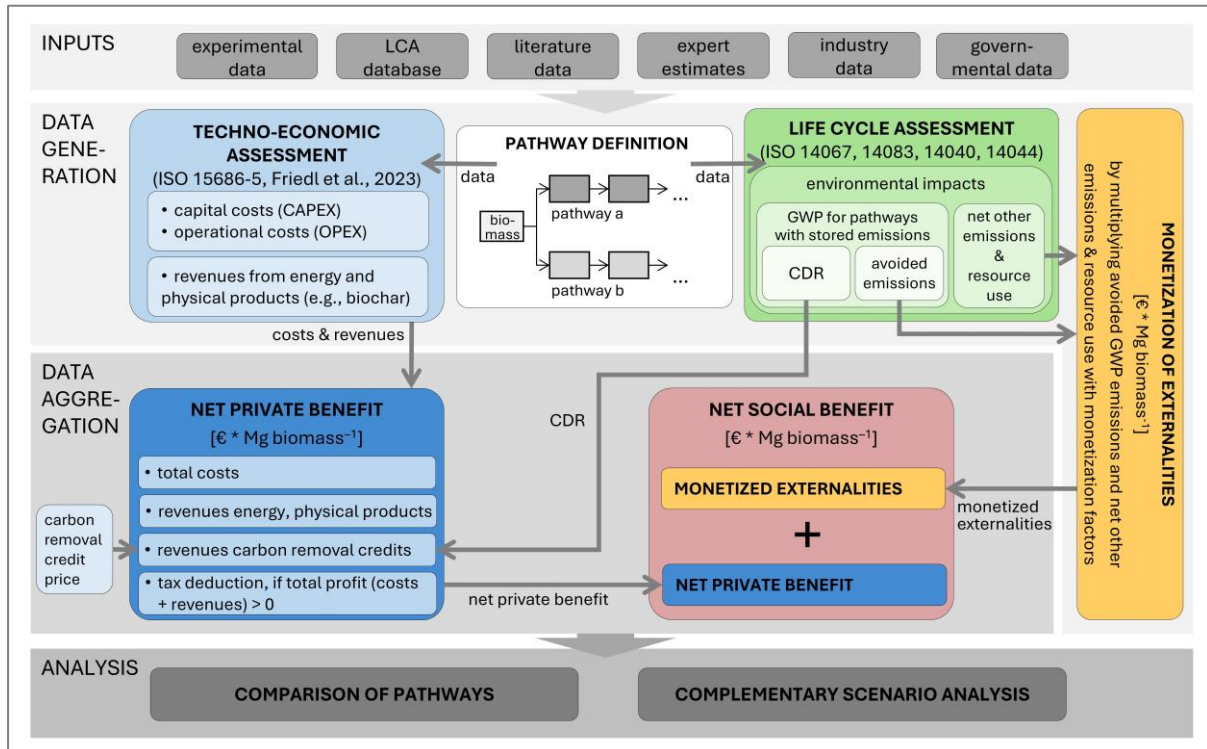


Figure 1. Methodological framework for evaluating biomass utilization pathways. GWP: global warming potential, CDR: carbon dioxide removal, LCA: life cycle assessment.

This section develops a detailed assessment framework for evaluating biomass utilization pathways from both the private and social perspective. Based on established cost-benefit analyses methods, the net private benefit (NPB) reflects the private investor perspective [21,23]. However, welfare economics emphasize that decisions should consider all affected parties and aim for Pareto efficiency, where gains can compensate for losses, leading to overall improvements in societal welfare [21]. In line with this rationale, the net social benefit (NSB) accounts for aspects relevant for the broader society, such as environmental externalities. Both NPB and NSB are expressed in monetary metrics (e.g., €). The NPB is calculated by summing private costs and revenues. It then serves as the basis for the NSB, which is obtained by adding the costs and benefits of externalities to the NPB, thereby reflecting social welfare considerations [21,23].

Figure 1 illustrates the iterative data flow necessary to derive both NPB and NSB. After data generation, biomass utilization pathway definition specifies system boundaries, process pathways, and outputs, forming the basis for subsequent assessment steps. TEA, an established methodology for economic analyses, identifies private levelized costs and revenues across the lifetime of a biomass utilization pathway [52,53]. These TEA results then provide the basis for the NPB. LCA, a standardized and widely applied methodology [31,54–56], identifies emission and resource use quantities for multiple environmental impact categories that occur along

the life cycle of a biomass utilization pathway. The LCA results serve as input to the NPB by quantifying CDR for generating credits, such as CRC. They further inform the NSB by providing environmental impacts for the monetization of externalities. By applying the outlined procedures below, NPB and NSB enable a comprehensive and transparent comparison of biomass utilization pathways. In the following, we describe the approach in more detail.

3.1 Pathway definition

As a first step, the relevant biomass utilization pathways are defined. Herein, system boundaries and all stages of biomass utilization (feedstock production and collection, transport, pre-processing, conversion, co-product handling, and, where relevant, long-term emission storage) are defined. Marketable products are identified so that the revenue they generate can be incorporated into the TEA. As these products may substitute conventional alternatives (e.g., bioenergy replacing conventional fossil-based energy), they are also crucial for informing the LCA.

Based on the defined pathways, a functional unit needs to be defined. To facilitate comparing biomass utilization pathways with multiple outputs (e.g., heat, fuels, biochar, and CRC), an input-related functional unit is required [12]. Thus, calculations and results along this framework are related to one metric ton of dry biomass at market, ready for input into utilization pathways (Mg biomass). Functional units may be adapted for other contexts (e.g., per biomass energy content, per hectare), but Mg biomass supports cross-technology comparability. Pathway specifications, system boundaries, and functional units should be iteratively refined during data gathering, following established data hierarchies and LCA best practice [31,54,57].

3.2 Techno-economic assessment

Based on pathway specifications, a TEA is performed, with all results expressed in monetary metrics per Mg biomass. The TEA produces costs and revenues for the private investor perspective that feed directly into the NPB calculation [21,23]. Herein, capital and operational expenses (CAPEX and OPEX) are quantified along the value chain, alongside revenues from marketable products, such as heat, fuels, electricity, and biochar. The TEA also identifies inputs that later need integration with LCA results, including prices for crediting emission removal.

TEA calculation standards stress the importance of a streamlined database [52,53]. Therefore, costs and revenues are harmonized to a common reference year using producer price indices or comparable deflators, ensuring comparability across data sources and years [58,59]. To reflect investor time preference, time-distributed costs and revenues are discounted to

equivalent annual values over a pathway's lifetime. Herein, discount rates should be selected according to the study context, as typical ranges in the literature vary [43,52].

3.3 Life cycle assessment

Since information beyond the TEA is needed to inform both the private and social perspectives, an LCA is conducted in parallel, following established standards [31,54–56].

As a first step of an LCA, goal and scope definition determines the system boundaries and functional units, which are here derived from the pathway definition (see above). In the next step, the life cycle inventory quantifies all positive emissions and resource use (i.e., elementary flows) that occur throughout the entire life cycle of a product or pathway. This includes all foreground and background processes contributing to environmental burdens, such as emissions released to or resources extracted from the environment. These elementary flows are then allocated to relevant impact categories in the life cycle impact assessment.

For assessing biomass utilization pathways, including GWP (100-year horizon) is essential, since multiple studies on biomass utilization pathways emphasize its significance [37,45,60]. Beyond GWP, additional impact categories, such as acidification, eutrophication, water use, and ozone depletion, should be considered to capture potential burden shifting and trade-offs across environmental dimensions [27]. Land use change may be excluded when comparing the same feedstock as the impact would be equal for all pathways. However, if feedstocks differ, land use change must be addressed explicitly [61]. For each selected impact category, the corresponding emissions and resource use flows of each biomass utilization pathway are then classified and converted into comparable units (e.g., CO₂eq, SO₂eq, water use) using characterization factors, following established ISO standards [31,54–56]. According to these standards, system boundaries, inventories and impact assessment methods are documented to ensure transparency and reproducibility.

Within this generic LCA framework, particular attention must be given to biogenic carbon flows when assessing the GWP of biomass utilization pathways, as carbon uptake during growth and carbon storage during utilization of biomass-derived products represents a (temporary) CO₂eq removal from the atmosphere. Short-term storage, like in intermediate biomass-derived products, is generally not considered carbon removal. Such storage is typically treated as biogenic CO₂eq emissions, usually assuming carbon neutrality in line with established conventions [62] and previous case studies [13]. However, biomass and biomass-derived products can enable carbon or CO₂eq storage over long-term timescales. Long-term storage, typically lasting 100 years or more, can offset positive pathway emissions, resulting in net

negative GWP contributions [30,63]. Examples include geological CO₂ storage, carbon preserved in durable biomass products, and stabilized biochar carbon applied to soils [27,61].

Based on these conventions, positive and negative GWP emissions can be quantified for each biomass utilization pathway. Positive pathway emissions capture the burdens associated with all processes along the pathway, while negative emissions reflect permanently stored emissions, such as in long-lived biomass products, geological formations, or stabilized biochar. Accordingly, the overall removal effect of a pathway is defined as the difference between permanently stored emissions and positive pathway emissions [27,61,63], expressed as:

$$E_{i,GWP,removed} = E_{i,GWP,stored} + E_{i,GWP,positive} \quad \forall i \in i \quad (1)$$

with $E_{i,GWP,removed}$ representing emissions removed, $E_{i,GWP,stored}$ being the permanently stored emissions and $E_{i,GWP,positive}$ expressing positive fore- and background pathway emissions arising along the value chain, all in Mg CO₂eq/Mg biomass⁻¹ for pathways i with stored GWP emissions.

These total removed emissions correspond to carbon dioxide removal (CDR). Net CDR occurs when the emissions stored by a biomass utilization pathway exceed its positive emissions. In such cases, the pathway achieves an overall net removal of CO₂eq from the atmosphere, as emissions remain retained in long-term storage [27,56,61].

In addition to the physical emissions and removals quantified above, LCA also applies a calculatory accounting framework to capture potential substitution effects beyond the actual system boundaries. These effects do not reflect actual emission reductions but rather represent hypothetical environmental credits that arise if a co-product of the analyzed system replaces a conventional product or process elsewhere [27,31].

Such cases occur when single processes generate multiple products, creating multifunctionality that must be addressed. Consistent with ISO guidance [31,54], we apply system expansion via substitution, the preferred approach for resolving multifunctionality in LCA. Here, a co-product of the biomass utilization pathway is assumed to substitute an equivalent external product, and the corresponding environmental burdens of that substituted product or process are credited as avoided emissions and resource use.

The magnitude of these avoided burdens depends entirely on the environmental characteristics of the substituted product or process, which can differ by region, technology, and carbon intensity [27]. Substitution credits are therefore higher when a carbon-intensive product is displaced and lower when a low-carbon or renewable alternative is substituted. For example, the substitution potential of electricity varies considerably between Poland's fossil-based and France's nuclear-based power mix [64].

Once defined, these avoided emissions and resource uses ($E_{i,o,avoided}$) are combined with the positive pathway emissions and resource use ($E_{i,o,positive}$) to determine the net effect for each pathway i and impact category o ($E_{i,o,net}$):

$$E_{i,o,net} = E_{i,o,positive} + E_{i,o,avoided} \quad \forall i \in i \quad (2)$$

with values expressed as emissions or resource use per unit biomass (e.g., Mg SO₂eq*Mg biomass⁻¹).

It is important to note that for biomass utilization pathways that include long-term emission storage, substitution-based avoided GWP emissions are not combined with positive pathway GWP emissions to prevent double counting [32,33]. In these cases, positive pathway emissions already serve as the reference for calculating CDR and therefore cannot simultaneously contribute to substitution-based avoidance.

The emission and resource use types described above form the basis for calculating private and social benefits within the assessment framework. Table 2 summarizes how the different types, each expressed as environmental impacts per Mg biomass, are interrelated. It indicates whether these types contribute directly, indirectly, or not at all to one another and shows their respective relevance to the calculation of private and social benefits, expressed in monetary terms per Mg biomass. The table also lists the variables representing each emission and resource use type within the framework's equations.

Net avoided emissions and resource use that are not captured within the NPB represent externalities that contribute directly to the NSB. For pathways involving GWP emission storage, the combination of permanently stored and positive pathway emissions determines the amount of CDR, which subsequently enters the NPB calculation through private revenues from removal crediting (i.e., CRC). Since positive emissions of pathways with stored GWP

emissions are already included in CDR and thus reflected in the NPB, only avoided GWP emissions contribute directly to their NSB. Overall, maintaining a clear distinction between the various emission and resource use types is essential for a transparent and consistent evaluation of biomass utilization pathways from both private and social perspectives.

Table 2. Emission and resource use types. CDR: carbon dioxide removal, symbols display whether a type feeds directly (●), indirectly (○) or not at all (–) into the respective calculation. NPB: net present benefit, NSB: net social benefit, #: expressed in environmental impacts per Mg biomass, *: expressed in monetary metric per Mg biomass

	Type	Description	Term applied in equation (for all pathways i , other impact env. categories o , or global warming potential GWP)	Contribution to the calculation of				
				net other emis-sions & resource use#	CDR#	CRC*	NPB*	NSB*
All other pathways and environmental impact categories	positive pathway	other positive pathway emissions & resource use	$E_{i,o,positive}$	●	–	–	–	○
	avoided	other avoided emissions & resource use	$E_{i,o,avoided}$	●	–	–	–	○
	net	net other emissions & resource use	$E_{i,o,net}$	n/a	–	–	–	●
GWP calculation for pathways with stored GWP emissions	positive pathway	positive pathway CO ₂ eq emissions	$E_{i,GWP,positive}$	–	●	○	○	○
	avoided	avoided CO ₂ eq emissions	$E_{i,GWP,avoided}$	–	–	–	–	●
	permanently stored	permanently stored CO ₂ eq emissions	$E_{i,GWP,stored}$	–	●	○	○	○
	CDR	permanently removed CO ₂ eq emissions	$E_{i,GWP,removed}$	–	n/a	●	○	○

3.4 Carbon removal credits calculation

Pathway definition, TEA, and the LCA form the foundation for monetizing externalities and integrating them with TEA results. These steps are necessary for calculating NPB and NSB. For clarity, euros (€) are used as the monetary metric in the calculation steps, although other currencies can also be used.

CRC revenues are calculated to capture the potential private benefits a pathway can generate from removal credits. This is done by multiplying the representative CRC market price with the amount of CDR determined above [65]:

$$CRC_i = P_i \times E_{i,GWP,removed} \quad \forall i \in i \quad (3)$$

with CRC_i being CRC and P_i denoting the average market price of CDR expressed in €*MgCO₂eq⁻¹ for all pathways i storing GWP emissions. The term $E_{i,GWP,removed}$, given in Mg CO₂eq*Mg biomass⁻¹, represents the total amount of CDR, as specified above.

3.5 Net private benefit calculation

The NPB can be derived using the information gathered and calculated above. It compasses all costs and revenues associated with a pathway, representing the returns accruing to investors or operators, typically excluding externalities [20,21]. Accordingly, the NPB represents the private investor perspective as follows:

$$NPB_i^{before\ tax} = \sum_{p \in P_i} REV_{i,p} + CRC_i - (CAPEX_i + OPEX_i) \quad \forall i \in i \quad (4)$$

$NPB_i^{before\ tax}$ refers to the NPB before taxes, $REV_{i,p}$ is the revenue from product p of pathway i , and CRC_i is the CRC, determined above. $CAPEX_i$ and $OPEX_i$ represent levelized capital and operational expenditures. All are expressed in €*Mg biomass⁻¹, respectively.

After combining CRC and TEA metrics, income tax treatments should align with jurisdictional rules to reflect realistic investment conditions [66,67]. Since corporate income tax applies only to positive profits (i.e., a positive NPB), the after-tax NPB is calculated as:

$$NPB_i^{after\ tax} = \begin{cases} NPB_i - t \times NPB_i, & \text{if } NPB_i > 0 \\ NPB_i, & \text{if } NPB_i \leq 0 \end{cases} \quad \forall i \in i \quad (5)$$

Here, $NPB_i^{after\ tax}$ represents the NPB after tax deduction, denoted in €*Mg biomass⁻¹, whereas t (dimensionless) denotes the tax rate, for instance 0.25 to indicate a tax of 25 %, applied on positive profits.

3.6 Net social benefit calculation

The NSB builds on the NPB. While the NPB captures private benefits and already accounts for CDR through CRC monetization, the NSB reflects the societal perspective by monetizing externalities not included in the NPB, such as avoided GWP emissions and net other emissions and resource use (see above). Various monetization methodologies exist in literature, including damage and prevention cost approaches [29,68]. Reviews and method comparisons can guide the method choice between these approaches [22,69,70].

Damage costs monetize the societal harm caused and are commonly applied in cost-benefit analyses and projections of potential future impacts [69]. Methods such as ReCiPe, Impact 2020, and TRACI typically follow a damage-based approach, where negative values indicate costs to society and positive values reflect avoided costs, i.e., benefits. In contrast, prevention costs estimate the expenditures required to avoid negative environmental impacts, for example by quantifying the costs of emission reduction measures [69,71].

Based on these considerations, a monetization method needs to be selected to provide the relevant monetization factors for NSB calculation. The choice should be justified and applied consistently across categories. Units of the monetization factors must correspond to the units of the environmental impacts. For instance, if acidification impacts are reported as $\text{Mg SO}_2\text{eq}^{-1} \cdot \text{Mg biomass}^{-1}$, the monetization factor should be expressed in $\text{€} \cdot \text{Mg SO}_2\text{eq}^{-1}$ to yield $\text{€} \cdot \text{Mg biomass}^{-1}$. These factors allow externalities to be monetized and integrated into the NSB.

For the final NSB calculation, net other emissions and resource uses and, for pathways involving GWP emission storage, avoided GWP emissions are monetized using their respective monetization factors. NSB is then generated by adding these monetized externalities to NPB after tax ($NPB_i^{\text{after tax}}$, expressed in $\text{€} \cdot \text{Mg biomass}^{-1}$) as follows:

$$NSB_i = NPB_i^{\text{after tax}} + \sum_{e \in E_{i,o}} EXT_{i,o} \times E_{i,o,net} + EXT_{i,GWP} \times E_{i,GWP,avoided} \quad \forall i \in i \quad (6)$$

for all pathways i where $EXT_{i,o}$ is the monetization factor of externalities in impact category o , e.g. expressed in $\text{€} \cdot \text{Mg SO}_2\text{eq}^{-1}$ for acidification and $\text{€} \cdot \text{m}^3$ for water use. $E_{i,o,net}$ represents the net emissions and resource use, e.g. given in $\text{Mg SO}_2\text{eq}^{-1} \cdot \text{Mg biomass}^{-1}$ for acidification and $\text{m}^3 \cdot \text{Mg biomass}^{-1}$ water use. In case of pathways including stored GWP emissions, $EXT_{i,GWP}$, expressed in $\text{€} \cdot \text{Mg CO}_2\text{eq}^{-1}$, denotes the monetization factor of GWP per

unit of impact, while $E_{i,GWP,avoided}$ ($\text{Mg CO}_2\text{eq} \cdot \text{Mg biomass}^{-1}$) denotes the avoided GWP emissions.

3.7 Synthesis

The procedures outlined above lead to final NPB and NSB, expressed in monetary terms per Mg biomass, that can be compared across biomass utilization pathways. This approach ensures that all criteria and corresponding literature gaps identified earlier are addressed. By applying an input-related functional unit (Mg biomass), comparability across pathways with multiple outputs is maintained. The resulting NPB and NSB metrics enable a holistic assessment of both private investor and broader societal perspectives. We incorporate both costs and revenues through a TEA, while multiple environmental impact categories are captured via an LCA. By carefully distinguishing emission and resource use types, we can accurately account for revenues from emission removal and normalize as well as monetize previously unaccounted externalities using established methodological approaches.

Supplementary scenario and sensitivity analyses could explore the sensitivity of NPB and NSB to key assumptions such as CRC price trajectories, technology efficiencies, feedstock costs, and discount rates. These analyses can help test the robustness of results and identify critical drivers in biomass utilization pathways [20]. The findings from such complementary scenarios can provide a basis for targeted recommendations for policymakers, investors, and practitioners. To illustrate and validate the framework, we apply it to an exemplary case study in the following section.

3.8 Demonstration of framework

We demonstrate the framework through a case study on miscanthus in Germany, comparing two utilization pathways. The case study demonstrates the methodological approach and illustrates how biomass utilization choices shape trade-offs between private and societal benefits at the pathway level. Miscanthus is a perennial crop that is increasingly being cultivated in Germany [72,73]. It combines high yields with low input requirements and offers potential for both energy generation and CDR applications [13,74–77].

For the biomass utilization pathways, we select combustion to generate bioenergy (BE) and pyrolysis for biochar carbon removal (BCR). This choice reflects both the status quo and the frontier of biomass use. BE represents the dominant current pathway, as combustion of biomass provides more than half of Germany's renewable energy supply [78]. However, BE is not necessarily emission neutral [79]. In contrast, BCR uses pyrolysis to heat biomass in an oxygen-reduced environment, producing both energy and biochar. By providing carbon storage via biochar at relatively low costs, BCR is considered a competitive BiCRS strategy [1,17,80]. Biochar stands out for its dual benefits of carbon storage and soil fertility improvement, although BCR's deployment remains limited and supportive policy frameworks are still evolving [81–85].

These two pathways highlight the key trade-offs in biomass utilization. BE provides renewable energy that substitutes fossil fuels, while BCR achieves permanent carbon storage. Both, however, involve potential downsides such as ecosystemic risks and economic uncertainties [7,28,84]. Therefore, we assess BE and BCR for miscanthus in Germany and model their performance from private and societal perspectives with the developed framework.

3.9 Specifications for the case study

The case study follows the steps outlined in chapter 3. In this section, we detail further specifications of the case study. Input values and corresponding sources are specified in Supplementary Material SM1. The functional unit is 1 Mg of miscanthus at market (dry mass). This reflects how miscanthus is commonly traded and processed and provides a consistent reference point for the case study.

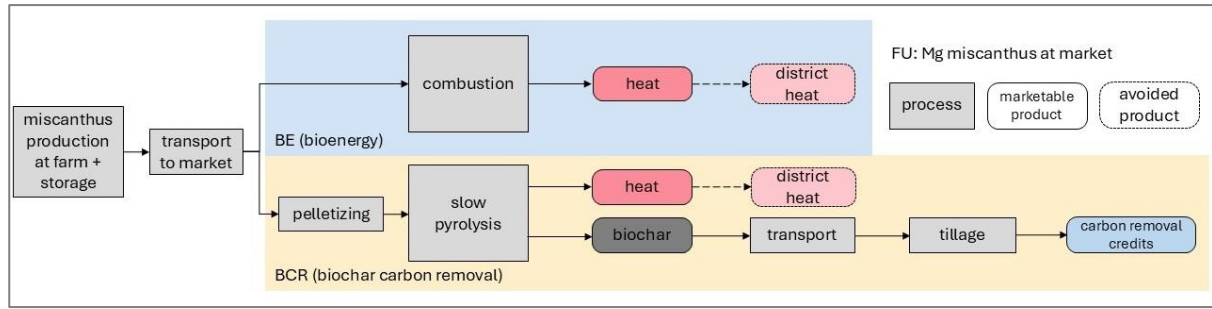


Figure 2. Defined pathways for the exemplary case study on miscanthus utilization in Germany.

Figure 2 illustrates the defined process pathways and their system boundaries. Both pathways begin with miscanthus cultivation, storage, and transport to the point of conversion. From there, the two pathways diverge. In the BE pathway, miscanthus is combusted in a standard biomass combustion plant [86], modeled based on process data from Wernet et al. [87]. This process generates heat as the sole marketable product. In the BCR pathway, miscanthus is first pelletized and then processed via slow pyrolysis [13]. This conversion yields marketable heat and biochar. The biochar is subsequently transported to agricultural fields, where it is tilled into the soil to achieve long-term emission storage. Heat from both BE and BCR is assumed to be sold into the district heating network. Applying system expansion with substitution, the produced heat displaces conventional fossil-based district heat, thereby avoiding the associated emissions and resource use [44,88].

Building on the defined system boundaries and functional unit, further specifications apply. Monetary terms are expressed in euros (€). Detailed inventory data and input specifications for the TEA and LCA are provided in SM1. In the TEA, all costs and revenues are standardized to 2024 price levels using the Producer Price Index [59]. As specified in SM1, all monetary values are discounted at 5% over the lifetime of the technologies. CRC market prices are taken from Höglund and Niparko [89]. For CDR calculation, only the BCR pathway is considered, as BE does not generate permanently stored emissions. We apply Eq. 1, further breaking down the stored emissions term ($E_{i,GWP,stored}$) to determine CDR for the BCR pathway accurately, based on Ruett et al. [13]:

$$E_{BCR,GWP,stored} = m_{BCR} \times k_{BCR} \times C_{BCR} \times 3.67 \quad (7)$$

Here, $E_{BCR,GWP,stored}$ expresses permanently stored GWP emissions for pathway BCR. m_{BCR} gives the biochar mass yield (Mg biochar*Mg miscanthus⁻¹) and k_{BCR} is the share of carbon assumed to be permanently stored (0.75, following Azzi et al. [90]). Due to lack of detailed data on temporal carbon leakage, we conservatively assume that all potential carbon

losses from biochar in soils (i.e., 25%) occur immediately. C_{BCR} denotes the carbon content of biochar ($\text{Mg C} \cdot \text{Mg biochar}^{-1}$), 3.67 is the factor converting carbon to CO_2eq .

Environmental impact assessment is conducted using the ReCiPe midpoint (H) method. We consider the impact categories GWP, acidification, freshwater and marine eutrophication, water use, and ozone depletion to capture co-benefits and trade-offs [27], but still provide all ReCiPe midpoint impact assessment results in SM2. GWP is assessed over a 100-year time frame, in line with relevant studies [37,45,60]. Biogenic CO_2 emissions from miscanthus, such as those from combustion, are assumed to be zero [62]. The impact category land use change is excluded because the same functional unit of biomass is assumed across all pathways [61].

As the applied impact assessment method yields midpoint environmental impacts, corresponding midpoint damage costs are used as monetization factors and were taken from de Vries et al. [29]. They reflect the social welfare loss caused or avoided by each unit of emission and resource use, thus matching practices in cost-benefit analyses [69].

These parameters all feed into CRC, NPB, and NSB calculations as described in chapter 3 above. The following section presents the results of applying this framework to the miscanthus case study.

4 Results

The comparative assessment of BE and BCR miscanthus utilization pathways focuses on benefits for private investors and broader society, assessed along NPB and NSB metrics. Further, we provide detailed GWP balances, as the impact category dominates monetized externalities (i.e. damage costs). This overview highlights the key differences and trade-offs between pathways.

Figure 3a illustrates the private investor perspective (NPB), showing both positive contributions (revenues) and negative contributions (costs) alongside net results. BE emerges as financially viable pathway, whereas BCR remains unprofitable. Biomass constitutes the major

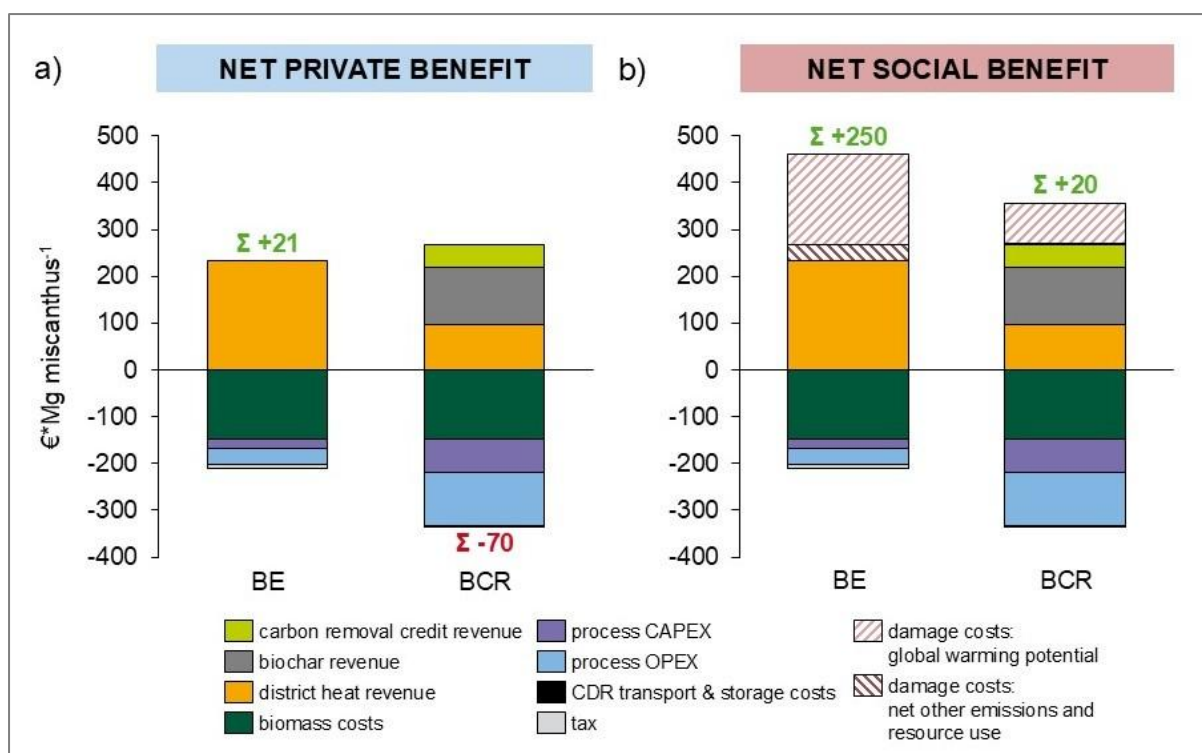


Figure 3. (a) Net present benefit and (b) net social benefit for miscanthus-based bioenergy (BE) and biochar carbon removal (BCR), disaggregated into (a) cost, revenues, (b) and damage costs.

cost driver for both pathways, while transport costs are minimal. Differences in NPB largely stem from high operational costs for BCR. For BE, revenues are primarily generated from district heat, while BCR revenues are distributed across biochar sales, heat, and CRC.

Figure 3b presents the societal perspective (NSB), calculated as NPB plus monetized externalities (i.e., damage costs). Both pathways are societally beneficial, but BE appears more attractive due to its combination of financial returns and avoided damage costs. GWP-related damage costs dominate the NSB, with other environmental categories contributing only marginally. The GWP damage costs applied in this study amount to $166 \text{ €} \cdot \text{Mg CO}_2\text{eq}^{-1}$ [29], whereas CRC are lower, quantified at $155 \text{ €} \cdot \text{Mg CO}_2\text{eq}^{-1}$ [89]. Therefore, current CRC price levels do not fully reflect societal benefits associated with CDR via BCR.

The results demonstrate that GWP is a decisive impact category, both regarding its contribution to damage costs for NSB and its role in generating revenue from CRC for NPB. To further illustrate GWP impacts, Figure 4 presents the GWP balance for each pathway, compiled of positive pathway emissions, permanently stored emissions, and (a) including or (b) excluding avoided emissions. Detailed assessment results of further impact categories are presented in SM2. Figure 4a shows that only BCR delivers permanently stored emissions, whereas BE generates large avoided emission quantities. The magnitude of avoided emissions depends

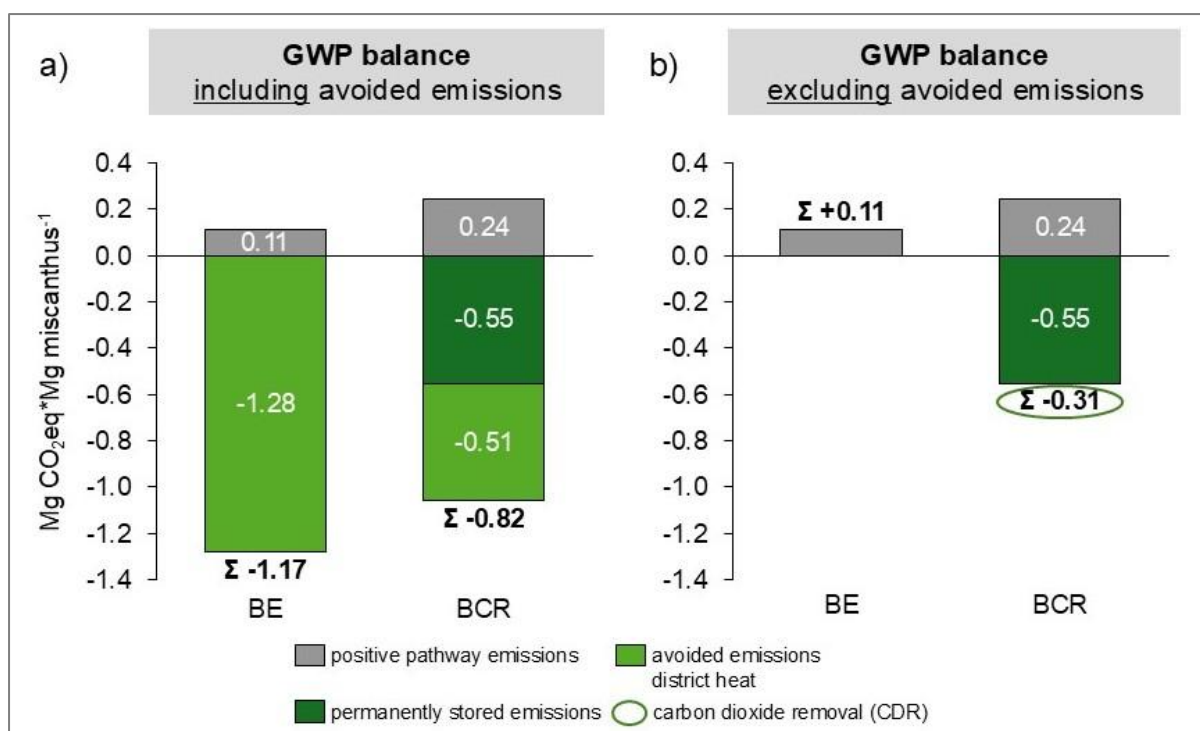


Figure 4. Global warming potential emission balance for miscanthus-based bioenergy (BE) and biochar carbon removal (BCR), disaggregated in positive pathway and permanently stored emissions, while avoided emissions from system expansion for district heat district heat are (a) included or (b) excluded.

on the emission profile of the substituted energy mix, being higher in high-emission systems and lower in low-emission mixes. When avoided emissions are excluded (Figure 4b), simulating a (future) emission-neutral energy system, BE results in net positive emissions while BCR still achieves stored emissions. This is reflected in the CDR outcome for BCR: Permanently stored emissions exceed positive pathway emissions, resulting in net emission removal and demonstrating BCR's effectiveness in generating CDR. Consequently, CDR can generate CRC revenue and contribute to private benefits.

Through the presented results, the framework can demonstrate a key trade-off along the case study: pathways generating positive private returns, such as BE, may not provide permanent carbon storage, whereas BCR, which enables CDR, may still be unprofitable under current cost and revenue structures. These results illustrate how integrating NPB and NSB and distinguishing avoided from removed emissions supports a comprehensive evaluation. Also, expressing all metrics per unit biomass allows comparison across pathways with different outputs. Overall, the case study underscores the value of a structured framework for assessing trade-offs between private investor and broader societal benefits.

5 Discussion

This study introduces a novel integrated assessment framework for evaluating biomass utilization pathways, demonstrated by an exemplary miscanthus case. The framework consistently integrates private and societal perspectives through two central metrics, NPB and NSB, expressed per unit of biomass input. It incorporates full economic parameters via techno-economic analysis, multiple monetized environmental impact categories via life cycle assessment, and a transparent treatment of emissions and resource use types that feed into NPB and NSB calculation. In doing so, it closes key gaps in existing approaches and enables a comprehensive evaluation. The following sections demonstrate the framework's applicability, discuss key insights, examine implications, and provide recommendations for policy and research.

5.1 Demonstration and comparison with literature

The framework allows consistent comparison of pathways with multiple outputs, by presenting all metrics per unit biomass. As demonstrated in our case study, this approach overcomes a common limitation in multi-output assessments. The framework is designed to be scalable and transferable across diverse feedstocks, sectors, and regions, providing guidance for decision-makers.

By incorporating both NPB and NSB metrics, the framework explicitly integrates private and societal perspectives, addressing a key gap in previous assessments that focus solely on environmental (e.g., LCA) and economic (e.g., TEA) outcomes. For instance, by integrating societal benefits, NSB demonstrates that otherwise unprofitable technologies can become profitable when externalities are monetized, as illustrated for BCR in our case study. This demonstrates the framework's ability to assess trade-offs between private and societal benefits and to highlight areas where targeted interventions could enhance both. By enabling simultaneous assessment of private investor and societal value, the framework supports a comprehensive and policy-relevant evaluation of biomass utilization pathways.

NPB and NSB calculation allows the identification of major private and societal benefits drivers. By incorporating all relevant costs and revenues, NPB can be assessed in detail. For instance, in the miscanthus case, BCR generates multiple revenue streams including CRC, yet these do not offset high operating costs in terms of NPB. BE achieves high NPB only from heat revenues but lacks CRC. For NSB, it becomes evident that GWP determines the magnitude of damage costs. These results illustrate the framework's capacity to identify leverage points for improving pathway performance and guiding biomass utilization decisions.

By monetizing, and thus normalizing, externalities derived from multiple impact categories, the framework demonstrates how different emissions and resource use contribute to societal

benefits. That way, the framework also supports accounting for currently unmonetized benefits, thereby guiding decision-makers to leverage existing or establish new markets for externalities.

Another innovation of the framework is the meticulous distinction of emission and resource types, which has often been overlooked in previous assessments [27,61]. This ensures transparent accounting of environmental burdens and provides a sound basis for monetization through CRC and damage costs. The case study illustrates how this approach prevents incomplete trade-off assessments: BE's negative GWP balance stems from avoided emissions through substituted district heat, whereas only BCR generates permanently removed emissions eligible for CRC revenue. By making such differences explicit, the framework clarifies which environmental factors drive private and societal benefits. Also, these insights imply that drivers may shift under different assumptions, such as energy mixes.

The miscanthus case demonstrates internal consistency, aligning with literature regarding BCR's high climate benefits but modest economic return [37,91,92], BE's higher NPB without permanent emission removal [2,93], and a positive NSB metric when applying damage costs [45,94]. Overall, the framework demonstrates consistency with prior evidence and thus offers a reliable tool to support policy design, strategic planning, and investment guidance.

5.2 Implications and recommendations

As demand for biomass grows, the need for informed pathway evaluation to decide biomass utilization priorities increases [3]. The framework enables a transparent and structured comparison of pathways. Transparency on the trade-offs of private and social value has clear implications for future biomass governance. Technologies with permanent CDR and positive NSB but negative NPB, such as BCR, could be strategically supported to maximize permanent emissions removal and societal welfare [95,96].

The framework also emphasizes the critical role of avoided emissions in assessing biomass utilization pathways. Our case study demonstrates that if avoided emissions were zero (e.g., in a fully decarbonized energy system), BE displays net-positive emissions, while BCR presents net-negative emissions due to permanently stored emissions. Thus, depending on future scenarios, the climate benefits of emission-substituting pathways may diminish, whereas BiCRS pathways retain value due to permanent CDR [2].

Compared to pathways that do not permanently store emissions, BiCRS (like BCR) could realize economic advantages if externalities are properly monetized through market instruments

or policy frameworks. As our case study reflects, current CRC prices for BCR are lower than avoided GWP damage costs [29,89]. Increased CRC prices may also lead to positive private benefits [13,48]. This underlines the importance of accurately accounting for CRC and setting appropriate prices.

Beyond individual case studies, the framework could complement system-level approaches by providing detailed pathway-level insights for strategic resource planning, funding prioritization, and technology support strategies. For instance, pathways identified as promising by energy system optimization models could be further evaluated with the presented framework to assess trade-offs between private and societal benefits. Its capacity to incorporate scenario analysis is particularly valuable for long-term planning, where policy, market, and technological conditions remain uncertain.

The framework additionally points to several broader recommendations. First, policy and investment assessments should integrate both private and societal assessment criteria, moving beyond simple metrics like levelized costs or emission factors that cannot navigate complex trade-offs. Specifically, markets and policies should distinguish between pathways that substitute CO₂eq emissions and those that remove them permanently. This ensures that permanent emission removal is recognized and rewarded, for instance through dedicated crediting systems with minimum prices. Such measures could particularly support emerging technologies like BCR [95,96]. Second, public funding could prioritize technologies with high NSB but low NPB by supporting early-stage innovation where market incentives are insufficient. This includes emission removal approaches such as BCR, which could become competitive under adequate policy support.

Finally, monetization of environmental externalities should be further developed and standardized. EU initiatives, including biochar standards [97] and CDR certification schemes [81,82], provide a foundation, but externalities beyond CRC should also be monetized [98]. Transparent monetization ensures societal value is visible and can inform decision-making.

5.3 Limitations and future research

While the framework offers a novel, holistic assessment approach, several limitations remain. First, the monetization of externalities relies on estimates, which are inherently uncertain [29]. Second, social impacts beyond monetized environmental externalities, such as resource conflicts, distributional effects, and public acceptance, are not captured due to methodological limitations [99,100]. Third, differences in data quality or scope may affect comparability across technologies and regions. Since biomass is typically sourced locally, regionally coherent data

for environmental impacts and cost modeling are essential. Finally, results are sensitive to the choice of monetization method. While damage costs quantify the societal costs of an impact and align with LCA midpoint indicators [29], alternative approaches, such as prevention costs, which estimate the expenses of avoiding impacts, may produce different outcomes [68,69,71].

Future applications of the framework can address these limitations and enhance its relevance. Utilizing primary input data from industry and stakeholders for pathway definition would improve closeness to practice and accuracy of assessments. To facilitate broader adoption, future work could explore making the framework and its underlying data structures available as an open-access tool, enabling stakeholders to apply it independently to their specific pathways and contexts. Remaining uncertainties in data inputs, such as variation in product prices (e.g., district heat [101], biochar [67], and CRC [89]) and monetization factors, can be systematically addressed through sensitivity and scenario analyses.

Scenario analyses can further explore alternative process configurations, technological progress, and evolving policy or energy contexts, providing forward-looking insights for long-term strategic planning. Exploring BiCRS emission storage over varying time horizons [63] or applying dynamic LCA [102] may offer additional understanding of the temporal emission dynamics. Where appropriate data is available, extending the framework to additional biomass types, utilization pathways, and regions would enhance comparability and support more robust decision-making across contexts. In this regard, it is important to note that, unlike in the present miscanthus-based assessment, biogenic emissions from longer-rotation crops such as wood may not be carbon-neutral [62].

Beyond quantitative metrics, future research could integrate complementary dimensions relevant to biomass utilization, including innovation potential, scaling challenges, stakeholder acceptance, and policy interactions [103]. Such integration could enable anticipation of challenges and enhance strategy development.

The framework is designed to accommodate these extensions, provided that assumptions and boundary conditions are transparently documented. Its versatility also allows application beyond individual case studies, enabling strategic decision-making at regional or national scales, such as technology support and funding prioritization. The capacity to incorporate uncertainty is particularly valuable for long-term planning where market, policy, and technological conditions are subject to change. Finally, the framework is scalable and transferable, providing a practical tool for guiding both research and policy in diverse biomass utilization contexts, bridging private economic goals with broader societal objectives.

6 Conclusions

This paper develops an integrated assessment framework to evaluate biomass utilization pathways in terms of both private and social benefits. The framework integrates TEA, LCA and monetization of externalities into two central metrics: NPB and NSB.

The framework addresses several gaps in existing assessments. First, it expresses all results per unit of biomass input, enabling consistent comparison across competing pathways with heterogeneous outputs. Second, all relevant costs and revenues are incorporated. Third, it links private investor incentives with societal benefits by monetizing externalities. Fourth, multiple environmental impact categories are integrated, allowing trade-offs to be assessed beyond single indicators such as GWP. Fifth, the framework distinguishes different emission and resource use types, providing a transparent translation into private and social benefit metrics. For example, this ensures that CRC is accurately captured within private benefits, while avoided emissions contribute to social value.

Application to miscanthus in Germany illustrates feasibility and relevance. BE achieves positive NPB through established revenues, whereas BCR delivers permanent emission removal with negative NPB. NSB is positive for both pathways, illustrating how the framework identifies synergies and conflicts between private incentives and societal benefits, thereby supporting informed assessment of biomass utilization pathways.

The framework provides a versatile tool for policymakers, investors, and researchers. Policymakers can identify where regulation or market mechanisms are needed to align private and societal objectives. Investors also gain clarity on the conditions under which pathways become financially viable. Researchers can systematically compare emerging technologies using consistent metrics.

In sum, the framework advances the assessment of biomass utilization pathways by integrating economic and environmental dimensions, applying rigorous emission and resource use accounting, and enabling harmonized comparison across pathways. It offers a structured basis for assessing trade-offs across biomass utilization pathways regarding their private and societal benefits, helping decision-makers identify pathways that generate both financial returns and societal value.

Supplementary Material

SM1: Data inventories and assumptions applied in the life cycle and techno-economic assessments

SM2: Detailed results for the net private and social benefit, techno-economic assessment, life cycle assessment, and associated damage costs. Includes results for all ReCiPe midpoint impact categories

Acknowledgements

Data statement

The data underpinning this study's calculations and findings are provided in the supplementary material. Additional inventory data can be obtained from the third parties listed in SM1 and SM2.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT by OpenAI in order to enhance readability of complex sentence structures. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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