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

Johanna Ruett [a,*], Ali Abdelshafy [b], Grit Walther [a]

[a] Chair of Operations Management, RWTH Aachen University, Kackertstraße 7, Aachen, 52072, Germany
[b] Energy and Industry Group, Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, the Netherlands

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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 social benefits. Existing assessments often emphasize economic performance and global warming potential while overlooking environmental externalities and inconsistently accounting for avoided and removed CO_2-equivalent (CO_2eq) 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 CO_2eq emission removal. BCR removes CO_2eq emissions long-term but results in negative NPB. Both pathways, however, show positive NSB, highlighting synergies and conflicts between private incentives and social 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.

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 its crucial role in achieving climate targets, biomass has been extensively addressed in the 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 outputs. This is particularly useful for biomass-derived products, as it reflects how effectively a resource is

* Corresponding author.
E-mail address: johanna.ruett@om.rwth-aachen.de (J. Ruett).

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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 private benefit after taxes for all pathways i
$NPB_i^{before\ tax}$ Net private 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 other impact categories (see Table 2)
p products
t tax rate

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
CO_2eq Carbon dioxide equivalent

List of units

€*m^3 $water^{-1}$ Euros per cubic meter water
€*Mg $biomass^{-1}$ Euros per megagram biomass
€*Mg SO_2eq^{-1} Euros per megagram sulfur dioxide equivalents
€*$MgCO_2eq^{-1}$ Euros per megagram carbon dioxide equivalents
m^3*Mg $biomass^{-1}$ Cubic meters per megagram biomass
Mg CO_2eq*Mg $biomass^{-1}$ Megagram carbon dioxide equivalents per megagram biomass
Mg SO_2eq*Mg $biomass^{-1}$ Megagram sulfur dioxide equivalents per megagram biomass

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 social 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), techno-economic assessments (TEA), or life cycle costing (LCC). 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 [36–41]. Even more comprehensive assessments, including those coupling process simulation with LCA and LCC, often lack quantitative, normalized

metrics that enable consistent comparison across biomass utilization pathways [26,28,42–45].

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 [46], or in graphical plots [47], limiting direct comparison. Output-based functional units (e.g., hydrogen, electricity) further restrict the ability to assess multiple biomass utilization pathways with heterogeneous outputs [2,47,48]. 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 [2,48,50], 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 [2,46,47,50,52,53]. 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. [48] 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 [48,49,51,52]. Reviews indicate that most BiCRS assessments remain focused on GWP, overlooking other impacts and limiting the ability to identify trade-offs [27,54].

Fifth, many studies focus on avoided emissions and neglect permanent emission storage, central to genuine CDR [48,52]. This can lead to suboptimal choices, such as combusting biochar instead of using it for long-term carbon storage [48]. Only a few studies systematically include CRC revenues [36,51], while others test CRC price thresholds rather than using market data [46,49,53]. Most analyses disregard CRC revenues, even studies focusing explicitly on BiCRS [2,47,50], limiting the economic assessment.

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 social benefits at the pathway level.

Against this background, this study develops a framework. It derives private and social benefit as two separate metrics, referenced to one unit of biomass input, so that pathways with heterogeneous outputs remain comparable and divergences between investor returns and social value are kept visible. Thus, the framework consistently integrates private and societal perspectives, including all relevant economic parameters, and incorporating multiple monetized environmental impacts. No reviewed study unites all these aspects (Table 1) so that one novelty lies in their consistent integration. A further novelty lies in introducing an accounting rule that separates substitution-based emission avoidance from permanent CDR and assigns each to only one of the two metrics to avoid double counting. In particular, this 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

This section develops a detailed assessment framework for

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. [48]	Biogenic municipal solid waste, sawdust	Anaerobic digestion-based hydrogen production, fast pyrolysis-based hydrogen production	x	x	✓	✓	x
Beiron et al. [47]	Woody biomass	Diverse configurations for a CHP plant with and without CCS	x	✓	x	x	x
Cheng et al. [46]	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. [50]	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. [51]	Biogenic municipal solid waste	Conventional landfill, combustion with CCS	✓	✓	x	✓	✓
Sacramento Rivero et al. [52]	Wood, sugarcane bagasse	Fuelwood utilization, charcoal utilization, electricity production in CHP	x	✓	x	✓	x
Woodall and McCormick [53]	Biogenic municipal solid waste; forestry residues	Combustion, combustion with CCS; gasification, wood burial	✓	✓	x	x	✓

evaluating biomass utilization pathways from both the private and societal 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 potential Pareto efficiency, where gains can compensate for losses, thereby supporting overall improvements in social welfare [23]. 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 combining 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].

Fig. 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 [55,56]. These TEA results then provide the basis for the NPB. LCA, a standardized and widely applied methodology [31,57–59], 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, preprocessing, 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 [31,57,60].

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 [55,56]. 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 [61,62]. 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 [46,55].

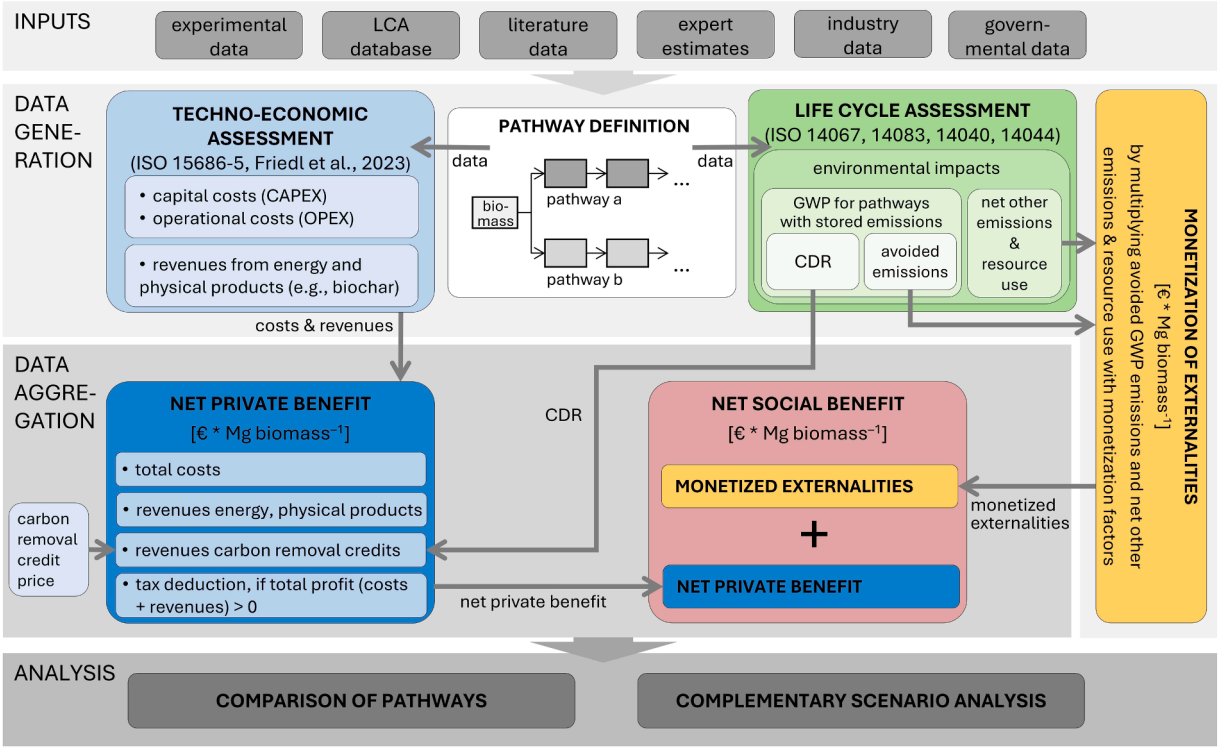


Fig. 1. Methodological framework for evaluating biomass utilization pathways. GWP: global warming potential, CDR: carbon dioxide removal, LCA: life cycle assessment.

3.3. Life cycle assessment

Since information beyond the TEA is needed to inform both the private and societal perspectives, an LCA is conducted in parallel, following established standards [31,57–59].

As a first step of an LCA, goal and scope definition determines the system boundaries and functional units, which are derived from the pathway definition here (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 [37,48,63]. 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 [64]. 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., CO_2eq, SO_2eq, water use) using characterization factors, following established ISO standards [31, 57–59]. 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) CO_2eq 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 CO_2eq emissions, usually assuming carbon neutrality in line with established conventions [65] and previous case studies [13]. However, biomass and biomass-derived products can enable carbon or CO_2eq 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 [30,66]. Examples include geological CO_2 storage, carbon preserved in durable biomass products, and stabilized biochar carbon applied to soils [27,64].

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 [27,64,66], expressed as:

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

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 CO_2eq*Mg biomass^{-1} for pathways i with stored GWP emissions.

These total removed emissions correspond to 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 CO_2eq from the atmosphere, as emissions remain retained in long-term storage [27,59,64]. The accounting boundary for CDR is the full pathway, from feedstock production to the point of long-term storage, and comprises all foreground and background emissions arising within the system boundary. Substitution credits are not admitted inside it.

In addition to the physical emissions and removals quantified above, LCA also applies a calculatory accounting framework to capture potential substitution effects beyond the system boundary. 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 [31,57], 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 [67].

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 ($E_{i,o,net}$):

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

with values expressed as emissions or resource use per unit biomass (e.g., Mg SO_2eq*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, making avoided and removed emissions mutually exclusive by construction. Removed emissions (Eq. (1)) enter NPB through removal crediting (Eq. (3)) and are thereby internalized, whereas avoided emissions from substitution remain non-internalized and enter NSB through externality monetization (Eq. (6)). Each is therefore accounted for and monetized only once, so that adding monetized externalities to NPB in order to obtain NSB does not monetize the same CO_2eq twice.

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

Table 2
Emission and resource use types. Symbols display whether a type feeds directly (●), indirectly (◯) or not at all (–) into the respective calculation. CDR: carbon dioxide removal, NPB: net private 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 for pathways with stored GWP emissions)	Contribution to the calculation of				
				net other emissions & 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_2eq emissions	$E_{i,GWP,positive}$	–	●	◯	◯	◯
	avoided	avoided CO_2eq emissions	$E_{i,GWP,avoided}$	–	–	–	–	●
	permanently stored	permanently stored CO_2eq emissions	$E_{i,GWP,stored}$	–	●	◯	◯	◯
	CDR	permanently removed CO_2eq emissions	$E_{i,GWP,removed}$	–	n/a	●	◯	◯

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 societal perspectives.

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 [68]:

$$CRC_i = P_i \times \left(-E_{i,GWP,removed}\right) \ \forall i \in I \tag{3}$$

with CRC_i being CRC and P_i denoting the average market price of CDR expressed in €*MgCO_2eq^{-1} for all pathways i storing GWP emissions. The term $E_{i,GWP,removed}$, given in Mg CO_2eq*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 encompasses 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:

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

$NPB_i^{before\ tax}$ 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 are aligned with jurisdictional rules to reflect realistic investment conditions [69,70]. Since corporate income tax applies only to positive profits (i.e., a positive NPB), the after-tax NPB is calculated as:

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

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 after-tax 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). Both metrics are thus built on the same private cost and revenue basis, so that their difference corresponds to the non-internalized externalities. Various externality monetization methodologies exist in literature, including damage and prevention cost approaches [29,71]. Reviews and method comparisons can guide the method choice between these approaches [22,72,73].

Damage costs monetize the societal harm caused and are commonly applied in cost-benefit analyses and projections of potential future impacts [72]. Methods such as ReCiPe, IMPACT 2002+, 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 [22,72,74].

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 Mg SO_2eq*Mg biomass^{-1}, the monetization factor should be expressed in €*Mg SO_2eq^{-1} to yield €*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 ($NPB_i^{after\ tax}$, expressed in €*Mg biomass^{-1}) as follows:

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

for all pathways i where $EXT_{i,o}$ is the monetization factor of externalities in impact category o, e.g., expressed in €*Mg SO_2eq^{-1} for acidification and €*m^3 water^{-1} for water use. $E_{i,o,net}$ represents the net emissions and resource use, e.g., given in Mg SO_2eq*Mg biomass^{-1} for acidification and m^3*Mg biomass^{-1} water use. In case of pathways including stored GWP emissions, $EXT_{i,GWP}$, expressed in €*Mg CO_2eq^{-1}, denotes the monetization factor of GWP per unit of impact, while $E_{i,GWP,avoided}$ (Mg CO_2eq*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.

Complementary sensitivity or scenario analyses form the final step of the framework. They vary key assumptions such as process costs, feedstock costs, discount rates, CRC price trajectories, and carbon storage permanence to test the robustness of results and to identify critical drivers in biomass utilization pathways [20]. The findings from such analyses can provide a basis for targeted recommendations for policymakers, investors, and practitioners. To demonstrate the framework, we apply it to an exemplary case study in the following section.

3.8. Demonstration of framework

We apply the framework to a case study comparing two utilization pathways for miscanthus in Germany. The case study demonstrates the methodological approach and illustrates how biomass utilization choices shape trade-offs between private and social benefits at the pathway level. Miscanthus is a perennial crop that is increasingly being cultivated in Germany [75,76]. It combines high yields with low input requirements and offers potential for both energy generation and CDR applications [13,77–80].

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 [81]. However, BE is not necessarily emission neutral [82]. 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 [1,17,83]. 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 [84–88].

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 [7,28,87]. Therefore, we assess BE and BCR for miscanthus in Germany and model their performance from private and societal perspectives with the developed framework. As contrasting pathways, they cover all framework components, in particular the distinction between avoided and removed emissions, while keeping the calculation traceable. The case study thereby illustrates the methodological approach rather than representing the full complexity of biomass conversion systems.

3.9. Specifications for the case study

The miscanthus case study follows the steps outlined in Sections 3.1 to 3.7. 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.

Fig. 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 [89], modeled based on process data from Wernet et al. [90]. 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 [47,91].

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 [62]. 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 [92]. 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. [93]). 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 (Mg C*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 [37,48,63]. Biogenic CO_2 emissions from miscanthus, such as those from combustion, are assumed to be zero [65]. The impact category land use change is excluded because the same functional unit of biomass is assumed across all pathways [64].

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

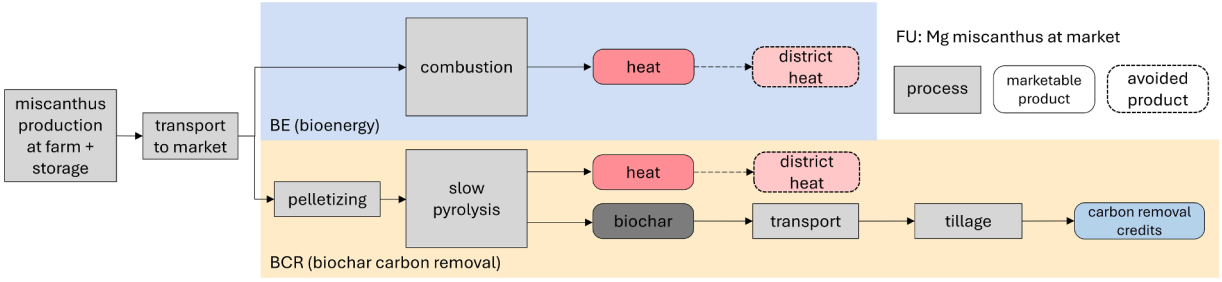


Fig. 2. Defined pathways for the exemplary case study on miscanthus utilization in Germany.

and resource use, thus matching practices in cost-benefit analyses [72].

These parameters all feed into CRC, NPB, and NSB calculations as described in Sections 3.1 to 3.7 above. A sensitivity analysis (SM2) complements the base case, varying each parameter individually while holding all others constant. For CRC price and biochar carbon permanence, reported ranges are applied [92,93]. Biomass cost, process CAPEX, process OPEX, district heat price, biochar price, and the discount rate are varied by ±20%. The following section presents the results of applying the 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.

Fig. 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 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.

Fig. 3b presents the societal perspective (NSB), calculated as NPB plus monetized externalities (i.e., damage costs). Both pathways are socially 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 €*Mg CO_2eq^{-1} [29], whereas CRC are lower, quantified at 155 €*Mg CO_2eq^{-1} [92]. Therefore, current CRC price levels do not fully reflect social 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, Fig. 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. Fig. 4a shows that only BCR delivers permanently stored emissions, whereas BE generates large avoided emission quantities. The magnitude of avoided emissions depends 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 (Fig. 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.

The sensitivity analysis (SM2) varies parameters individually while

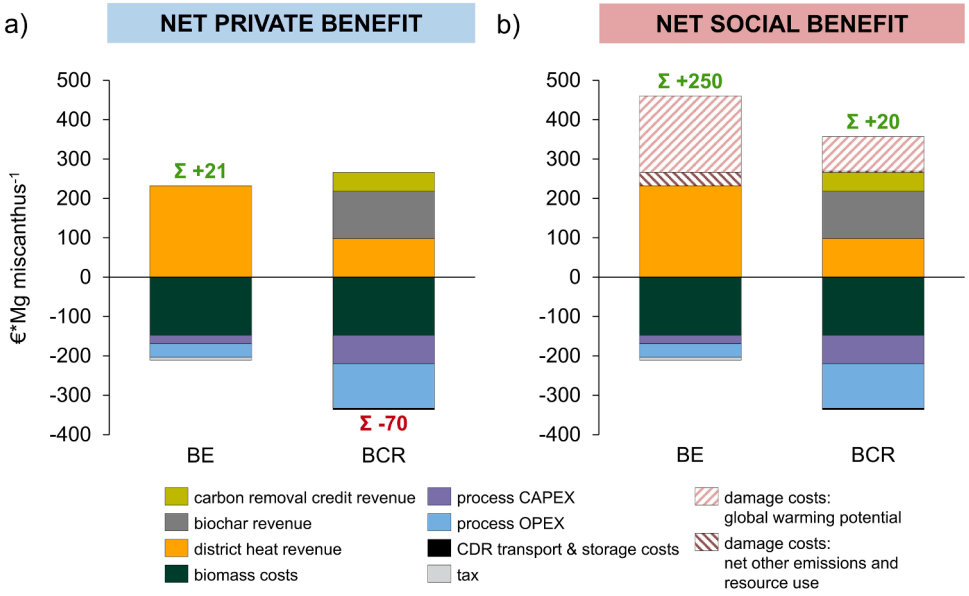


Fig. 3. (a) Net private benefit and (b) net social benefit for miscanthus-based bioenergy (BE) and biochar carbon removal (BCR), disaggregated into (a) cost, revenues, and (b) damage costs.

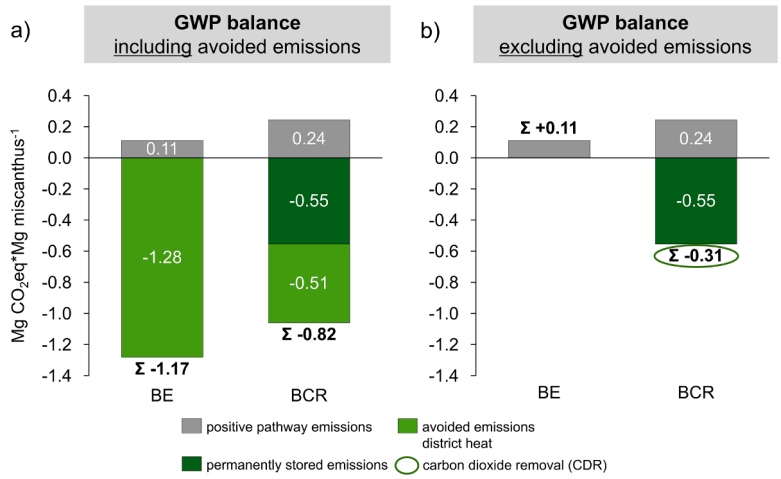


Fig. 4. Global warming potential emission balance for miscanthus-based bioenergy (BE) and biochar carbon removal (BCR), disaggregated in positive pathway and permanently stored emissions, while avoided emissions from system expansion for district heat are (a) included or (b) excluded.

all others remain at base case values. For BE, NPB ranges from −18 to 56 €*Mg miscanthus^{-1} around a base case of 21 €*Mg miscanthus^{-1}. District heat price is the dominant driver, followed by biomass cost; either is sufficient to turn NPB negative, reflecting the pathway's reliance on a single revenue stream. Process OPEX, process CAPEX, and the discount rate have comparatively minor effects. NSB for BE ranges from 210 to 285 €*Mg miscanthus^{-1} and remains positive throughout, as the monetized avoided emissions from district heat substitution exceed the range of the economic variation. For BCR, NPB remains negative in every variation, ranging from −100 to −30 €*Mg miscanthus^{-1} around a base case of −70 €*Mg miscanthus^{-1}. Biomass cost is the strongest driver, followed by CRC price, biochar price, and process OPEX. District heat price, biochar carbon permanence, and process CAPEX follow. No single parameter variation yields a positive NPB, indicating that a combination of cost reductions and revenue increases would be required for economic viability. NSB for BCR ranges from −9 to 61 €*Mg miscanthus^{-1} and turns negative under higher biomass costs, higher process OPEX, and lower biochar price, while remaining marginally positive under lower district heat prices and lower biochar carbon permanence. Across all variations, BE exceeds BCR in both NPB and NSB, so that the ranking of the two pathways is robust within the parameter ranges tested.

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 and across the parameter ranges tested. 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 social 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 identify implications for decision-makers 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 and LCC) outcomes. For instance, by integrating social 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 social benefits and to highlight areas where targeted interventions could enhance both. By enabling simultaneous assessment of private investor and social value, the framework supports a comprehensive and policy-relevant evaluation of biomass utilization pathways.

The NPB and NSB metrics can also be located within the established terminology of LCC [94,95]. The NPB corresponds to the conventional LCC perspective, covering internal costs and revenues of a single stakeholder, although it is referenced here to an input-related functional unit rather than to a project or final product [94,95]. Since the NSB monetizes all environmental impact categories included in the assessment, it corresponds to a full environmental LCC [94], with the deviation that the monetized externalities are added to a conventional rather than an environmental LCC. The NSB does not constitute a societal LCC, which additionally monetizes social impacts such as well-being or job quality [94,95]. The term social in NSB follows cost-benefit analysis terminology, denoting benefits and costs beyond those accruing to a single actor [23]. Here, these are restricted to monetized environmental externalities. Reporting NPB and NSB alongside each other avoids reducing the assessment to one aggregated figure, which has been criticized [95].

NPB and NSB calculation allows the identification of major private and social benefit 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 social 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 use types, which has often been overlooked in previous assessments or has been addressed through reporting conventions rather than an accounting rule [27,64,95]. The framework thereby ensures transparent accounting of environmental burdens, avoids double counting (Table 2), 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 social 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 [37,96,97], BE's higher NPB without permanent emission removal [2,98], and a positive NSB metric when applying damage costs [48,99]. Overall, the framework demonstrates consistency with prior evidence and thus offers a useful tool to support policy design, strategic planning, and investment guidance.

5.2. Implications

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. For the configuration assessed, BCR combines permanent CDR and a positive NSB with a negative NPB. Its NPB remains negative under every single parameter variation, while its NSB stays positive in all but three. This locates the divergence between private and social benefit in the structure of the pathway rather than in individual cost or price assumptions. Technologies with permanent CDR and positive NSB but negative NPB, such as BCR, could be strategically supported to maximize permanent emissions removal and social welfare [100,101].

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 [29,92]. While literature reports that increased CRC prices can render biochar systems privately profitable [13,53], higher CRC prices alone do not yield a positive NPB for BCR in our sensitivity analysis. This result indicates that CRC pricing acts alongside cost reductions and other revenue increases rather than as a single lever. The framework distinguishes substituted from permanently stored CO_2eq emissions, a differentiation that single indicators such as levelized costs or emission factors do not resolve. On this basis, it can quantify how crediting designs, for instance minimum price levels for permanent removal, affect private and social benefit, which is particularly relevant for emerging technologies such as BCR [100,101]. It also quantifies the gap between private and social benefit, indicating the scale at which support would have to operate and how combinations of cost and revenue instruments would have to be dimensioned to close it.

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 social benefits. Its capacity to incorporate scenario analysis is particularly valuable for long-term planning, where policy, market, and technological conditions remain uncertain.

Finally, monetization of environmental externalities remains to be further developed and standardized. EU initiatives, including biochar standards [102] and CDR certification schemes [84,85], provide a foundation, but externalities beyond CRC are not yet covered [103]. Transparent monetization ensures social 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 case study serves as a demonstration of the methodology and does not represent the full complexity of biomass conversion systems. Second, social impacts beyond monetized environmental externalities, such as resource conflicts, distributional effects, and public acceptance, are not captured due to methodological limitations [104,105]. 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, externality monetization requires methodological choices that influence results. Damage costs quantify the social costs of an impact and align with LCA midpoint indicators [29], whereas alternative approaches, such as prevention costs, which estimate the expenses of avoiding impacts, may produce different outcomes [71,72,74]. Within the damage cost approach, monetization factors are derived for particular regions, pollutant sources, and time horizons, and they neither resolve ethical questions nor fully represent values attached to effects reaching across generations [29]. Beyond the choice of method, monetization itself rests on contested weighting decisions, which can shift the relative importance of impact categories [106,107]. Pathway rankings obtained under a common set of factors are therefore more robust than the absolute values underlying them.

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.

Scenario analyses can further explore alternative process configurations, technological progress, additional externality monetization factors, and evolving policy or energy contexts, providing forward-looking insights for long-term strategic planning. Exploring BiCRS emission storage over varying time horizons [66] or applying dynamic LCA [108] 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 [65].

Beyond quantitative metrics, future research could integrate complementary dimensions relevant to biomass utilization, including innovation potential, scaling challenges, stakeholder acceptance, and policy interactions [109]. 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 social 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 social 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 social benefits, helping decision-makers identify pathways that generate both financial returns and social value.

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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 and Claude by Anthropic 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.

CRediT authorship contribution statement

Johanna Ruett: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ali Abdelshafy:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Grit Walther:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This research was financially supported by the Bioeconomy Science Center's NewBIAS project. The scientific activities of the Bioeconomy Science Center were financially supported by the Ministry of Culture and Science within the framework of the NRW Strategieprojekt BioSC (No. 313/323-400-00213). The research was also supported by the NRW-Profilbildung by the Ministry of Culture and Science, project ACCeSS – Active Carbon Capture for Sustainable Synthesis (PB22-028C). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2026.102180.

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 the sensitivity analysis and all ReCiPe midpoint impact categories.

Data availability

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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