Title: A Modular BECCS Process Chain Framework from Biomass to Carbon Removal

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Abstract

Bioenergy with Carbon Capture and Storage (BECCS) is widely discussed as a key pathway for achieving net-negative greenhouse gas emissions. However, the complexity and context-specific nature of BECCS systems continue to delay their deployment. This paper introduces a modular process chain that decomposes BECCS into transparent modules—from feasibility evaluation through to CO_2 storage. Developed within the German research initiative "CDR-Atlas", the framework integrates technical, ecological, and governance-related aspects, including feedstock differentiation, land management, biomass treatment, conversion technologies, CO_2 logistics, and stakeholder dynamics. Each module is informed by peer-reviewed literature, supporting traceability and scientific robustness. Drawing from literature and stakeholder engagement, the process chain supports planning, communication, and systemic transparency. Its modular character allows adaptation across geographies, project scales, and policy environments. We propose this framework as a complementary tool to modeling approaches, supporting transparent system analysis, identifying implementation bottlenecks, and enhancing governance readiness in CDR deployment.

1. Introduction

Achieving net-zero and net-negative emissions targets requires not only rapid emission reductions but also the deployment of scalable carbon dioxide removal (CDR) technologies. Such approaches must ensure durable storage of CO_2 while operating within regulatory and monitoring frameworks. Among these, Bioenergy with Carbon Capture and Storage (BECCS) is one of the most studied and policy-relevant options (Babin et al., 2021; Ishaq and Crawford, 2025). BECCS combines renewable biomass-based energy conversion with CO_2 capture and long-term geological storage, thereby offering the potential for durable removals (Fuss et al., 2018).

The feasibility of BECCS depends on multiple interlinked factors, including biomass availability, land use and cultivation practices, pre-treatment logistics, conversion efficiency, and the development of CO_2 transport and storage. Societal perceptions related to land competition, infrastructure siting, and distributional impacts influence project development and siting conditions. While existing studies have modeled BECCS in global scenarios or assessed individual steps such as feedstock supply or capture technology, few efforts have provided a transparent, systematically structured framework that reflects the full deployment logic of BECCS (Slade et al., 2014; Torvanger, 2023).

This paper addresses this gap by presenting a modular BECCS process chain that structures the operational sequence from biomass sourcing and preparation through conversion and CO_2 capture to transport and storage. The framework was developed within the CDR-Atlas initiative in Germany to support planning, stakeholder dialogue, and systematic assessment across disciplines. It integrates peer-reviewed literature, existing BECCS assessments, and workshop-based engagement with experts from natural sciences, engineering, governance, and monitoring, reporting, and verification (MRV) systems.

By introducing modular entry points and decision nodes, the framework provides a structured analytical framework that can be applied across geographies, project scales, and policy contexts. Rather than prescribing fixed pathways, it enables transparent exploration of feasibility conditions, trade-offs, and risks associated with different BECCS configurations.

2. Methods

2.1 Modular Framing and System Rationale

The methodological core of this study lies in the development of a modular process chain that represents the full operational structure of BECCS. The modularity is not merely a visual convenience but reflects a system-oriented approach rooted in industrial ecology and transition studies (Geels, 2002; Bausch and Grunwald, 2021). Segmenting BECCS into discrete but interlinked modules enables the tracing of interdependencies, such as how the choice of feedstock affects available conversion technologies and CO_2 transport infrastructure. Each module represents one major stage in the process chain — from integrated method and biomass selection to CO_2 storage, including key operational sub-steps, including MRV entry points and decision nodes. This framing supports interdisciplinary understanding and iterative refinement, particularly in participatory planning settings or at early project stages where comprehensive system overviews are critical. Feedback loops and decision nodes across technological, ecological, social, and governance domains are explicitly incorporated to capture interactions between key technical and system-level components. While governance and MRV aspects are addressed as cross-cutting elements throughout the framework, their detailed methodological implementation is not the primary focus of this process-chain description. Instead, MRV considerations are integrated conceptually across modules, while more detailed monitoring and verification frameworks are discussed in the dedicated MRV section (Section 3.9) of this paper.

2.2 Literature Synthesis and Thematic Structure

The framework builds upon a structured synthesis of peer-reviewed publications, technical reports, and institutional assessments, including IPCC reports (IPCC, 2022; IPCC, 2024), complemented by sources addressing monitoring and governance aspects where applicable. Sources were selected based on their relevance to core BECCS process components and alignment with established system boundaries. This informed the identification and structuring of key process elements across the BECCS chain. Some elements were derived from recurring themes in review papers; others were selected based on their repeated inclusion across policy reports, sectoral assessments, and techno-economic analyses.

2.3 Stakeholder Integration and Expert Dialogue

To refine the process structure and align it with practical implementation considerations, three iterative meetings were held with domain experts, complemented by two additional consultations on MRV and on governance. These exchanges addressed recurring issues such as the alignment of feedstocks with conversion methods, pre-treatment dependencies, and the positioning of MRV-relevant stages within the process chain, which were iteratively refined and incorporated. The consultations also highlighted the need for a structure that supports both top-down strategy development and bottom-up implementation planning. The framework is primarily informed by peer-reviewed literature, complemented by structured expert input and iterative conceptual refinement.

2.4 Visual Implementation Principles

Initial drafts were created using Miro, a collaborative whiteboard platform, allowing shared development of logic and layout. The final version was implemented using scalable vector graphics (SVG) within the CDR-Atlas web framework to support interactive layers, modular data linking, and integration with on-click information boxes for each feedstock and process module. Color schemes followed accessibility guidelines (Wong, 2011), while node geometries reflected process functions. Flow logic was tested with expert and non-expert users to ensure usability across disciplines. Particular attention was given to intuitive flow, clear categorization, and intermodular coherence.

2.5 Scope and Limitations

The process chain does not aim to simulate dynamic behavior, quantify costs, or provide region-specific LCA or techno-economic results. Instead, it complements techno-economic modeling and GIS-based scenario planning by providing a structural and communicative interface. The framework is best used in early-stage planning, cross-sectoral coordination, and education. Some components are informed by expert input and inductive structuring based on existing knowledge rather than formal systems modeling. These include, for instance, the schematic placement of governance and MRV elements or distinctions in land preparation and cultivation types that reflect practical implementation needs rather than standardized methodological frameworks.

2.6 Terminology and Process Definitions

To ensure clarity for an interdisciplinary readership, this study defines key concepts relevant to the BECCS process chain. Bioenergy with carbon capture and storage (BECCS) refers to the integration of biomass conversion into energy carriers with CO_2 capture and geological storage, resulting in net removal of atmospheric CO_2. Monitoring, reporting, and verification (MRV) denotes the systematic measurement, documentation, and independent validation of CO_2 removals across the process chain and is essential for transparency, accountability, and storage integrity (IPCC, 2022; IPCC, 2024).

Feedstocks are grouped into four main categories: agricultural biomass, forest biomass, waste biomass, and microalgae and aquatic biomass. Agricultural biomass is further subdivided into sugar-rich, starch-rich, and herbaceous feedstocks, with wetland biomass treated as a specific subcategory of herbaceous biomass due to its distinct ecological and management characteristics (Cherubini, 2010; Fajardy and Mac Dowell, 2017). This classification reflects shared cultivation origins alongside differences in handling, processing requirements, and conversion suitability.

These categories form the basis for the integrated method and biomass selection step, providing the structural linkage to subsequent modules such as pre-treatment, conversion, product upgrading, and CO_2 transport and storage. Detailed descriptions of conversion technologies, pre-treatment options, and methodological assumptions are provided in Appendix 1.

3. Results

Overview

The BECCS system is structured into eight modules that together form a complete process chain (Figure 1). Each module represents one major step in the BECCS pathway. While a module marks a large unit in the chain, it often contains several smaller operational steps. This structure provides a transparent representation of system components and their interrelations. The process chain represents a conceptual system framework rather than a detailed engineering design. Individual steps may vary depending on feedstock properties, technological configuration, and site-specific conditions.

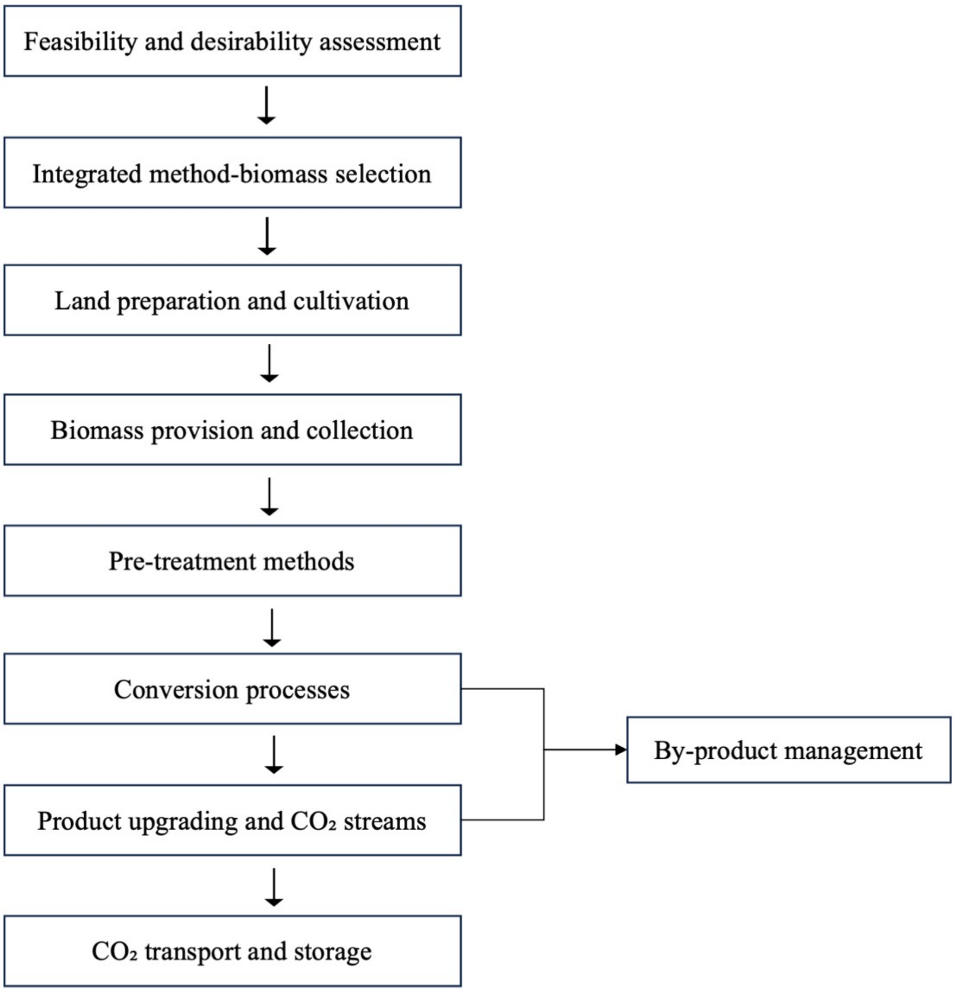


Figure 1. Schematic overview of the modular BECCS process chain. The figure presents eight main modules, ranging from feasibility and desirability assessment through integrated method and biomass selection, land preparation and cultivation, biomass provision and collection, pre-treatment processes, conversion processes, product upgrading and CO_2 streams, to CO_2 transport and storage. By-product management is represented as a side stream associated with the conversion and upgrading stages. Cross-cutting elements, such as MRV and societal dimensions, are conceptualized as integral components across all modules. Each box represents a major process stage comprising multiple operational sub-steps, which are detailed in subsequent figures and sections.

The first two modules represent entry points: the Feasibility Assessment examines whether a BECCS project is technically, logistically, and economically feasible in a given location. This distinction follows the feasibility/desirability framework proposed by Tank et al. (2025). Both gates must be passed before moving on.

Next comes the *Integrated Method and Biomass Selection module*, which links the choice of conversion method with suitable biomass types. This step includes the main technological pathways—combustion, thermochemical conversion (gasification and pyrolysis), fermentation, and anaerobic digestion—and aligns each with compatible feedstocks: agricultural, forest, microalgae/ aquatic biomass, with wetland biomass treated as subcategories of herbaceous biomass within the agricultural group and waste biomass. Recent literature indicates that waste biomass (e.g., industrial, municipal, or post-consumer materials of biological origin) is now frequently treated as a distinct feedstock category in bioenergy and BECCS studies (e.g., Honegger et al. 2023).

The field-level steps *Land Preparation* and *Cultivation* describe how the chosen biomass can be grown and collected under local conditions. *Biomass Provision and Collection* covers harvesting, transport, and, if needed, short-term storage.

The next step, represented by the Pre-treatment Processes module, prepares biomass for subsequent conversion by modifying its physical, chemical, or biological properties. Typical pre-treatment approaches include size reduction, drying, torrefaction, hydrolysis, or other physicochemical treatments that improve feedstock handling, stability, and conversion efficiency depending on feedstock characteristics and the selected conversion pathway (Mata-Alvarez et al., 2014).

The Processes for Conversion module forms the technological core of BECCS and encompasses major biochemical and thermochemical pathways such as fermentation, combustion, gasification, pyrolysis, and anaerobic digestion. These processes convert biomass into solid, liquid, or gaseous energy carriers, including solid bioenergy products, liquid biofuels, and biogas, which can subsequently be used to generate heat, electricity, or transport fuels (Sims et al., 2010; IPCC, 2024).

In addition to energy carriers, biomass conversion generates CO_2-containing process streams. Depending on the conversion pathway, CO_2 may be separated during fuel upgrading processes such as biogas upgrading or bioethanol purification, or captured during energy conversion processes such as combustion or gasification. The separated CO_2 can then be directed to capture systems and subsequently transported and stored in geological formations (Fajardy and Mac Dowell, 2017; IPCC, 2024).

Product upgrading refers to processing steps that improve the quality of energy carriers produced during biomass conversion (e.g., biofuels, biogas, or syngas), while CO_2-rich gas streams generated during upgrading or energy conversion are separated and directed toward capture, transport, and geological storage (Searle and Malins, 2014).

Depending on the selected conversion pathway, additional material streams may arise, including biochar from pyrolysis, digestate from anaerobic digestion, or ash residues from combustion processes. These materials require appropriate by-product management and may be reused within bioenergy systems, applied as soil amendments, or managed according to environmental and regulatory requirements (Lehmann and Joseph, 2015; Cesaro and Belgiorno, 2023).

3.1. Feasibility and desirability assessment

Feasibility assessment evaluates whether BECCS can be implemented under given conditions (Figure 2). It evaluates whether local or regional conditions are suitable for implementing a BECCS system from a technical, logistical and economic perspective. This includes the availability of sustainable biomass feedstocks, the suitability of land without major conflicts with food production or biodiversity protection, and the accessibility of infrastructure for biomass conversion, CO_2 transport, and geological storage (Popp et al., 2017; Smith et al., 2021). Feasibility also includes the question of whether (MRV) systems can be integrated in a robust way over time. MRV systems are required to enable transparent accounting of negative emissions (Smith et al., 2021; Bellamy et al., 2019). Finally, the availability of financing and clear responsibilities for long-term CO_2 liability and storage stewardship are critical (Honegger et al., 2021). If these conditions are not met, implementing BECCS in a given region may result in technical, regulatory, or environmental challenges—highlighting the importance of this first module (Tank et al., 2025; Baatz et al., 2025).

Desirability assessment complements this technical screening by asking: *Should BECCS work here?* It shifts the perspective toward societal and ethical dimensions. This module considers whether a BECCS project is supported or rejected by local communities, whether it aligns with broader climate strategies, and whether its benefits and burdens are fairly distributed. Societal acceptance is a critical enabler—or barrier—for any carbon removal effort, and depends on perceived risks, transparency, and procedural inclusion (Bellamy et al., 2017; Fridahl, 2017). Political alignment is equally important: projects that do not fit into national or regional decarbonization pathways may face resistance or regulatory delays (IPCC, 2023). Additionally, potential conflicts with land-use priorities—such as food production, tourism, or nature conservation—must be carefully considered (Popp et al., 2014). Secure land tenure and stakeholder involvement in early planning stages are essential for just and legitimate deployment (Torvanger, 2023). This second assessment thus acts as a societal filter that enables consideration of societal acceptance, distributional aspects, and policy alignment.

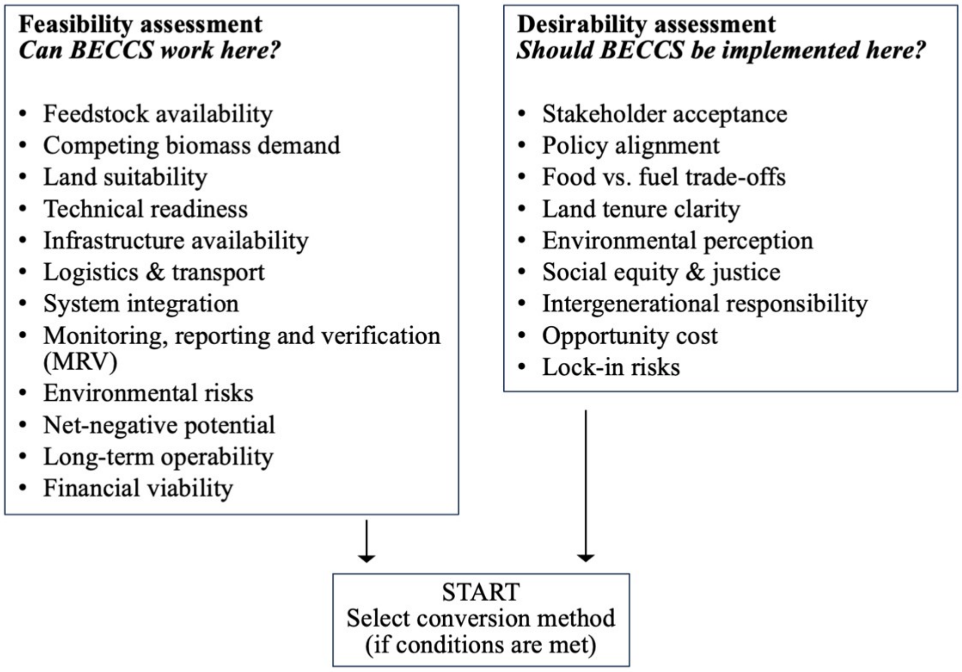
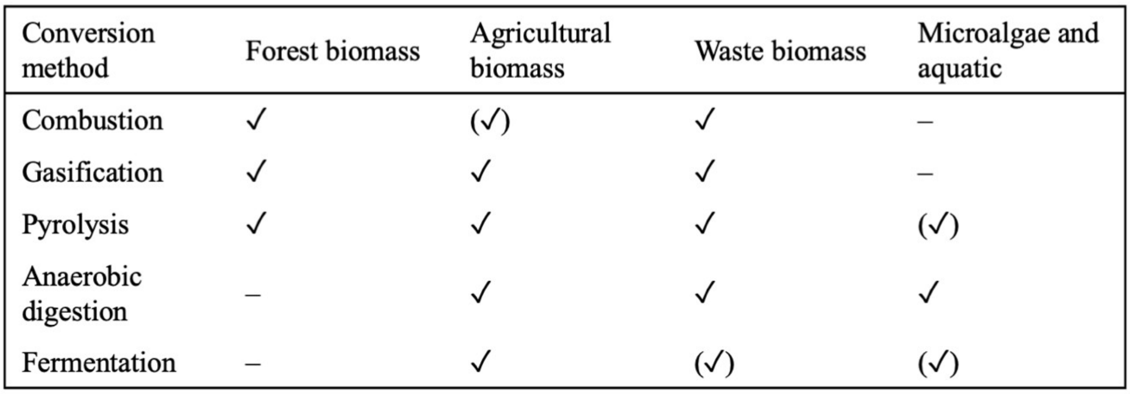


Figure 2. Feasibility and desirability assessments as entry gates to the BECCS process chain. The figure illustrates an initial screening step that evaluates key technical, ecological, and societal boundary conditions before further specification of feedstocks and conversion pathways. These assessments are not intended to represent a comprehensive decision framework but rather serve as early-stage entry gates that identify whether a BECCS pathway should be explored further. More detailed feedstock- and method-specific assessments are conducted in subsequent stages of the process chain.

Only if both feasibility and desirability conditions are fulfilled, the process can move forward to method selection. This logic defines an initial entry point that integrates technical, environmental, and societal aspects from the very beginning of any BECCS pathway.

3.2. Method Selection and Feedstock Categorization

Once the feasibility and desirability of a BECCS deployment have been evaluated for a given region, and both assessments yield positive outcomes, the process transitions into its first technical decision point: the Integrated Method and Biomass Selection module. This marks the entry into the engineering and operational dimension of BECCS planning, where suitable biomass types are aligned with compatible conversion methods in an integrated assessment. Because conversion methods differ significantly in terms of temperature regime, biochemical requirements, infrastructure needs, and carbon capture compatibility, their selection has downstream effects on every subsequent module of the chain. This relationship between feedstock characteristics and conversion pathways is summarized in Figure 3.



Conversion method	Forest biomass	Agricultural biomass	Waste biomass	Microalgae and aquatic
Combustion	✓	(✓)	✓	–
Gasification	✓	✓	✓	–
Pyrolysis	✓	✓	✓	(✓)
Anaerobic digestion	–	✓	✓	✓
Fermentation	–	✓	(✓)	(✓)

Figure 3. Integrated method and biomass selection. The table illustrates the linkages between major feedstock categories—forest, agricultural, waste, and microalgae and aquatic biomass —and the corresponding conversion methods in BECCS systems. The waste biomass category includes heterogeneous streams such as municipal solid waste, waste wood, organic residues, and processed fuels such as solid recovered fuels (SRF), whose compatibility with individual conversion methods depends on composition and pre-treatment. Symbols indicate compatibility: ✓ established; (✓) conditional; – not suitable.

The core conversion methods represented in this framework include fermentation, anaerobic digestion, and a collective category termed “Thermochemical Conversion Methods,” encompassing hydrothermal carbonization, combustion, gasification, and pyrolysis. These technologies are not interchangeable, and each has specific feedstock requirements as well as carbon capture implications. For instance, fermentation is predominantly suited for biomass that is rich in sugars or starch, as these compounds can be efficiently converted into ethanol or other biofuels. Feedstocks such as sugar beet, corn, food waste, and even microalgae like Chlorella and Spirulina have been used in fermentation (Kheshgi and Prince, 2005; Scarlat et al., 2015). Anaerobic digestion, by contrast, operates under microbial processes and accepts a broader range of wet, biodegradable substrates, including herbaceous plants, municipal organic waste, wetland grasses, and algal residues (IPCC, 2022; Owsianiak et al., 2024).

Waste-to-energy pathways extend beyond direct incineration and may include the combustion of municipal solid waste and waste wood, co-incineration of solid recovered fuels (SRF) (see also ISO, 2021b) for classification frameworks of recovered fuels), and thermochemical conversion routes such as gasification and pyrolysis.

Combustion systems—whether for direct electricity generation or combined heat and power generation—are technically mature but require dry material. Forest-derived biomass such as wood chips or sawmill residues are therefore well suited, while herbaceous biomass may only be suitable if sufficiently dried (Owsianiak et al., 2024). Further thermochemical conversion methods such as gasification and pyrolysis operate at elevated temperatures in low-oxygen environments and enable the production of syngas, bio-oil, and biochar. Gasification systems are optimized for forest biomass or pelletized herbaceous materials with low moisture content, while pyrolysis systems are especially suited for forest and herbaceous biomass, including wetland-derived biomass, due to their tolerance of higher moisture content (Lehmann and Joseph, 2015). However, the structural properties of herbaceous biomass can reduce conversion efficiency (Smith et al., 2021). Waste-to-energy pathways, particularly combustion and co-incineration of municipal solid waste and waste wood, are well-established and widely applied (Thrän et al., 2025; Milledge et al., 2020).

The feedstock–conversion linkages in this framework reflect both theoretical compatibility and practical experience from research projects and commercial-scale pilots. Forest biomass is commonly associated with combustion, gasification, and pyrolysis, whereas wet agricultural biomass—typically sugar-rich or starch-rich—is more closely linked to fermentation and anaerobic digestion. Herbaceous biomass, such as straw or hay, and wetland biomass, offer potentials for anaerobic digestion, gasification, or pyrolysis if sufficiently dried or pelletized. Residues from wood processing and waste wood are also typically converted in combustion or gasification, while wet biomass is used in fermentation or anaerobic digestion after separation and cleanup. Microalgae and aquatic biomass, though often associated with lower technology readiness levels in bioenergy processes, have demonstrated compatibility with fermentation and anaerobic digestion due to their high biochemical conversion yields (Pancione et al., 2024; Lefvert and Grönkvist, 2023).

These interconnections are essential for interpreting BECCS as a modular and context-dependent system. Rather than a fixed sequence, it represents a network of process options where biomass characteristics, conversion technologies, and regional conditions jointly influence the configuration of each deployment.

3.3. Land Preparation, Cultivation, and Biomass Provision and Collection

3.3.1 Overview of Upstream Biomass Modules

Following the selection of a suitable conversion method and its corresponding feedstock category, the BECCS process chain proceeds through a sequence of upstream modules. These include a) *land preparation*, b) *feedstock cultivation*, and c) *biomass provision and collection*, the latter comprising three operational subphases: c1) *harvesting and collection*, c2) *transport* and c3) *temporary storage options*. After harvesting and transport, biomass feedstocks are often subject to temporary storage prior to conversion or pre-treatment, which serves to balance seasonal supply, control moisture, and preserve biomass quality. Together, these components describe the upstream stages of biomass provision within the BECCS process chain.

While these activities are extensively documented in agronomic, silvicultural, ecological, and industrial literature (IPCC, 2019), this paper provides a structured description of their application to BECCS. Rather than reproducing detailed technical manuals, the following section outlines the key operational steps for the main feedstock types represented in the process chain. These include *sugar-rich biomass, starch-rich biomass, herbaceous biomass (including wetland biomass), forest biomass, waste biomass,* and *microalgae and other aquatic biomass*. For each of these feedstock types, the steps of land preparation, cultivation, harvesting and collection, and transport are described in the order in which they appear in the process chain (Figure 1).

The third subphase of biomass provision, *temporary storage options*, is treated collectively at the end of this module, as practices for short-term storage often depend more on downstream conversion needs and logistical integration than on biomass type alone.

Scientific references are provided throughout, and more comprehensive insights into the ecological, agronomic, and logistical nuances can be found in specialist publications (e.g., Cherubini, 2010; Wichtmann et al., 2016; Milledge et al., 2020).

Although wetland biomass is often grouped under herbaceous or agricultural categories in conventional bioenergy classifications, it is treated here as a specific subcategory of herbaceous biomass due to its distinct hydrological, ecological, and management characteristics.

3.3.2. Sugar-rich agricultural biomass

a) Land preparation: Following the selection of a suitable feedstock category and conversion pathway, sugar-rich biomass systems—such as those relying on sugarcane (*Saccharum officinarum*) or sugar beet (*Beta vulgaris*)—require a sequence of well-coordinated agronomic practices to ensure high productivity and ecological integrity. This section outlines the upstream components for sugar-rich biomass in BECCS systems, spanning from land preparation through to harvesting and transport.

For sugar-rich crops, initial land preparation includes the selection of cultivars with elevated sugar content, tailored to regional conditions. High-sucrose varieties are critical for maximizing ethanol yield in fermentation-based BECCS routes, as they provide greater amounts of fermentable sugars per hectare and enable more efficient conversion rates. Varietal selection is typically followed by comprehensive soil testing to assess nutrient availability, pH levels, and water-holding capacity. Based on the results, site-specific nutrient regimes—especially nitrogen application—are planned to promote vigorous crop establishment (Karp et al., 2022).

b) Feedstock cultivation: During the cultivation phase, maintaining high sugar productivity requires active management of pests and diseases known to reduce sucrose accumulation. Integrated pest management (IPM) strategies and biological controls are increasingly applied to reduce pesticide dependency and environmental impact. Additionally, optimized irrigation schedules and monitoring of canopy development are essential to sustain photosynthetic efficiency and sucrose storage in the stem tissues (Amorim et al., 2011). In sugar beet systems, weed suppression and mechanized thinning further contribute to maintaining high root quality and sugar concentration (Gnansounou and Dauriat, 2005).

c) Biomass provision and collection:

c1) Harvesting and collection: Sugar-rich biomass is harvested using specialized agricultural machinery adapted to either cane or beet morphology. For instance, sugarcane is typically cut at ground level with whole-stalk or chopper harvesters, depending on downstream processing

needs, while sugar beet harvesting requires lifting equipment that minimizes root damage (Karp et al., 2022). The timing of harvest is critical, as peak sucrose content occurs shortly before physiological maturity.
c2) Transport: Post-harvest, biomass is loaded into covered trailers or sealed containers to minimize sucrose loss and microbial contamination during transit. Transport logistics are closely integrated with fermentation facilities to reduce storage time and preserve sugar quality, particularly in tropical environments where enzymatic degradation can occur rapidly (Amorim et al., 2011). In several BECCS pilot systems, field-to-plant distances are limited to <50 km to reduce transport emissions and maintain feedstock freshness (IPCC, 2022).

3.3.3. Herbaceous agricultural biomass

Following the selection of the feedstock category and the transition from the general cultivation section, this module details the specific steps associated with *Herbaceous biomass*. This category includes feedstocks such as *Miscanthus* × *giganteus*, grassland residues, straw and wetland, each requiring tailored preparation and harvesting practices, which are represented directly in the BECCS process chain. Wetland biomass as a specific herbaceous subcategory

a) Land preparation: Land preparation for herbaceous biomass typically includes soil tillage and pH adjustments to ensure balanced nutrient availability, particularly for nitrogen and phosphorus. While straw and grassland biomass often require minimal fertilization to maintain the stability of existing soil ecosystems, miscanthus cultivation is more sensitive to micronutrient deficiencies and may require targeted nutrient interventions (Kwaśniewski et al., 2021; Winkler, 2020). Soil conditioning before planting is therefore critical to ensure robust crop establishment.

b) Feedstock cultivation: During the establishment phase, herbaceous crops such as *Miscanthus* × *giganteus* are commonly planted using rhizomes at densities of approximately 16,000 per hectare. Effective mechanical weed control during the first growing season is essential to reduce competition and allow for the development of a closed canopy, which supports moisture retention and early biomass accumulation (Teagasc, 2011; Kwaśniewski et al., 2021). Typical fertilization strategies apply around 60 kg nitrogen per hectare annually to support the high biomass yields expected from perennial energy crops (Moon-Sub Lee et al., 2017).

c) Biomass provision and collection:

c1) Harvesting and collection: Herbaceous biomass is generally harvested in late winter or early spring, when moisture content falls below 30 %, improving storability and reducing transport emissions (Kwaśniewski et al., 2021). Miscanthus, for example, is harvested using forage harvesters or balers, although shredded straw technology is also increasingly used to improve transport efficiency by densifying the material (Shahidi et al., 2021). The timing of the harvest directly influences the biomass quality, including ash content and calorific value, and is therefore a key variable in BECCS supply chain planning.

c2) Transport: Transportation of herbaceous biomass typically occurs in the form of compressed bales or shredded material. Moist biomass is prone to microbial degradation and associated emissions; for this reason, miscanthus is usually transported at moisture levels below 25 % (Kwaśniewski et al., 2021). Optimizing moisture content, bale density, and logistics coordination remains essential to minimize emissions and economic costs.

Wetland biomass (paludiculture)

Wetland biomass is treated here as a specific subcategory of herbaceous biomass due to its distinct hydrological, ecological, and management characteristics.

a) Land preparation: Wetland biomass cultivation, often referred to as *paludiculture*, focuses on the productive use of rewetted peatlands and other wet or formerly drained ecosystems. Land preparation involves rewetting previously drained areas by adjusting water levels through dike removal, ditch blocking, or controlled irrigation infrastructure. This process halts peat degradation, restores hydrological function, and prepares the site for the cultivation of wet-adapted species such as *Phragmites australis* (common reed), *Typha spp.* (cattail), or *Carex spp.* (sedges). This practice supports both biomass provisioning and climate mitigation through avoided emissions and potential carbon sequestration (Wichtmann et al., 2016; Tanneberger et al., 2021).

b) Feedstock cultivation: The cultivation of wetland biomass requires careful selection of species that are adapted to saturated conditions and capable of high biomass yields. Species such as *Typha latifolia*, *Phragmites australis*, and *Schoenoplectus lacustris* are commonly used in central Europe. These plants are typically not fertilized and rely on naturally available nutrients in the wetland ecosystem. Management focuses on water level control to optimize growth while ensuring the long-term stability of the peat body. Unlike conventional crops, these species are not re-sown annually; they regenerate vegetatively and form permanent vegetation cover (Wichtmann et al., 2016).

c) Biomass provision and collection:

c1) Harvesting and collection: Harvesting is conducted with specialized low-ground-pressure machines or amphibious vehicles, often during winter or dry periods to minimize soil disturbance and preserve the peat layer. Harvesting equipment may include adapted mowers, balers, or chippers, depending on the biomass form (e.g., whole shoots vs. shredded material). Timing and method are crucial to avoid damage to sensitive ecosystems and to maintain long-term site productivity. In many pilot projects, mobile field systems are used to cut, collect, and pre-compact biomass directly on-site (Tanneberger et al., 2021).

c2) Transport: After collection, wetland biomass is transported to processing or drying facilities. Due to its typically high moisture content, efficient logistics are essential to minimize energy losses and emissions. Transport methods include tractors with trailers, amphibious harvesters with on-board transport capability, or lightweight forwarders, depending on the site's accessibility. Proximity to utilization sites (e.g., for combustion, anaerobic digestion, or insulation material production) plays a major role in determining the feasibility and carbon balance of paludiculture systems (Tiemeyer et al., 2020).

3.3.4. Starch-rich agricultural biomass

a) Land preparation: The cultivation of starch-rich biomass, such as maize and cassava, requires site-specific land preparation techniques tailored to the crop's morphological and agronomic needs. For cassava, land clearing is followed by ridge formation or mounding to facilitate root expansion and avoid waterlogging, particularly in humid tropical environments. Soil loosening to depths of 25–30 cm is common to promote tuber development and reduce compaction stress. In maize cultivation, pre-sowing tillage is used to optimize seedbed structure and moisture retention while suppressing early weed emergence. Conservation tillage techniques are increasingly recommended to reduce erosion and preserve soil carbon stocks in BECCS-compatible land-use schemes (Lal, 2020).

b) Feedstock cultivation: Starch-rich crops are cultivated with a focus on optimizing starch accumulation, which is directly influenced by nitrogen availability, sunlight duration, and planting density. In cassava systems, low-input farming is often feasible, though site-specific fertilizer applications—particularly potassium and phosphorus—can significantly boost yield without excess nitrogen loss. Maize requires more intensive nutrient management and is sensitive to planting time and pest pressure. Modern cultivation approaches for starch-rich biomass integrate precision agriculture tools and crop rotation to maximize starch yield per hectare while limiting environmental burdens (Tanzer and Ramirez, 2019). Pest and weed control are often mechanical or integrated with organic practices in BECCS-oriented constellations to maintain overall GHG mitigation benefits.

c) Biomass provision and collection:

c1) Harvesting and collection: Harvesting practices for starch-rich crops are highly mechanized in the case of maize and semi-manual to fully manual for cassava, depending on the region. Maize is typically harvested using combine harvesters that separate grains and collect cobs, which are then either stored or processed into bioethanol feedstock. Cassava roots are usually hand-harvested or uprooted using lightweight equipment to minimize tuber damage, which is critical due to the crop's rapid post-harvest deterioration (Burns et al., 2010). Efficient timing of harvest is essential to preserve starch content and reduce spoilage.

c2) Transport: Transport logistics for starch-rich biomass require particular attention to bulk density and degradation risk. Maize grains, once dried, can be transported in bulk over long distances with minimal spoilage, using silos and grain trailers. Cassava, in contrast, is perishable and must be processed within 24–72 hours after harvest to avoid enzymatic degradation of starch and associated yield losses. This temporal sensitivity limits the feasible transport radius and often necessitates decentralized processing units or rapid delivery to biorefineries located near cultivation sites. The choice of transport method—truck, tractor trailer, or conveyor—depends on infrastructure, distance, and the scale of operation.

3.3.5. Forest Biomass

The use of forest-driven woody biomass (former forest biomass) within BECCS systems relies on long-term, site-specific management strategies that integrate ecological, silvicultural, and carbon removal objectives. This section describes the key steps from land preparation to transport, following the structure outlined in the process chain.

a) Land preparation: Land preparation for forest biomass feedstocks often involves the conversion of degraded, previously harvested, or underutilized lands into managed forest systems suitable for biomass production. Site selection is critical and typically guided by factors such as soil characteristics, slope, accessibility, and prior land use history (van der Hilst et al., 2013). In some cases, afforestation or reforestation of marginal land is implemented, while in others, former agricultural plots are transitioned into short-rotation plantations (Berndes et al., 2016). Mechanical clearing, soil conditioning, and infrastructure development (e.g., access roads) are conducted in compliance with sustainability guidelines to minimize soil disturbance and erosion.

b) Feedstock cultivation: Cultivation in this context refers to the establishment and maintenance of forest stands optimized for biomass harvesting. Species selection plays a central role, with preference given to fast-growing, high-yield trees such as poplar, willow, or eucalyptus in temperate climates (González-García et al., 2012). Planting density, rotation length, and thinning regimes are tailored to maximize aboveground biomass accumulation while preserving soil carbon stocks and biodiversity (Zanchi et al., 2012). Short-rotation coppice systems are often favored due to their rapid regrowth and compatibility with mechanized harvesting (Bentsen et al., 2014). Weed control, fertilization, and irrigation may be applied during establishment phases, especially in degraded or nutrient-poor sites, but are typically reduced in mature stands (Berndes et al., 2016).

c) Biomass provision and collection:

c1) Harvesting and collection of forest biomass is performed using specialized forestry equipment such as harvesters, forwarders, or feller-bunchers, depending on the stand structure and topography (Spinelli and Magagnotti, 2011). Biomass may be extracted as whole trees, logs, or residues such as branches and tops. In short-rotation systems, mechanical harvesting can achieve high efficiency and low soil disturbance, particularly when carried out under dry soil conditions and with low-pressure tires (Hytönen et al., 2018). Collection logistics also account for moisture content, since freshly harvested wood can contain up to 50 % water by weight, affecting both transport efficiency and downstream conversion processes (Mola-Yudego and Aronsson, 2008). Depending on the method of processing, biomass may be chipped or bundled directly at the felling site.

c2) Transport of forest biomass typically involves trucks, trailers, or in some cases, rail systems to move the material from forest sites to conversion or storage facilities. The form of biomass (e.g., roundwood, chips, bundles) strongly influences loading practices and energy efficiency during transport (Röser et al., 2008). Strategies to reduce greenhouse gas emissions during this phase include optimizing route planning, using high-capacity vehicles, and limiting transport distances through decentralized pre-processing hubs (Searle and Malins, 2016). In some cases, mobile chipping units are employed on-site to increase bulk density and reduce haulage volume (Spinelli et al., 2012). Moisture reduction prior to transport can further improve calorific value and overall efficiency (Kärkkäinen et al., 2021).

3.3.6. Waste Biomass

Although waste biomass is not explicitly defined as a primary category in ISO 17225-1 (2021a), recent frameworks increasingly recognize it as an essential BECCS feedstock.

a) Land preparation: For waste biomass sources, land preparation is generally not required in the conventional sense, as the feedstocks are by-products of urban, industrial, or agricultural processes. These include sewage sludge, food waste, industrial residues, digestate from anaerobic digestion, post-consumer organic materials, and waste wood (Bacenetti et al., 2021). Unlike forest residues, which originate from managed forestry operations, waste wood typically arises from construction, demolition, or post-industrial activities. Its utilization requires compliance with waste handling regulations, particularly regarding coatings, adhesives, or heavy metal contamination.

Instead of land-based interventions, infrastructure must be in place to collect, segregate, and preprocess the waste streams, often in or near urban or industrial areas (Makarichi et al., 2018). Regulatory requirements for handling hazardous components, such as heavy metals in sludge or contaminants in municipal solid waste, necessitate tailored planning and monitoring prior to feedstock utilization (Werther and Ogada, 1999; Fytili and Zabaniotou, 2008). As such, the preparation phase for waste biomass focuses less on land use and more on logistical and regulatory integration.

b) Feedstock cultivation: Unlike conventional biomass sources, waste biomass is not cultivated per se. Instead, it is generated as a residual output from existing systems, including wastewater treatment plants, food supply chains, and industrial production (Olsson et al., 2020). However, optimization of upstream processes can increase the quality and quantity of waste biomass available for BECCS. For example, improving the organic load in wastewater or enhancing separation in municipal solid waste can significantly improve feedstock consistency (Zhou et al., 2022). In the case of digestate, the feedstock quality depends on the type of input biomass and the operational parameters of the anaerobic digestion process

(Tambone et al., 2010). Although not actively cultivated, these upstream conditions functionally serve as the 'production environment' for waste-derived biomass.

c) Biomass provision and collection:

c1) Harvesting and collecting waste biomass requires a well-coordinated infrastructure tailored to each waste stream. Sewage sludge is typically collected via centralized wastewater treatment plants using sedimentation and dewatering technologies (Fytili and Zabaniotou, 2008). Food and organic waste are gathered through municipal or commercial collection systems, which may include source separation and anaerobic digestion pre-treatment facilities (Bacenetti et al., 2021). Post-consumer and industrial waste often require preprocessing to remove non-biodegradable or contaminated fractions, employing screening, shredding, and drying technologies (Makarichi et al., 2018). Reliable and traceable collection systems are essential to ensure the quality and safety of the biomass stream and to comply with environmental and health regulations (Olsson et al., 2020).

c2) Transport logistics for waste biomass vary depending on the physical state and contamination risk of the material. Liquid or semi-solid feedstocks such as sludge or digestate require sealed tankers and may involve short-distance transport due to odor and biohazard risks (Werther and Ogada, 1999). Solid waste streams like organic residues or post-consumer biomass are typically transported via containerized trucks or compactor vehicles (Zhou et al., 2022). To reduce the environmental footprint and cost, decentralized pre-treatment facilities near waste sources are increasingly implemented, limiting the need for long-haul transport (Bacenetti et al., 2021). Special handling and documentation protocols are often mandated to ensure traceability and regulatory compliance, particularly when transporting hazardous or contaminated fractions (Fytili and Zabaniotou, 2008).

3.3.7. Microalgae and aquatic biomass

a) Land Preparation: Unlike terrestrial biomass types, microalgae and aquatic biomass cultivation does not require traditional land preparation. Instead, the selection and construction of suitable aquatic systems is the foundational step. These systems include open raceway ponds, vertical panel reactors, and closed photobioreactors, which can be installed on non-arable land or integrated into marine or industrial environments. Site selection considers solar exposure, access to CO_2 and nutrients, water availability, and potential for co-location with industrial point sources. Where marine biomass is targeted (e.g., seaweed), nearshore installation sites with appropriate current, depth, and nutrient dynamics are identified and permitted under local regulations (Milledge et al., 2020).

b) Feedstock cultivation: Microalgae and other aquatic biomass species are cultivated under controlled nutrient, light, temperature, and pH conditions to optimize growth and biochemical composition. The specific cultivation method—whether open pond or photobioreactor—affects productivity, contamination risk, and scalability. Chlorella and Spirulina, for example, are widely grown under autotrophic or mixotrophic conditions for high lipid or protein yields, depending on the target product (Khan et al., 2018). In seaweed systems, such as those cultivating Ulva or Laminaria, nutrient uptake from surrounding waters and growth rates are monitored seasonally. Cultivation systems may also integrate nutrient-rich effluents (e.g., from wastewater treatment) and flue gas as CO_2 source, creating synergistic systems with carbon removal co-benefits (Lage et al., 2018).

c) Biomass provision and collection:

c1) *Harvesting* and collection: Harvesting methods for microalgae and aquatic biomass vary depending on the organism and cultivation system. Microalgae are typically separated from water via flocculation, centrifugation, or membrane filtration, which account for a substantial portion of energy input in the biomass supply chain (Milledge et al., 2020). Seaweed and other macroalgae can be harvested manually or mechanically using boats equipped with rakes, cutters, or conveyor systems. Collection timing is aligned with maximum biomass yield and desired biochemical profiles. In marine systems, seasonal harvesting aligns with regional growth cycles and avoids ecological disturbances (Khan et al., 2018).

c2) Transport: Following harvesting, microalgal biomass is either dewatered on-site or partially dried before transport to reduce mass and volume. Transport options depend on proximity to processing facilities and moisture content of the biomass. In co-located systems such as industrial BECCS facilities, microalgae may be cultivated on-site to utilize point-source CO_2 and reduce transport requirements (Lage et al., 2018; Khan et al., 2018). In marine systems, seaweed is commonly transported via refrigerated trucks or barges, especially when intended for fermentation or biorefining.

3.3.8. Temporary storage options

After harvesting and transport, biomass feedstocks are often subject to temporary storage prior to conversion or pre-treatment. This step serves multiple functions, including buffer capacity for seasonal harvests, supply-chain coordination, moisture control, and the preservation of biomass quality. While earlier stages in the process chain are highly feedstock-specific, temporary storage strategies tend to converge across biomass types and are therefore described collectively in this section.

Closed storage systems are commonly applied across various feedstock categories to protect biomass from microbial degradation, nutrient loss, and rehydration. Covered silos, airtight containers, or tarpaulin-covered stacks are typically used for sugar-rich biomass and herbaceous crops, where sugar degradation and fermentation risks are particularly high. In these cases, rapid spoilage can occur if ambient moisture is not effectively controlled, and storage duration must be minimized (Karp et al., 2022).

For oil- or fat-rich biomass types, such as lipid-containing algae or food processing residues, temperature-controlled storage may be necessary to prevent oxidation, rancidity, and microbial contamination. These materials are sensitive to thermal and microbial processes that compromise both carbon content and suitability for downstream conversion (Khan et al., 2018; Zhou et al., 2022).

Dried forest biomass, including forest residues and short-rotation coppice, is often stored in ventilated open yards. These facilities promote air circulation, reduce moisture content, and allow for effective bulk handling. When properly managed, logs, branches, and woodchips can be stored for extended periods with limited quality loss. However, prolonged exposure may lead to microbial activity, carbon loss, and in rare cases, self-heating and combustion (IPCC, 2022; Slade et al., 2014).

Storage requirements for waste biomass vary substantially based on its physical state and contamination level. Sewage sludge and digestate, for example, require containment strategies that minimize emissions, leachate, and odor. Liquid fractions are generally held in sealed anaerobic tanks, while solid components are placed in enclosed or covered areas with drainage and emission control systems (Tambone et al., 2010; Bacenetti et al., 2021).

Wetland biomass from paludiculture systems presents unique challenges due to its high-water content and risk of anaerobic degradation. Mechanical drying is rarely feasible, and biomass must often be processed quickly or temporarily held in open or semi-covered storage with minimal retention time. These systems also bear a risk of methane emissions during holding periods, particularly under anaerobic conditions (Tiemeyer et al., 2020).

Microalgae and aquatic biomass exhibit very limited storage stability. Their high-water content and microbial sensitivity make rapid processing essential. Short-term refrigerated storage or cool tanks are sometimes used to delay degradation for several hours to a few days, depending on species and environmental conditions. However, long-term storage is typically avoided unless the biomass is pre-processed via drying, lipid extraction, or fermentation within a controlled timeline (Milledge et al., 2020).

Across all biomass categories, storage infrastructure must be aligned with the physical and biochemical characteristics of the feedstock and the logistical requirements of downstream processes. Design and management of storage systems have substantial implications for greenhouse gas emissions, material losses, and the overall life cycle performance of BECCS pathways (Cherubini et al., 2009; Hanssen et al., 2020). The different pre-treatment pathways are illustrated in Figure 4.

3.4 Pre-treatment Methods

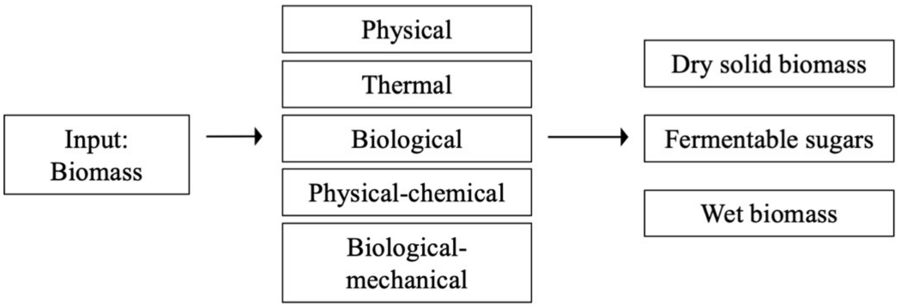


Figure 4. Feedstock-specific pre-treatment pathways. The diagram illustrates the main categories of pre-treatment processes—physical, thermal, and biological—applied to biomass feedstocks in BECCS systems. These processes transform raw biomass into standardized intermediate forms, including dry solid biomass, wet biomass, and fermentable sugars. The resulting intermediates determine the suitability of biomass for subsequent conversion pathways.

After temporary storage, each biomass type enters a specific pre-treatment pathway. The required operations depend on physical and chemical properties and are selected to meet the input conditions of the chosen conversion process. This step ensures that moisture content, particle size, and composition are compatible with downstream requirements for processes such as fermentation, gasification, pyrolysis, anaerobic digestion, or combustion.

The process chain reflects this branching structure by listing dedicated pre-treatment routes for each feedstock category. The following sections describe the corresponding operations for each feedstock category in the order shown in the process chain: forest biomass, sugar-rich biomass, starch-rich biomass, herbaceous biomass (including wetland biomass), waste biomass, and microalgae and aquatic biomass. The following sections describe the respective operations for each category based on their role in the process chain.

3.4.1 Forest Biomass – Pre-treatment

Following temporary storage, the selection of appropriate pre-treatment steps for forest biomass depends on both the intended conversion method and specific feedstock characteristics such as moisture content, particle size, and lignin composition. In the process chain, two categories of pre-treatment are identified for this biomass type: physical and thermal.

Physical pre-treatment typically includes sorting, shredding, drying, and pelletizing. These operations are applied either individually or in combination to improve material homogeneity and energy density, reduce moisture content, and ensure compatibility with downstream systems. For instance, shredding and sorting are essential to eliminate oversized fractions or contaminants that may interfere with combustion or gasification (IPCC, 2022). Drying and pelletizing further stabilize the feedstock and enhance storage and transport efficiency, but their necessity depends on the type of combustion system used. As noted in the accompanying process information, pelletizing and drying depend on the type of combustion system (e.g., fluidized bed vs grate firing) and on feedstock properties (Biswas et al., 2014). Thermal pre-treatment, such as torrefaction, may be applied when high energy density, improved grindability, and hydrophobicity are required. Torrefaction involves heating the biomass in an oxygen-deprived environment at temperatures between 200 and 300 °C, resulting in partial devolatilization and mass loss, but improved storage properties and combustion behavior (Prins et al., 2006; Bach and Skreiberg, 2021). This approach is particularly beneficial for gasification pathways that require a homogenous, low-moisture input material.

The process diagram does not prescribe a fixed sequence but rather highlights typical operations applicable to forest biomass. The decision to apply physical or thermal pre-treatment—or a combination of both—is made based on the conversion method selected and the properties of the harvested biomass. Moisture content, in particular, acts as a key determinant, influencing not only the pre-treatment requirements but also the efficiency and emissions profile of the subsequent conversion step (Kärkkäinen et al., 2021; Slade et al., 2014).

3.4.2 Sugar-rich Biomass - Pre-treatment

Sugar-rich biomass—such as sugarcane, sugar beet, or high-sugar-content residues—is typically subjected to physical and biological pre-treatment steps prior to conversion. The primary goal is to preserve sugar integrity and prepare the material for biochemical processing pathways such as fermentation.

The physical pre-treatment involves sorting, shredding, drying, and optionally pelletizing. Drying reduces microbial degradation and stabilizes the feedstock for transport or storage. Pelletizing is not mandatory and is usually applied when bulk density needs to be increased or transport over longer distances is required. The order of these steps is not strictly fixed; it depends on downstream process requirements and the initial feedstock condition.

The biological pre-treatment consists of enzymatic hydrolysis, which breaks down complex carbohydrates into fermentable monosaccharides. This step increases the availability of sugars for subsequent conversion processes and is a critical interface between raw biomass and fermentation-based carbon dioxide removal.

Both types of pre-treatments are selected based on feedstock moisture, contamination, and processing pathway. Where high sugar content is to be preserved, enzymatic hydrolysis follows immediately after mild physical pre-processing, ensuring minimal loss and maximum conversion efficiency.

3.4.3 Starch-rich Biomass – Pre-treatment

Starch-rich biomass, including feedstocks such as potatoes, maize, or cereal grains, typically undergoes a combination of physical and biological pre-treatment steps. Initial mechanical processing such as milling or grinding is commonly applied to increase surface area and improve accessibility of starch granules. This is followed by enzymatic hydrolysis using amylolytic enzymes to convert starch polymers into fermentable sugars under controlled temperature and pH conditions. These steps are essential to ensure high conversion efficiency and are particularly relevant for BECCS pathways that rely on fermentation for ethanol or other biofuels (Mosier et al., 2005; Karp et al., 2022).

The resulting product is classified as fermentable sugars and is then transferred to the selected conversion route. As with sugar-rich biomass, this pathway can enable high carbon conversion rates with comparatively low pre-processing energy requirements. Consistency in sugar yield and low contamination are key performance factors that determine the effectiveness of this pathway within BECCS systems.

533.4.4 Herbaceous Biomass – pre-treatment

Herbaceous biomass, including feedstocks such as straw, miscanthus, grassland, and wetland residues, follows two pre-treatment pathways: a physical-chemical route and a thermal route, as indicated in the process chain diagram.

The physical-chemical pre-treatment comprises sorting, shredding, drying, and pelletizing. These operations are used either in sequence or individually, depending on the specifications of the downstream conversion method. Sorting removes non-biomass impurities and standardizes particle size. Shredding increases surface area for drying or reaction efficiency. Drying lowers moisture content to improve storage stability and combustion properties, while pelletizing increases bulk density and transportability. Although pelletizing is shown as a typical step in the diagram, it remains optional and is applied primarily when required by the transport infrastructure or the type of combustion or gasification unit (e.g., fluidized bed vs. grate systems) (Bach and Skreiberg, 2021; Biswas et al., 2014).

The thermal pre-treatment pathway involves torrefaction, a mild pyrolytic process conducted under low-oxygen conditions at 200–300 °C. This step enhances grindability, hydrophobicity, and energy density of the biomass, which is especially relevant for thermochemical conversion routes such as combustion or gasification (Prins et al., 2006; Bach and Skreiberg, 2021). The decision to apply torrefaction depends on the target output and the need for improved handling and storage.

Both pre-treatment routes prepare herbaceous biomass for downstream thermochemical conversion, depending on feedstock condition and system requirements. The process diagram does not prescribe a fixed order of operations but emphasizes flexibility based on conversion technology and biomass condition. Pelletization and drying depend on system requirements and feedstock composition (Basu, 2018).

3.4.5 Waste Biomass – Pre-treatment

Waste biomass, including sewage sludge, industrial residues, digestate from anaerobic digestion, and post-consumer organic materials, generally requires a tailored pre-treatment strategy due to its heterogeneous composition and variable contamination levels. In the process chain, two categories of pre-treatment are identified for this feedstock: physical and biological.

Physical pre-treatment comprises sorting, shredding, drying, and in some cases pelletization. Sorting and shredding remove non-biodegradable or contaminated fractions and standardize particle size, thereby improving homogeneity and handling. Drying is applied to reduce microbial activity and stabilize the biomass, especially for high-moisture fractions such as sludge. Pelletization is not obligatory but can be employed to increase bulk density and facilitate storage or transport, particularly when downstream systems rely on uniform input material (Makarichi et al., 2018; Bacenetti et al., 2021).

Biological pre-treatment includes microbial leaching and enzymatic hydrolysis. Microbial leaching is primarily used to reduce heavy metals and other hazardous compounds in sewage sludge, improving its suitability for energy recovery (Fytili and Zabaniotou, 2008). Enzymatic hydrolysis is applied to convert complex polymers in organic waste into simpler, fermentable substrates. This step enhances biodegradability and increases the efficiency of subsequent conversion pathways such as anaerobic digestion or fermentation (Olsson et al., 2020; Zhou et al., 2022).

The choice and sequence of pre-treatment operations depend on the waste stream's origin, moisture content, and contamination risk. While sewage sludge often requires both dewatering and microbial stabilization prior to further processing, food waste may undergo only shredding and hydrolysis before entering biochemical conversion. In all cases, pre-treatment serves to reduce environmental risks and prepare heterogeneous residues for integration into BECCS conversion technologies.

3.4.6 Microalgae and Aquatic Biomass – Pre-treatment

Microalgae such as Chlorella and Spirulina follow two pre-treatment routes in the process chain, a physical and a biological route, and there is an additional direct path in which untreated wet biomass proceeds to anaerobic digestion without drying or pelletization (Milledge et al., 2020).

The physical route comprises conditioning steps such as sorting, shredding or fractionation, drying, and optional pelletization, depending on the requirements of the downstream conversion pathway. Pelletization is optional and applied only when required by transport or storage logistics, while drying is essential for thermochemical routes due to the very high moisture content of algal biomass (Milledge et al., 2020; Khan et al., 2018).

The biological route consists of enzymatic hydrolysis, which disrupts cell walls and releases fermentable carbohydrates, improving yields in fermentation and anaerobic digestion. The connection to the Fermentable Sugars node applies only if sugar-rich algae are used, as indicated in the diagram.

Microalgal cultures typically contain very little dry matter, so dewatering is often the dominant energy input prior to conversion. Minimal preparation for the ‘untreated wet biomass → anaerobic digestion’ route may be limited to simple separation to ensure pumpability (Milledge et al., 2020). Macroalgae are being explored for thermal and biochemical routes, but large-scale BECCS deployment pathways remain insufficiently demonstrated. This framework therefore focuses on microalgae as the currently better characterized operational pathway (Khan et al., 2018). The overall routing of biomass through thermochemical and biochemical conversion pathways, including the separation into distinct conversion gateways, is illustrated in Figure 5. Waste-derived fuels and residues can enter both pathways depending on their composition and level of pre-treatment.

3.5 Conversion processes: routing, transport and outputs

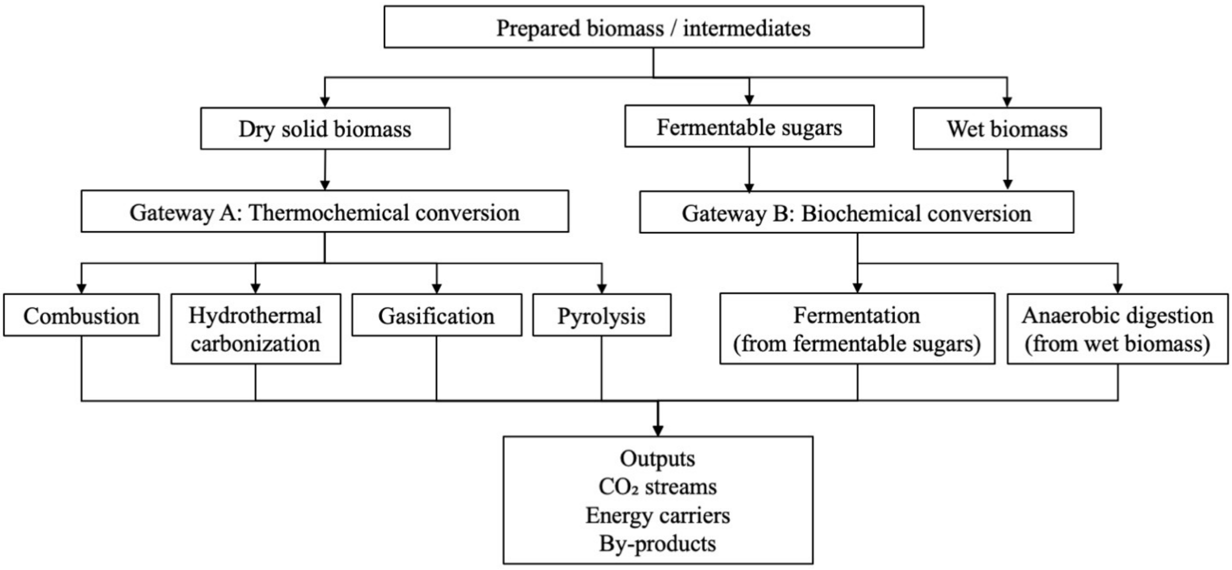


Figure 5. Conversion gateways of the BECCS process chain. The diagram distinguishes two main conversion routes: Gateway A comprises thermochemical pathways, including combustion, hydrothermal carbonization, gasification, and pyrolysis, while Gateway B represents biochemical pathways, including fermentation and anaerobic digestion. Fermentation is applied to fermentable sugars, whereas anaerobic digestion processes wet biomass. The conversion processes generate CO_2 streams, energy carriers, and by-products, which are directed to subsequent upgrading and management stages. Waste-derived fuels and residues may enter both thermochemical and biochemical pathways depending on their composition and level of pre-treatment.

Once a conversion method is selected, the process chain branches into two technical gateways. Gateway A directs dried or pelletized biomass into thermochemical conversion processes, while Gateway B covers fermentable sugars that are routed to biochemical conversion, and untreated wet biomass for anaerobic digestion (Kothari et al., 2010; Mata-Alvarez et al., 2014). Across both routes, CO_2-containing gas streams are transferred to the *Product Upgrading and* CO_2 module, where the gas streams undergo cleaning, conditioning, and compression prior to the transport and long-term storage of CO_2. In parallel, co-products are directed to *By-Product Management*, while residual flue gases that are not fully captured are monitored under *Outputs from Combustion*. This routing structure reflects established technology linkages and experience from pilot and commercial facilities (Raganati et al., 2024; IPCC, 2024).

3.5.1 Thermochemical conversion (Gateway A)

Thermochemical conversion includes combustion, hydrothermal carbonization, pyrolysis, and gasification. These processes operate at elevated temperatures under low-oxygen or pressurized conditions and are generally suited for dry feedstocks such as forest biomass and herbaceous biomass with low moisture content, although hydrothermal carbonization is specifically designed for high-moisture feedstocks (Funke and Ziegler, 2010; Libra et al., 2011). Combustion is the most established thermochemical pathway and is applied either in direct power generation or combined heat and power systems. It is suitable for dry feedstocks such as forest biomass, pelletized herbaceous material, or selected well-characterized waste fractions (IPCC, 2022). Flue gases are treated by post-combustion CO_2 capture, after which the CO_2 is routed to *Product Upgrading and* CO_2 for conditioning (Raganati et al., 2024). Residual ash is managed under *By-Product Management*, while remaining flue gases are reported in *Outputs from Combustion*.

Hydrothermal carbonization (HTC) operates between 180 and 280 °C under autogenous pressure and is designed for high-moisture feedstocks such as sewage sludge, agricultural residues, and algae (Petrović et al., 2024; Owsianiak et al., 2024).

It primarily produces a solid hydrochar phase, along with an aqueous phase and minor gaseous products, the latter containing mainly CO_2 with smaller fractions of CO, H_2 and CH_4. When separated and captured through pressure swing adsorption, membranes, or chemical absorption, the CO_2 stream is directed to *Product Upgrading and* CO_2 for compression and storage (Abd et al., 2024; Gkotsis et al., 2023). HTC also generates hydrochar, which can be combusted or gasified internally to provide process energy or externally managed as a by-product. The aqueous phase requires treatment before reuse or disposal. Although HTC avoids the need for prior drying, its continuous heat demand remains a challenge, partly mitigated by internal energy recovery from gaseous or solid fractions (Funke and Ziegler, 2010; Libra et al., 2011).

Pyrolysis decomposes biomass in the absence of oxygen, producing bio-oil, biochar, and non-condensable gases. Vapors and oils are typically combusted or upgraded, enabling CO_2 capture downstream, while biochar and liquid condensates are directed to *By-Product Management*. Biochar is also recognized as a potential durable carbon sink in negative-emission portfolios (Deng et al., 2024). In some systems, pyrolysis can constitute an intermediate stage in gasification processes, preceding oxidation and reduction steps (Basu, 2018).

Gasification converts dried or pelletized feedstocks into a syngas mainly composed of CO and H_2, with smaller fractions of CO_2 and CH_4. The syngas is cleaned and conditioned, often including a water–gas shift reaction to convert CO to CO_2 and H_2, before CO_2 is separated and captured as a pre-combustion stream and routed to *Product Upgrading and* CO_2 (Basu, 2018). Char, tar, and slag fractions are transferred to *By-Product Management*.

3.5.2 Biochemical conversion (Gateway B)

Biochemical conversion comprises fermentation and anaerobic digestion. It primarily processes fermentable sugars derived from sugar-rich and starch-rich biomass, while anaerobic digestion additionally treats wet biomass streams such as manure, sewage sludge, and food waste (Mata-Alvarez et al., 2014).

These streams are transported in sealed liquid systems such as food-grade tank trucks, ISO tank containers, or rail tank cars. The primary route is fermentation, in which sugars and starches are converted to ethanol. The fermentation off-gas is a high-purity CO_2 stream that can be dehydrated and compressed at relatively low energy demand (Fajardy and Mac Dowell, 2017; Boot-Handford et al., 2014).

In addition, residues from fermentation can be routed to anaerobic digestion, producing biogas from which CO_2 is separated and directed to *Product Upgrading and CO_2* (Salas et al., 2024). Anaerobic digestion additionally processes wet biomass streams such as manure, sewage sludge, food waste, and algal residues.

Depending on contamination level and solids content, these materials may undergo targeted pre-treatment steps prior to anaerobic digestion—typically including removal of physical contaminants, adjustment of water content, and, where required, hygienisation or mild hydrolysis to enhance biodegradability. Thermal drying or torrefaction are generally avoided due to their high moisture content (Mata-Alvarez et al., 2014; Cesaro and Belgiorno, 2023). These feedstocks are typically transported via slurry trucks, pumps, or pipelines to anaerobic digesters. The process produces biogas consisting mainly of CH_4 and CO_2. Internal pipelines transfer the gas to upgrading units, where CO_2 is separated and routed to *Product Upgrading and CO_2 Compression and Storage*. Upgraded biomethane is supplied as an energy product, while digestate is transferred to *By-Product Management*.

3.6. Product Upgrading and CO_2 Streams

This module integrates gas cleaning, CO_2 separation, purification, and compression steps required to prepare captured carbon dioxide for transport and geological storage. After conversion, the CO_2-rich streams produced across all pathways form the key link between biomass conversion and subsequent CO_2 conditioning, transport, and geological storage. Their treatment begins with CO_2 cleaning and purification, followed by compression to meet the pressure and purity requirements for transport and permanent storage (Thiedemann et al., 2025). This step defines the physical state and readiness of captured CO_2 for injection and monitoring within geological formations.

In hydrothermal carbonization, process streams, including a minor gaseous fraction containing CO_2, CH_4, CO and H_2 are separated using pressure-swing adsorption, membrane separation or chemical absorption, before the CO_2 fraction is compressed (Funke and Ziegler, 2010; Libra et al., 2011). CO_2 is separated primarily through absorption-based processes, with adsorption and cryogenic methods applied in specific cases, while remaining flue gas fractions that are not fully captured are reported as monitored outputs (Boot-Handford et al., 2014; Rochelle, 2009).

Gasification produces a syngas composed mainly of CO and H_2, which is subjected to cleaning and conditioning, often including a water–gas shift reaction, before CO_2 is separated and compressed (Leung, Caramanna, and Maroto-Valer, 2014; Boot-Handford et al., 2014). These thermochemical routes align with established biomass-to-liquid (BtL) and biomass-to-X (BtX) system architectures used in renewable-fuels design, where cleaned syngas can be directed toward methanol synthesis, Fischer–Tropsch fuels, or hydrogen separation before CO_2 is captured and routed to geological storage. Fermentation produces a high-purity CO_2 stream that can be dehydrated and compressed with relatively low energy demand (Fajardy and Mac Dowell, 2017; Boot-Handford et al., 2014; Lefvert and Grönkvist, 2023).

Parallel to CO_2 handling, the upgrading stage refines the remaining energy carriers to specification for fuel use or grid integration.

Biogas from anaerobic digestion is upgraded to biomethane through CO_2 separation, or alternatively combusted with subsequent CO_2 capture, while hydrogen derived from gasification can be separated as an energy carrier or further processed into synthetic fuels such as methanol or Fischer–Tropsch products. (Ryckebosch, Drouillon, and Vervaeren, 2011; Sun et al., 2015; Boot-Handford et al., 2014).

Hydrochar generated during hydrothermal carbonization may either be combusted with CO_2 capture to supply process heat or used in material applications, depending on its physicochemical properties and contamination levels (Funke and Ziegler, 2010; Libra et al., 2011).

Upgrading also produces by-products—including digestate, ash, slag, tar, and biochar—that require additional management to support resource efficiency and ensure environmental performance. These side streams, represented in adjacent modules of the process chain, fall outside the core BECCS conversion sequence but influence downstream circular economy opportunities, industrial utilization pathways and MRV-related reporting obligations (Lück et al., 2025). Similarly, combustion processes generate energy outputs such as heat and electricity, as well as monitored flue-gas fractions, which form part of the extended system inventory but not the primary upgrading logic of BECCS.

This stage connects directly to the subsequent CO_2 transport and storage module, where infrastructure, routing options, storage permanence and leakage-risk considerations are addressed in greater detail (Bellamy and Lezaun, 2019; Morrow et al., 2020). The downstream integration of CO_2 compression, transport, and storage is illustrated in Figure 6. The figure highlights how technical infrastructure is linked with governance, monitoring, and verification requirements across the final stages of the BECCS process chain.

3.7. CO_2 Transport and Storage

The downstream integration of CO_2 compression, transport, and storage is illustrated in Figure 6. The figure highlights the connection between technical infrastructure and monitoring, reporting, and verification (MRV) requirements in the final stage of the BECCS process chain. This final stage completes the BECCS system by linking biomass conversion processes to permanent carbon storage and associated regulatory frameworks.

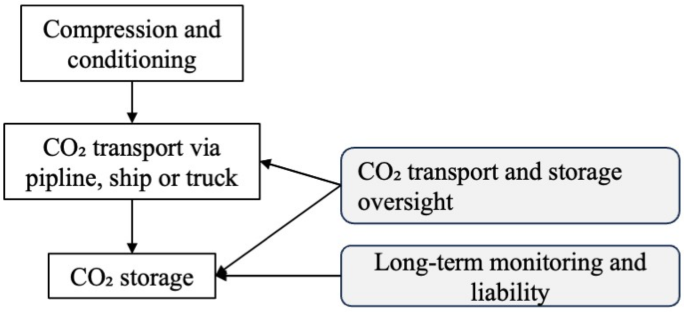


Figure 6. CO_2 transport and storage pathways in BECCS systems. The figure illustrates the downstream process from CO_2 compression and conditioning to transport via pipeline, ship, or truck, and subsequent geological storage. In parallel, governance and monitoring elements—including transport and storage oversight as well as long-term monitoring and liability—are represented as cross-cutting components that ensure system integrity and permanence.

After compression, the captured CO_2 is directed to transport and storage infrastructures that enable long-distance transfer and permanent storage, which together form the downstream component of the BECCS system. Pipelines constitute the dominant mode for transporting large volumes because of their cost efficiency, high capacity and technical maturity for industrial-scale applications (IPCC, 2022). For coastal or international routes, liquefied CO_2

can be shipped at intermediate pressures and low temperatures, although this option requires additional cooling and conditioning prior to loading (IPCC, 2022). In situations with limited infrastructure or small processing facilities, transport by truck or rail may be applied, even though these modes are less suited to the scales required for BECCS (Zakkour et al., 2020).

Geological storage takes place in deep formations at depths typically greater than eight hundred meters, where CO_2 exists in a supercritical state and becomes immobilized through multiple trapping mechanisms, including structural, residual, solubility and mineral trapping (Bachu, 2022). Deep saline aquifers account for the largest global storage potential, while depleted oil and gas fields offer additional advantages because well-characterized reservoirs facilitate risk assessment and require fewer exploratory surveys (IPCC, 2022). In addition to these conventional options, mineral carbonation in basaltic or ultramafic formations can provide highly permanent storage, although these pathways are constrained by location and slower reaction kinetics (Bui et al., 2018).

Across all pathways, the upgrading stage links directly to the transport-and-storage module through compression, which ensures that CO_2 streams meet the purity and pressure thresholds required for injection (Zakkour et al., 2020). This connection establishes the link between conversion facilities and geological storage, enabling the long-term removal of biogenic CO_2 from the atmosphere. As governance and MRV requirements increase at the storage stage, issues such as well integrity, reservoir performance, leakage detection and storage permanence are addressed under dedicated regulatory frameworks and are treated in detail in the cross-cutting MRV section of this paper.

3.8 Societal Dimensions

Societal dimensions are considered cross-cutting elements within the BECCS process chain. Unlike technical modules that operate sequentially, participation and societal perspectives intersect with multiple stages of the system. During land preparation and cultivation, participatory planning can mitigate conflicts over land use and enable recognition of co-benefits such as biodiversity conservation and rural development. In the conversion and product upgrading phases, societal involvement may shape technology choices, infrastructure deployment, and local employment opportunities. For CO_2 transport and storage, stakeholder engagement and transparent governance are essential to address concerns regarding safety, monitoring, and long-term liability. These societal dimensions are therefore embedded as a transversal component of the process chain, complementing technical considerations with societal and institutional factors (Bellamy et al., 2019; Morrow et al., 2020).

3.9 MRV as a Cross-Cutting Framework in BECCS

Monitoring, reporting and verification (MRV) provide a cross-cutting governance framework that interfaces with multiple modules of the BECCS process chain and supports the integrity of carbon-removal claims across diverse geographic contexts, including local land management, regional regulatory environments, and global accounting standards.

Because BECCS integrates biological biomass systems, biochemical and thermochemical conversion, engineered CO_2 capture, transport and geological storage, the MRV architecture must accommodate heterogeneous data streams and regulatory conditions across local, regional, national, and international levels. This multilayered structure ensures that carbon flows can be traced, audited and certified in alignment with global climate policy frameworks while remaining compatible with region-specific legislation (IPCC, 2022; ISO 27914, 2019; ISO 27915, 2019).

At the local level, sustainable land use, biomass supply traceability and societal acceptance form critical entry points for MRV. Local permitting regimes, community engagement processes and environmental impact assessments shape land-preparation and cultivation practices, thereby influencing associated emissions and the biogenic carbon baseline of a BECCS system (Bellamy and Lezaun, 2019; Carton et al., 2020). Regional supply-chain governance ensures that harvested biomass is documented through chain-of-custody systems, transport emissions are monitored and local feedstock conditions are included in MRV boundaries (Souza et al., 2015; IPCC, 2022). In a European context, for example, the Renewable Energy Directive II/III and the EU Sustainability Criteria govern feedstock eligibility; meanwhile, national biomass-certification systems (e.g., Netherlands SBP) exemplify regional traceability frameworks.

At the regional level, the example of the European Union illustrates how global MRV principles can be translated into binding regulation. The EU Carbon Removal Certification Framework (CRCF, 2023) introduces detailed requirements for monitoring uncertainties, defining removal system boundaries, and certifying permanence. The EU CCS Directive (2009/31/EC) sets out well-integrity, long-term liability and monitoring obligations for geological storage, which are directly relevant to BECCS operations in Europe. In North America, the U.S. EPA Class VI well permitting rules together with the 45Q tax-credit monitoring requirements represent a mature MRV system for CO_2 injection and storage, which BECCS projects must incorporate. These regional variations demonstrate that MRV frameworks can adapt to different governance contexts while maintaining global comparability.

Downstream of conversion, MRV becomes increasingly architecture-intensive as it covers upgrading, compression, transport, and storage. During pre-treatment and conversion, mass and energy balances, CO_2-stream purity, flue-gas composition, and separation efficiencies determine the amount of biogenic carbon captured and must be documented for accurate removal accounting (IPCC, 2022; Smith et al., 2023). By-product streams—including digestate, ash, slag, tar and biochar—must be incorporated into MRV systems to avoid unaccounted carbon liabilities and to maintain a transparent material-flow record (Woolf et al., 2021; Buchspies and Kaltschmitt, 2020). At the upgrading stage, MRV interfaces with carbon market mechanisms, fuel quality verification and the issuance of removal credits: operators must demonstrate verified carbon-intensity reductions, traceability of energy carriers and secure certification of negative emission status.

The transport and storage domains represent the critical end-points of MRV systems, where governance, safety protocols and long-term permanence become binding. Transport-related emissions from compression, shipping, or pipeline transfer must be included in the system balance, while storage monitoring requires seismic surveys, pressure logging, tracer tests, and site-integrity verification in compliance with ISO standards and regional regulations (IPCC, 2022; Morrow et al., 2020). In Europe, MRV practices must conform to both EU CCS Directive requirements and the CRCF's permanence reporting rules. In the U.S., ongoing monitoring under the EPA's Class VI regime sets a benchmark for long-term injection site surveillance. Globally, frameworks such as the ISO standards and the IPCC guidelines provide consistency and comparability between projects across jurisdictions.

By integrating local feedstock governance, regional regulatory frameworks and global accounting norms into a coherent verification architecture, the MRV system provides a robust foundation for certifying carbon removals, aligning BECCS operations with both market mechanisms and climate policy obligations. It ensures that BECCS projects are not only technically operational but also socially legitimate, legally compliant and globally comparable—thereby supporting consistent assessment and comparability across deployment contexts.

3.10. By-Product Management

By-product management is linked to the conversion module within the process chain, representing secondary flows that accompany energy and CO_2 streams but do not constitute the core removal pathway. These include solid residues such as ash from combustion, slag and tar from gasification, and biochar from pyrolysis and gasification, which may be stored or utilized in material applications. Liquid by-products arise from hydrothermal carbonization in the form of water streams requiring treatment or reuse, and from pyrolysis as oils and condensates. Anaerobic digestion yields digestate, while fermentation produces residues such as distiller's grains and nutrient-rich fractions that can serve as fertilizer or co-substrates if regulatory standards are met (e.g., related to hygiene, heavy metal contents). These standards vary regionally and strongly influence whether by-products are considered valuable resources or liabilities (IPCC, 2022; Bui et al., 2018). Collectively, these flows are managed to minimize environmental burdens and, where possible, to create additional value, for instance through nutrient recycling, energy recovery, or material substitution (Funke and Ziegler, 2010; Cesaro and Belgiorno, 2023; Libra et al., 2011; Raganati et al., 2024).

4. Discussion

4.1 Technical integration and efficiency trade-offs

The modular process chain highlights that technical feasibility in BECCS is determined not only by conversion efficiencies but also by the integration of supporting processes across the system. Hydrothermal carbonization, for example, remains highly energy-demanding, and although internal energy recovery from gaseous fractions and hydrochar can partially offset heat requirements, net efficiency is contingent on access to low-carbon energy sources (Funke and Ziegler, 2010; Libra et al., 2011). Coupling HTC with industrial waste heat or renewable energy inputs therefore represents a key innovation pathway. Similarly, upgrading and CO_2 capture stages increasingly benefit from material advances, such as the CALF-20 sorbent series for pressure swing adsorption in biogas upgrading, which improves methane recovery while lowering energy penalties (Shin et al., 2025). Beyond capture performance, the system-level efficiency of BECCS depends on integration with optimized CO_2 transport chains. Recent modelling of multi-modal CO_2 transport networks shows that combining pipelines, ships, trucks, and trains in shared infrastructures can lower overall costs and emissions compared to single-mode configurations. These insights underscore the importance of treating conversion, upgrading, and transport as interdependent stages rather than isolated units.

4.2 Governance and societal legitimacy

A recurring challenge across BECCS pathways relates to societal acceptance and legitimacy. Public trust in CO_2 transport corridors and geological storage sites has been shown to be a precondition for deployment (Bellamy et al., 2019; Morrow et al., 2020). Moreover, concerns around land use competition, biomass sourcing, and fairness strongly shape societal perceptions of BECCS (Fridahl, 2017; Gough and Mander, 2019). Governance frameworks must therefore be reflexive and adaptive, embedding participatory processes from early stages onward. As Bellamy et al. (2017) note, governance approaches for carbon removal technologies must be “reflexive, inclusive and adaptive to local contexts” (p. 196). The modular process chain makes such entry points visible by integrating decision nodes for feasibility, desirability, societal considerations, and MRV. Policy frameworks such as the European Renewable Energy Directive III (RED III) provide enabling conditions by recognizing removals under sustainability criteria (European Commission, 2023), thereby linking BECCS deployment to broader decarbonization strategies.

4.3 Research gaps and innovation pathways

Despite significant progress in system integration, several uncertainties remain. Life-cycle assessments consistently show that compression energy, transport emissions, and storage leakage risks must be included to avoid overestimating net removals (IPCC, 2024). While MRV protocols for fermentation and biogas upgrading are increasingly standardized (IPCC, 2022, Smith et al. 2021), comparable frameworks for emerging pathways such as hydrothermal carbonization or pyrolysis remain under development. Aquatic biomass exemplifies both opportunity and uncertainty. While microalgae cultivation has demonstrated compatibility with fermentation and anaerobic digestion (Khan et al., 2018), macroalgae pathways remain excluded from operational BECCS due to the lack of verified CDR permanence and MRV protocols. These feedstocks may represent innovation pathways but cannot yet be counted toward durable removals. Similar gaps exist in the treatment of heterogeneous waste streams, where regulatory standards determine whether residues are valorized as resources or treated as liabilities (Olsson et al., 2020; Bacenetti et al., 2021).

Another uncertainty arises from hard-to-estimate costs related to BECCS processes. Because of the lack of large-scale testing of the coupling of bioenergy, carbon capture units, and storage sites, BECCS costs are usually given in wide ranges (Thrän et al., 2025). More robust cost estimates will likely emerge once BECCS facilities become operational and cost estimates can be based on real-life examples instead of modeling. Additional research needs have also been highlighted in recent policy-oriented assessments focusing on MRV standardization and implementation challenges (DBFZ, 2024).

4.4 Contribution of the modular process chain

Compared to narrowly focused assessments, the process chain provides a structured representation that brings technical, logistical, and contextual considerations into a single, transparent framework. Its modular design clarifies how upstream feedstock choices influence downstream conversion, upgrading and storage options, and it indicates where MRV and governance considerations become relevant along the chain. Rather than analyzing or quantifying trade-offs, it offers a scaffold that helps users organize assumptions and identify decision points across different project scales and regional contexts. This function aligns with recent calls for tools that improve transparency and facilitate dialogue between conceptual modelling, sustainability constraints and governance requirements (Kazlou et al., 2024; Oh et al., 2025; Honegger et al., 2023).

By combining peer-reviewed literature with stakeholder insights, the process chain offers a structured lens that can support interdisciplinary dialogue and scenario-oriented discussions. It is particularly useful in participatory planning contexts, where clarity, adaptability and transparency help align expectations and identify early decision points for BECCS deployment. The modular representation also makes it easier to connect the chain with national system analyses, which increasingly emphasize the importance of transparent, assumption-based frameworks that reflect real system constraints such as biomass availability, conversion efficiencies, sustainability considerations and public acceptance. Recent German system studies underscore this need and highlight the wide uncertainty ranges associated with BECCS costs due to the absence of large-scale integration of carbon capture units and CO_2 transport and storage infrastructure (Thrän et al., 2025).

4.5 Observed barriers and lessons learned from BECCS deployment

4.5.1 Peer-reviewed evidence from global BECCS deployment

Peer-reviewed analyses of BECCS deployment show a persistent implementation gap between modelled global potentials and real-world projects. Multiple systematic reviews conclude that BECCS remains at a developmental stage, with only a limited number of industrial facilities operating at meaningful scale and none yet approaching the gigaton-level removals assumed in integrated assessment models. (Fajardy and Mac Dowell, 2017; Fuss and Johnsson, 2021). These findings underline that technological feasibility does not automatically translate into deployment feasibility, particularly in regions where infrastructural, regulatory, and social constraints interact strongly with biomass availability and conversion configurations. National system analyses for Germany similarly highlight that only a subset of bioenergy facilities is technically or geographically suitable for CO_2 capture and storage, despite significant biogenic carbon flows (Thrän et al., 2025).

One of the most mature categories of BECCS applications is fermentation-based CO_2 capture in the bioethanol industry. Peer-reviewed work on the Illinois Industrial CCS project reports high capture efficiencies from nearly pure fermentation streams, robust monitoring systems and well-characterized storage sites (Nelson et al., 2020; Middleton et al., 2020). Although this pathway exhibits strong technical performance, economic modelling indicates that scale-up remains contingent on substantial policy incentives and favourable siting, given the narrow industrial base and limited number of large bioethanol facilities (Sanchez et al., 2018).

A second body of evidence concerns biomass-fired combined heat and power plants. Analyses of planned BECCS retrofits at Drax in the United Kingdom assess the technical feasibility of integrating post-combustion capture into large biomass units (Bui et al., 2018). Critical assessments, however, point to substantial uncertainties related to lifecycle emissions, pellet supply chains, carbon debt and biodiversity risks associated with forest-biomass sourcing (Searchinger et al., 2018; Ter-Mikaelian et al., 2015). Taken together, these studies show that BECCS can deliver net-negative, near-neutral or even net-positive climate outcomes depending on conversion efficiency, feedstock type and land use dynamics.

Nordic district heating systems provide an additional peer-reviewed evidence base for BECCS integration. Studies evaluating the Stockholm Exergi concept suggest that large-scale BECCS at CHP facilities could deliver significant removals when paired with low-carbon electricity systems and offshore CO_2 storage, although high specific costs and uncertainties about long-term revenue streams remain central barriers (Zetterberg et al., 2021; Hanssen et al., 2020). Similar evaluations in the pulp and paper industry indicate that biogenic CO_2 streams can be integrated into capture processes, but that system-wide climate benefits are highly sensitive to energy balances, process configurations and the end-use of by-products (Karlsson et al., 2021).

Across peer-reviewed work, key systemic barriers recur: (1) competition for sustainable biomass, particularly residues; (2) geographical mismatch between emitters and storage sites; (3) high capital and operating costs under uncertain policy conditions; (4) lack of harmonized MRV frameworks and certification methodologies for carbon removal (e.g., the emerging EU Carbon Removal Certification Framework, CRCF) (European Commission, 2022); and (5) social acceptance challenges rooted in earlier CCS controversies (Gough and Mander, 2019; Tanzer and Ramírez, 2019). These findings collectively indicate that the primary barriers to BECCS deployment are not technological but systemic, spanning infrastructure, governance, sustainability criteria, and public legitimacy.

A further line of evidence stems from the IPCC Sixth Assessment Report (IPCC, 2022), which—although not peer-reviewed in the strict academic sense but subject to an extensive multi-stage scientific review—provides the most authoritative synthesis of BECCS pathways. The IPCC identifies lifecycle emissions, land-use dynamics and regional resource constraints as key determinants of BECCS sustainability, and that robust governance, MRV and land-sector safeguards are essential to deliver durable removals as synthesized in IPCC AR6 WGIII.

4.5.2 Non-peer-reviewed contextual evidence

In addition to peer-reviewed analyses, several real-world BECCS- and CCS-related initiatives provide contextual insights into practical and institutional aspects of BECCS deployment. The examples below are included solely for descriptive background; the information is based on operator reports, regulatory documents and technical summaries rather than peer-reviewed literature.

Large-scale CCS projects such as Sleipner (operational since 1996) and Quest (since 2015) demonstrate that geological CO_2 storage can function reliably under long-term monitoring frameworks. At the same time, setbacks at projects like Petra Nova in Texas—where operations were suspended in 2020 following economic and equipment-related difficulties—illustrate how capture and storage systems can be affected by fluctuating energy markets, reliability issues, and policy uncertainty. Although these cases do not involve BECCS, they highlight types of infrastructural and economic risks that may also arise in biomass-based systems.

Early BECCS-related proposals in Germany, including planned CO_2 storage pilots in Brandenburg and Schleswig-Holstein, did not progress beyond initial stages due to political resistance and local opposition, despite underlying technical assessments. These experiences suggest that public trust, perceptions of storage safety and the role of regional governance are critical factors shaping the feasibility of future BECCS deployment.

Although these non-peer-reviewed examples cannot serve as scientific evidence, they provide useful contextual background for interpreting the barriers identified in the peer-reviewed literature. They indicate that implementation challenges often stem from institutional coordination, long-term liability concerns and questions of social legitimacy—elements that align with the systemic constraints highlighted in Section 4.5.1.

Conclusions

Achieving net-zero and net-negative emissions will require not only rapid and sustained emission reductions but also the deployment of reliable carbon dioxide removal (CDR) technologies. BECCS is widely discussed as a key carbon dioxide removal option, as it combines renewable energy provision with the prospect of durable CO_2 sequestration (Fuss et al., 2018). At the same time, its realization depends on the alignment of technological, ecological, and societal dimensions.

This paper introduced a modular process chain that structures BECCS into transparent and systematically assessable stages, ranging from feasibility and desirability assessments through feedstock selection, biomass provision, pre-treatment, conversion, product upgrading, and CO_2 transport and storage. Developed within the German CDR-Atlas initiative, the process chain integrates insights from the scientific literature and stakeholder dialogue to provide a structured framework for early-stage planning and participatory assessment of BECCS pathways. Rather than prescribing specific deployment trajectories or simulating system dynamics, the framework offers a transparent logic for organizing assumptions, parameters, and stakeholder perspectives across different implementation contexts.

The process chain clarifies where BECCS technologies are comparatively mature, where they remain at pilot-scale readiness, and where societal participation, land-use considerations, and governance arrangements shape deployment potential. In doing so, it highlights that technological feasibility alone is insufficient for successful deployment. Instead, transparent governance structures, institutional coordination, and long-term liability frameworks are critical factors shaping the feasibility and long-term deployment of BECCS pathways (Bellamy et al., 2019; Morrow et al., 2020). Overall, the modular process chain provides a transparent and adaptable framework that supports interdisciplinary assessment, early-stage planning, and governance-oriented analysis of BECCS systems.

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Appendix 1: Terminology and Process Definitions

Anaerobic digestion describes the microbial breakdown of wet organic materials such as manure, food waste, or algae in oxygen-free environments, producing biogas. The CO_2 fraction in the raw biogas can be separated and stored, although robust process control is required to minimize fugitive methane emissions (Cesaro and Belgiorno, 2023).

Combustion refers to the direct burning of biomass in the presence of oxygen to generate heat or power. When coupled with CO_2 capture systems—typically post-combustion chemical scrubbing—this process can deliver net negative emissions if total life-cycle emissions remain below the amount of CO_2 captured (Fajardy and Mac Dowell, 2017).

Fermentation is a biochemical pathway in which sugar- or starch-rich biomass (e.g., sugarcane, maize) is converted by microorganisms into ethanol. During this conversion, high-purity CO_2 is released as a by-product, which is technically well suited for capture and storage (Searle and Malins, 2014; Sims et al., 2010).

Feedstocks in this study are grouped into four main categories. Agricultural biomass includes herbaceous crops, sugar-rich crops, and starch-rich crops cultivated as dedicated energy crops rather than as residues. Forest biomass covers wood residues and plantation material. Wetland biomass refers to paludiculture feedstocks such as reeds. Waste biomass encompasses municipal, industrial, and agricultural residues. Aquatic biomass comprises microalgae and seaweed. Each feedstock type aligns with specific conversion methods, for instance algae in anaerobic digestion or sugarcane in fermentation (Milledge et al., 2019; Li and Yao, 2024).

Gasification is a thermochemical process in which biomass is heated under low-oxygen conditions at temperatures typically above 700 °C, producing a synthesis gas composed mainly of carbon monoxide, hydrogen, and CO_2. This syngas can be upgraded into fuels or chemicals, while the CO_2 fraction is available for capture and permanent storage (Basu, 2018).

Hydrothermal carbonization (HTC) mimics natural coalification by converting wet biomass under moderate temperatures (180–280 °C) and elevated pressure into hydrochar. This process is particularly suitable for high-moisture feedstocks such as sewage sludge, agricultural residues, and algae (Cavali et al., 2023; Heidari et al., 2019).

Monitoring, Reporting and Verification (MRV) denotes the systematic measurement, documentation, and independent validation of CO_2 removals along the BECCS chain. Robust MRV frameworks are essential for transparency, performance assessment, and storage integrity. They must address the entire process chain, from biomass carbon accounting through capture efficiencies and transport losses to geological storage permanence (IPCC, 2024). Project methodologies illustrate how to quantify net removals in BECCS power and heat applications, including boundary setting, leakage accounting, and permanence tests, while policy analysis highlights cost drivers that influence scalability.

Pre-treatment processes prepare biomass for conversion and can be categorised into physical (size reduction, drying), physicochemical (steam explosion, acid treatment), mechanical (extrusion, pressing), biological (fungal or enzymatic treatments), and thermal (torrefaction, HTC). These steps improve feedstock properties and increase conversion efficiency (Mata-Alvarez et al., 2014).

Pyrolysis refers to the thermal decomposition of biomass in the absence of oxygen. Depending on process temperature and residence time, it yields varying proportions of biochar, bio-oil, and syngas. The biochar fraction can contribute to long-term carbon sequestration, although permanence and stability are strongly influenced by feedstock type and process parameters (Lehmann and Joseph, 2015; Woolf et al., 2021).

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