RESEARCH **Open Access**

Assessing BECCUS impacts on the SDGs through a value chain assessment for climate mitigation and energy transition

Joris Herbermann[1*], Bob van der Zwaan[2,3,4] and Drielli Peyerl[1,2*]

*Correspondence:
Joris Herbermann
jorisherbermann@gmail.com
Drielli Peyerl
d.peyerl@uva.nl
[1]Postgraduate Program in Environmental Science (PROCAM), University of São Paulo, São Paulo, Brazil
[2]Faculty of Science (HIMS), University of Amsterdam, Amsterdam, The Netherlands
[3]TNO, Energy and Materials Transition (EMT), Amsterdam, The Netherlands
[4]School of Advanced International Studies (SAIS), Johns Hopkins University, Bologna, Italy

Abstract
As the urgency for climate mitigation intensifies, Bioenergy with Carbon Capture, Utilization, and Storage (BECCUS) is emerging as a prominent negative emissions technology with significant potential to contribute to carbon removal efforts and sustainable energy systems. This work analyses whether the BECCUS value chain can support progress toward the 2030 Agenda by assessing the impacts across the 17 Sustainable Development Goals (SDGs) and their 169 targets. By applying the Value Chain Assessment methodology, we assess BECCUS value chain across five segments. Each segment is evaluated in terms of its positive or negative influence, as well as its direct or indirect impact, and in terms of its temporality. A new step is introduced to complement this assessment by identifying the Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) enablers for formulating policy recommendations. Our findings reveal that the five segments of the BECCUS value chain have a range of direct and indirect impacts on 15 out of all 17 SDGs, particularly SDG 13 (climate action). However, these segments also raise concerns, particularly SDG 9 (industry, innovation, and infrastructure), due to an imbalance in technology access between the Global North and South. In total, 53 out of the 169 SDG targets are impacted by at least one segment of the BECCUS value chain. Our analysis also identifies 107 positive effects (55 direct and 52 indirect) and 46 negative effects (9 direct and 37 indirect). This research provides an evidence-based strategic framework and policy recommendations for the sustainable deployment of BECCUS value chain.

1 Introduction

The urgent need for climate change mitigation and sustainable energy systems has led to an increasing interest in potential negative emissions technologies (NETs), particularly those that integrate Carbon Capture Utilization and Storage (CCUS) with bioenergy production [1]. Among these, Bioenergy with Carbon Capture Utilization and Storage (BECCUS) has emerged as a key technology capable of removing CO_2 from the atmosphere while simultaneously contributing to the global energy transition and climate change mitigation [2]. BECCUS is often positioned as a key technology strategy in scenarios that limit global warming to 1.5 °C, as outlined by the Intergovernmental Panel on Climate Change (IPCC) [3]. However, despite its theoretical potential, the impact and complexity of BECCUS value chain in large-scale implementation remain a subject of debate, especially concerning sustainable development aspects [4, 5].

Sustainable development seeks to achieve a long-term balance between economic growth, environmental protection, and social well-being by integrating these dimensions in decision-making [6]. Aligned with this definition, the SDGs, established by the United Nations in 2015, provide a framework for addressing global challenges by 2030 [7]. Comprising 17 goals and their 169 targets, they cover a wide range of topics including climate change, environmental sustainability, and socio-economic development [8]. BECCUS has the potential to positively or negatively impact multiple SDGs. While the SDGs set a 2030 horizon for global action, this study adopts a long-term perspective to evaluate the synergies and trade-offs of BECCUS in relation to sustainable development. This approach acknowledges that many impacts will only become fully evident beyond 2030, yet assessing them in the present is essential to ensure continued alignment with the SDGs over time. At its core, BECCUS can make a positive contribution to climate mitigation. On the other hand, it can also present trade-offs in sustainable development.

One of the main gaps in the literature is the lack of clarity regarding how BECCUS value chain can contribute, through in-depth analyses, to the progress of sustainable development. Existing studies focus mainly on the technical and climate mitigation potential of BECCUS, with limited attention to its broader environmental, socio-economic, and governance impacts across the entire value chain. Most analyses are also restricted to single dimensions (e.g., environmental or economic) or focus on individual segments of the value chain (e.g., biomass production or capture technology) [9–12]. For instance, the study by Hansson et al. (2020) emphasizes its role in delivering large-scale carbon removals, while also warning of sustainability trade-offs related to land-use change, biodiversity loss, and water consumption [13]. Similarly, Fajardy et al. argue that the overall climate benefit of BECCS depends on critical factors such as feedstock sourcing, supply chain emissions, and the deployment context [14]. In a related study, Möllersten and Gustavsson conducted one of the first broad assessments of BECCS value chain and its links to the 17 SDGs in the district heating sector and biomass-based combined heat and power (CHP) plants within the Swedish energy system [9].

Expanding the analysis, this work evaluates whether the BECCUS value chain can support progress toward the 2030 Agenda by assessing the impacts across the 17 SDGs and their 169 targets. It addresses the following research question: What strategies and policy measures can enhance the positive contributions of BECCUS to the SDGs while minimizing its potential risks and trade-offs? To achieve this aim and answer the research question, we employ the Value Chain Assessment (VCA) methodology, originally developed by Peyerl & van der Zwaan (2024) for sustainability assessments of the value chain [15]. The VCA approach analyses the BECCUS value chain by organizing it in five main segments: biomass supply, bioenergy conversion and carbon capture, transportation, utilization, and CO_2 storage [15]. It systematically assesses the technology's direct or indirect interactions and positive or negative influence on the 169 SDGs targets across each segment. This research maps BECCUS's impacts across short- or medium to long-term time horizons, ensuring a comprehensive assessment of its contribution to the progress of Agenda 2030. Additionally, a PESTLE analysis (Political, Economic, Social, Technological, Legal, and Environmental) is conducted as a further step to assess the aspects influencing BECCUS deployment and to develop recommendations for scaling it up.

This study presents a multidimensional perspective on BECCUS, contributing to both academic research and policy development in the context of climate mitigation and energy transition strategies. By mapping its interactions with the SDGs and their targets, the analysis provides a strategic perspective on how to optimize the deployment of BECCUS, offering policy recommendations that mitigate potential risks. Furthermore, in this work can serve as a model for future assessments of other NETs and climate mitigation technologies. As the global community intensifies efforts to meet the Paris Agreement targets and the Agenda 2030, evidence-based insights into sustainable technology deployment will be critical for guiding decision-making processes. Ultimately, this study contributes to the broader discourse on sustainable energy transitions, offering insights for policymakers, industry stakeholders, and researchers.

2 Literature review

The global energy transition requires deploying technologies capable of delivering deep decarbonization while supporting SDGs. In this context, recent reviews call for such integrated, multidimensional assessments of BECCUS. Duval-Dachary et al., for example, stress the need for a comprehensive life-cycle assessment (LCA) of BECCS supply chains to ensure net climate benefits and minimize resource trade-offs [16]. In contrast, Yeung et al. highlight interdisciplinary challenges in deploying BECCUS, including socio-economic acceptance, technology readiness, and policy coordination, underscoring the need for multi-level governance strategies [4]. Koytsoumpa et al. have emphasized the importance of embedding BECCUS within circular bioeconomy strategies, exploring carbon utilization pathways that can create added value and reduce resource intensity [17].

BECCUS also raises important questions of climate justice, energy justice, and global equity [18–20]. The concentration of technological capabilities, financing mechanisms, and infrastructure in the Global North risks exacerbating North–South inequalities, as developing countries often face barriers in accessing technology, intellectual property, and carbon markets [20–23]. From an energy justice perspective, issues of distribution, recognition, and participation must be considered to ensure that the socio-economic benefits and environmental risks of net-zero technologies such as BECCUS are shared fairly across regions and communities [24, 25]. Incorporating these critical perspectives strengthens the understanding that deployment of BECCUS is not only a technical challenge but also a matter of justice and equity within the global energy transition.

Global deployment remains limited but is growing, with five operational plants in 2024, 56 in advanced development, and 37 in the early planning stages, according to the Global CCS Institute in 2024 [26]. Existing projects are concentrated in countries with robust policy support, carbon pricing mechanisms, and established permitting processes, such as the United States, the United Kingdom, and Sweden. Recent legislative advances in countries like Brazil also signal emerging interest in integrating BECCUS into national mitigation strategies (Law No. 14.248/2024) [27]. However, national approaches differ significantly, highlighting the need for policy alignment and international cooperation to ensure equitable and effective impacts of BECCUS.

3 Methods and data collection

We adopt part of and add a new step to the VCA to evaluate the potential impacts of the BECCUS value chain on the 169 SDG targets [15]. The VCA is first applied to the green hydrogen value chain, offering a rigorous basis for analysing BECCUS. This method is systematic and multidimensional, providing a structure for assessing the sustainable development of technological value chains. This VCA is highly flexible, allowing it to be applied to a range of energy technologies, including BECCUS. As Peyerl and van der Zwaan mentioned, the VCA was partly created to be applied to a broader range of energy technologies or energy carriers within the value chain [15]. In this way, their impacts on the 2030 Agenda can be analysed in a quantitative manner.

The VCA begins with an extensive literature review as a first step. It then proceeds with a set of steps that evaluate the influence of each segment of the BECCUS value chain on all 17 SDGs and their 169 targets. In our case, we divided the BECCUS value chain by distinguishing five segments: (i) biomass supply, (ii) bioenergy conversion & carbon capture, (iii) transportation, (iv) utilization, and (v) storage of carbon dioxide. Each segment represents a part of the value chain. In this study, we apply four already existing steps of the VCA to BECCUS and then introduce an additional step. Each segment's influence on the SDGs is assessed in terms of direct, indirect, or unknown impacts, with further classifications made based on whether the influence is positive or negative and its temporality (short-term (≤ 2030), or medium- to long-term (> 2030). A PESTLE analysis is introduced as the final step, identifying the political, economic, social, technological, legal, and environmental enablers and constraints. Figure 1 summarizes the steps followed in this study.

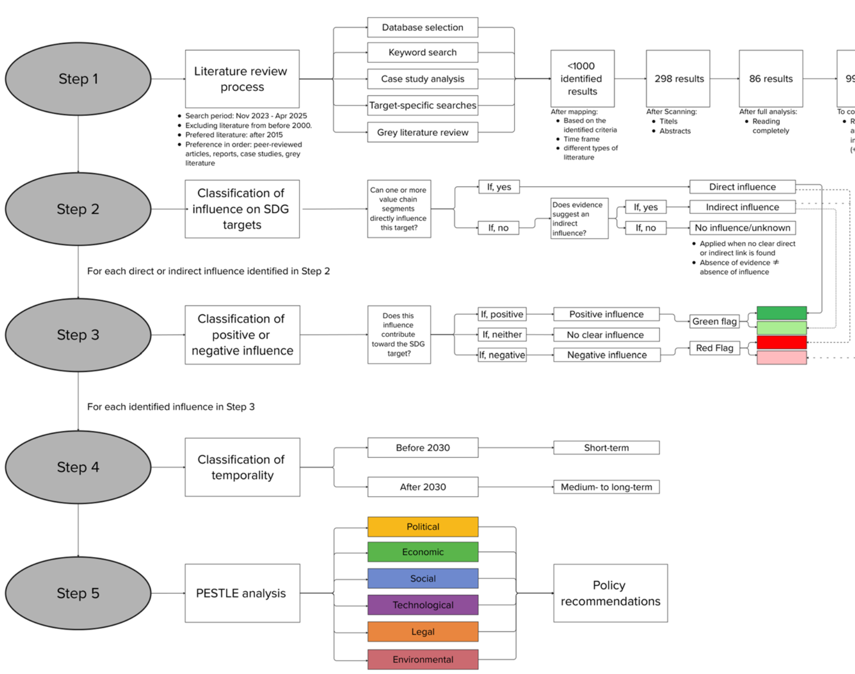

Fig. 1 Illustrates the five steps, from the literature review and SDG influence classification to the derivation of policy recommendations. It integrates the inclusion criteria, influence typologies, and temporal dimensions to ensure transparency and replicability

3.1 BECCUS value chain assessment

Step 1: Literature review process.

The literature review for this assessment follows a five-step approach designed to ensure comprehensive and systematic mapping of the relevant knowledge base:

1. Database selection: We identify databases capable of systematically covering the scientific literature and grey literature relevant to BECCUS and its sustainable development (e.g., Google Scholar & Web of Science). After applying exclusion criteria based on the abstracts, a total of 99 references are selected and quoted in the database (See the Supplementary Material for a detailed description of this review process).
2. Keyword search: SDGs keywords are selected to capture studies related to BECCUS, bioenergy, and their intersections with the 17 SDGs and their 169 targets.
3. Case study analysis: Particular focus is placed on case studies examining BECCUS's biomass supply, bioenergy conversion & carbon capture, transportation, utilization and storage of carbon dioxide.
4. Target-specific searches: Targeted searches are conducted to identify evidence connecting BECCUS to specific SDG targets.
5. Grey literature review: Reports from international organizations, governmental agencies, and industry publications are reviewed to supplement academic sources.

Step 2: Classification of influence on SDG targets.

Through the 99 references collected in step 1, each segment of the BECCUS value chain is assessed for its influence on all 169 SDG targets. The classification is based on three categories: direct influence, indirect influence, or no influence/unknown.

- Direct influence: If a segment directly affects the progress of an SDG target, it is classified as a direct influence. For example, biomass supply can directly influence SDG target 1.5 (build resilience to environmental, economic, and social disasters) by enhancing resilience through sustainable land management practices [28].
- Indirect influence: If evidence suggests a secondary or intermediate impact, the influence is classified as indirect. For example, transportation of captured CO_2 may indirectly influence SDG target 9.1 (develop sustainable, resilient and inclusive infrastructure) by requiring investments in sustainable infrastructure and innovation [29].
- No influence/unknown: This category is applied when there is no evidence of a direct or indirect link between BECCUS and a given SDG target. In such cases, the absence of evidence does not imply that an influence is impossible, only that it is not apparent in the current assessment. For example, several targets under SDG 16 (peace, justice and strong institutions) show no clear connection to BECCUS. Likewise, targets for which available research is limited or inconclusive are classified as "unknown."

To operationalize this step, we posed the following guiding questions for each of the 169 SDG targets:

i. Can one or more BECCUS value chain segments directly influence the progress of this target?

  - If yes, classify as direct influence and proceed to the next segment.
  - If no, continue to question 2.

ii. Does any evidence suggest an indirect influence of the segment on this target?

  - If yes, classify as indirect influence and proceed to the next segment.
  - If no, classify as no influence/unknown and proceed to the next target.

Step 3: Classification of positive or negative influence.

For each direct or indirect influence identified in Step 2, assess whether it represents a potential benefit or drawback for the SDG target. This classification uses guiding questions to systematically assign a "green flag" (positive) or "red flag" (negative).

For each influence, ask:

1. Does this influence contribute to progress toward the SDG target?
   - If yes, classify as positive influence (green flag).
   - Example: Carbon storage under BECCUS reduces atmospheric CO_2, directly supporting SDG target 13.1 (strengthen resilience to climate-related hazards) [17, 30].
2. Does this influence risk hindering or negatively impacting the SDG target?
   - If yes, classify as negative influence (red flag).
   - Example: Potential increases in water pollution from underground CO_2 storage could negatively affect SDG target 6.3 (Improve water quality by reducing pollution) [31–33].
3. If neither positive nor negative effects are supported by evidence:
   - Classify as having no clear influence or mark as further research needed.

Step 4: Classification of temporality.

For each identified influence, assess when its impacts are likely to occur by using the following guiding questions. This step ensures that the timing of BECCUS's sustainable development effects is systematically classified as short-term or medium- to long-term.

For each influence, ask:

1. Is the impact expected to manifest by 2030?
   - If yes, classify as short-term influence (≤ 2030).
   - Example: Early-stage deployment of BECCUS infrastructure can immediately support SDG target 9.2 and 9.4 by creating jobs and driving technological innovation [34–36].
2. Is the impact expected to emerge primarily between 2030 and beyond?
   - If yes, classify as medium- to long-term influence (> 2030).

- Example: The cumulative climate mitigation benefits of widespread deployment of BECCUS, such as significant contributions to SDG target 13.1 through negative emissions, are expected over the medium- to long-term [2, 28].

Step 5: PESTLE analysis and policy recommendations.

Building upon the insights from steps 1 to 4, a PESTLE analysis is conducted to assess the broader systemic factors influencing the deployment of BECCUS and its alignment with the SDGs. This approach allows for a structured assessment of external drivers and barriers that shape the feasibility and effectiveness of BECCUS within different contexts [37].

- Political: Policy instruments, governmental support, and international climate agreements play a critical role in shaping the deployment of BECCUS. National energy policies, carbon pricing mechanisms, and subsidies for bioenergy and carbon capture technologies are examined to assess their impacts on SDG targets.
- Economic: The financial viability of BECCUS depends on factors such as carbon credit markets, investment flows, and cost-competitiveness relative to alternative mitigation strategies. Special attention is given to how economic incentives can promote the deployment of BECCUS while minimizing trade-offs related to social and environmental dimensions.
- Social: The social acceptance of BECCUS is analysed by examining public perception, job creation potential, and impacts on local communities, particularly in regions where bioenergy feedstocks are sourced, or carbon storage sites are located. Potential equity concerns, such as land use competition and displacement risks, are also considered.
- Technological: The technological readiness and scalability of BECCUS are assessed, including advancements in biomass processing, carbon capture efficiency, and long-term storage integrity. Barriers related to infrastructure development and integration with existing energy systems are also mapped.
- Legal: Regulatory frameworks governing carbon capture, bioenergy production, and environmental impact assessments are reviewed to determine their role in either facilitating or hindering the deployment of BECCUS. Legal uncertainties surrounding carbon storage liability and cross-border transport regulations are also identified as critical challenges.
- Environmental: The sustainable development of BECCUS is evaluated by analysing its resource demands, such as land and water usage, and its overall net impact on emissions reductions. The potential for unintended consequences, such as biodiversity loss or competition with food production, is also incorporated into the assessment.

These analyses are used to formulate policy recommendations aimed at optimizing BECCUS into climate mitigation and energy transition strategies while ensuring alignment with the SDGs.

3.2 Conceptual definition

To ensure clarity and rigor in applying the VCA methodology to BECCUS, we define the key concepts used in this study.

Direct influence refers to a clear, immediate relationship between a segment of the BECCUS value chain and an SDG target. This influence arises when the value chain's activities directly contribute to achieving a specific goal. For instance, SDG target 12.5 (By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse) can be directly influenced by BECCUS through carbon capture and storage processes. The production segment supports this by integrating bioenergy systems with CCS, while the end-use segment contributes through efficient energy use [3, 38].

Indirect influence occurs when BECCUS impacts SDG targets through secondary processes or intermediate effects, rather than direct actions. This often involves catalysing broader developments in related sectors or systems. For example, SDG target 8.4 (Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programs on sustainable consumption and production, with developed countries taking the lead) may be indirectly influenced by the adoption of BECCUS value chain [39, 40].

No influence or *still unknown* is assigned when no evidence is found that supports either a direct or indirect relationship between BECCUS and an SDG target. For instance, target 4.5 (eliminate gender disparities in education) has no apparent connection to the activities of the BECCUS value chain. Similarly, areas where research is insufficient or inconclusive are categorized as still unknown.

A *green flag* represents a positive contribution of BECCUS to SDG progress. For instance, SDG target 7.2 (substantially increase the share of renewable energy in the global energy mix) can benefit positively from BECCUS by providing scalable bioenergy systems with integrated carbon capture, thereby enhancing renewable energy use and reducing reliance on fossil fuels [3, 30].

A *red flag* indicates fields where BECCUS could potentially hinder SDG progress or requires significant improvement to align with sustainable development objectives. For example, SDG target 6.4 (substantially increase water-use efficiency across all sectors) may face challenges from the water demands of bio-energy production. Addressing such issues through innovation and improved resource management is essential to mitigate negative impacts [41–43].

Temporality considers the timing of BECCUS's impacts on SDG targets, classified into short-term and medium- to long-term effects. Short-Term (≤ 2030): Impacts expected to occur in the near future, such as the deployment of pilot BECCUS projects and their immediate contributions to climate mitigation goals like SDG target 7.2 (By 2030, increase substantially the share of renewable energy in the global energy mix) [3]. Medium- to long-term (> 2030): Effects that will unfold over extended periods, driven by technological advancements, policy evolution, and large-scale adoption. For example, long-term storage solutions developed through BECCUS can significantly contribute to carbon neutrality goals [40, 44, 45].

PESTLE analysis examines the external, broad-scale influences on a system and helps identify how macro-level factors may affect strategic decisions and inform policy recommendations.

BECCUS value chain consists of a series of interconnected parts and borders the entire process of biomass sourcing, conversion, carbon capture, utilization, storage, and potential further applications [2, 46].

(i) Biomass supply: The segment involves sustainable growth, harvesting, and transportation of biomass feedstock [47]. This segment needs to consider factors like land-use change, biodiversity impacts, and efficient logistics to ensure a sustainable supply chain [48].
(ii) Bioenergy conversion & carbon capture: This segment focuses on converting biomass into usable energy forms like heat, power, or biofuels through one of the current four generations in bioenergy conversion [49]. Here, efficiency and minimizing emissions during conversion are crucial aspects [50]. Carbon capture (post-, pre-, and oxy combustion) involves capturing the CO_2 released just before, just after or during bioenergy conversion. This process occurs at the same facility on the currently existing BECCUS sites [26]. Their possible impact on SDG's is therefore reviewed together.
(iii) Transportation: The transport infrastructure segment of BECCUS contains temporary storage, and the transportation of CO_2 to utilization sites and permanent on- and offshore storage sites. According to Bui et al. the technologies for CO_2 transport are already well established [51]. While most studies focus on pipeline transportation, ship and rail transport remain viable alternatives as well [51].
(iv) Utilization: In this approach, the captured CO_2 becomes a valuable resource, used as a feedstock for various products. Some promising applications include synthetic fuels, chemicals, mineral carbonation, and enhanced oil recovery (EOR) [52].
(v) Storage of carbon dioxide: This segment of the value chain focuses on the permanent isolation of captured CO_2 from the atmosphere. This approach is crucial for achieving negative emissions [53]. Captured CO_2 is injected deep underground into suitable geological formations with high storage capacity. Selecting a storage site considers factors like geological suitability, storage capacity, and robust monitoring & verification plans [54]. Safe and secure storage practices are essential to ensure the long-term effectiveness of BECCS and its contribution to mitigating climate change [55].

This breakdown allows for a more comprehensive analysis of the BECCUS value chain, promoting its potential for achieving negative emissions while minimizing its environmental and social impact.

3.3 Limitation of analysis

While this study employs a rigorous VCA methodology to evaluate the relationship between BECCUS and the SDGs, certain limitations must be acknowledged.

First, the analysis relies heavily on available literature and case studies, which may not comprehensively capture all possible influences of BECCUS across diverse regional and technological contexts. The nascent stage of the deployment of BECCUS means that much of the evidence is drawn from pilot projects or theoretical models, potentially limiting the generalizability of the findings. Some sources may seem outdated, but they remain relevant due to the limited research on BECCUS. Second, the classification of influences (direct, indirect, or no influence/still unknown) is subject to interpretation of the authors, specialists in the field and the research group based on existing data. This introduces the possibility of bias, particularly in areas where evidence is sparse or conflicting. Third, the temporal dimension of BECCUS impacts, distinguishing between short-term and medium- to long-term effects, depends on projections and assumptions about technological advancements and policy developments. These assumptions may not account for unexpected barriers or opportunities that could significantly alter outcomes.

Lastly, as BECCUS value chain continues to advance and more studies are published, it is essential to reassess its potential impacts on the SDG targets regularly. This ongoing assessment will help incorporate emerging insights from new research and practical applications. These updates may lead to adjustments in classifying positive and negative influences, refining our understanding of BECCUS's contributions to sustainable development.

4 Results and discussion

4.1 BECCUS and SDGs

BECCUS is increasingly recognized as a crucial technology for achieving carbon neutrality and is closely associated with SDG 13 (Climate Action). However, the five segments of the BECCUS value chain have direct and indirect impacts on 15 out of the 17 SDGs.

Figure 2 presents the main findings of this analysis, which examines how the BECCUS value chain influences sustainable development across the 169 targets of the 17 SDGs. The literature review indicates that each stage of the BECCUS value chain affects at least one SDG, either directly or indirectly. In total, 53 out of the 169 SDG targets are impacted, with 37 targets influenced by multiple stages of the value chain.

The SDGs most frequently affected, each linked to three or more targets across the value chain, are SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals). Across all 153 identified interactions between BECCUS value chain segments and SDG targets (out of a possible 845), indirect influences (89) outnumber direct ones (64). Indirect impacts are most prevalent in SDGs 2, 4, and 13.

Overall, the analysis identifies 107 positive effects (55 direct and 52 indirect) and 46 negative effects (9 direct and 37 indirect).

4.2 BECCUS value chain assessment

The *biomass supply* segment plays a critical role in setting the foundation for the BECCUS value chain, with significant positive direct impacts on 11 SDGs and 25 out of 169 targets. For example, biomass supply enhances soil health and biodiversity by integrating sustainable agricultural practices, such as agroforestry and crop rotation. This contributes to building resilience in rural communities against climate-related hazards, directly supporting SDG target 1.5 [28, 56]. Furthermore, biomass supply advances SDG target 7.2 by providing a renewable energy source [40]. International collaboration in developing sustainable biomass supply chains also drives progress toward SDG target 7.a [57, 58]. Economically, the cultivation and processing of biomass create new jobs and boost rural economies, aligning with SDG 8 [60, 61]. Additionally, the use of biomass as a carbon sink and renewable energy feedstock enhances climate adaptation and mitigates climate-related risks, contributing to SDG target 13.1 [28, 56].

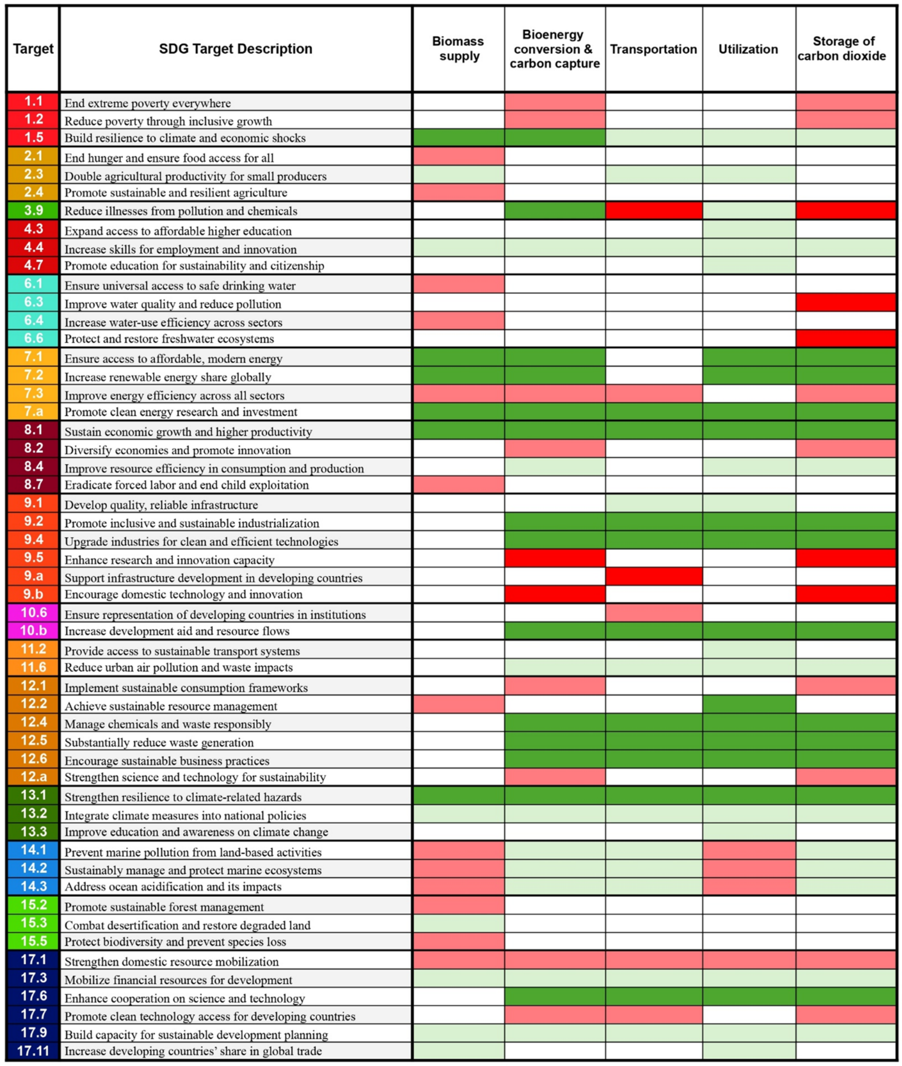

Fig. 2 Direct positive (dark green bar), indirect positive (light green bar), direct negative (dark red bar) and indirect negative (light red bar) impacts on SDG targets separated by part (i) to (v) of the value chain (from left to right). Respectively, all the way on the left, from up to down, all the impacted SDG targets and a short description of each target

Through these mechanisms, the biomass supply stage not only supports specific SDG targets but also creates broader socio-economic and environmental benefits, reinforcing its pivotal role in the BECCUS value chain. However, it is important to note possible negative impacts, such as the fact that currently most biomass is made through traditional agriculture methods, which creates risks for energy efficiency as it relies on existing technology, SDG target 7.3 [4, 30]. For example, many sugarcane-based bioenergy systems still depend on outdated harvesting and processing techniques and schedules that limit overall energy conversion efficiency [61]. The second crop biomass supply value chain for BECCUS remains underexplored in current literature [62]. This stage also carries risks for SDG targets 2.1 and 2.4. For instance, increased biomass demand may lead to land-use competition with food crops, potentially affecting food availability and affordability [63–65]. Moreover, expanding monoculture biomass plantations can undermine sustainable food production systems and resilient agricultural practices, particularly in vulnerable regions [66, 67].

The *bioenergy conversion and carbon capture* segment has significant positive direct impacts on 12 SDGs, and 30 out of 169 targets build upon the foundations established in the biomass supply stage, sharing just some of the same direct positive impacts on SDG targets 9.2, 9.4, 12.4, and 12.5. The conversion of biomass into bioenergy and the simultaneous capture of carbon emissions not only contribute to energy diversification and emissions reductions but also drive industrial innovation [68, 69]. This aligns with SDG target 9.2 by fostering the development of sustainable industries and enhancing economic opportunities through green technologies [70, 71]. Furthermore, adopting advanced carbon capture technologies and enhancing energy efficiency in bioenergy facilities supports SDG target 9.4 and demonstrates how industrial processes can transition toward sustainable practices by reducing greenhouse gas emissions per unit of output and integrating cleaner technologies into existing infrastructure, thereby contributing directly to more resource-efficient and environmentally sound industrial operations [17, 34].

Regarding SDG target 12.4, the bioenergy conversion and carbon capture segment emphasizes responsible management of industrial by-products and waste. The integration of carbon capture technology minimizes emissions, while sustainable bioenergy processes reduce environmental pollution [38]. Additionally, through innovative approaches like biochar production or the repurposing of carbon emissions into valuable products, this stage contributes to achieving SDG target 12.5 by promoting circular economy principles [72]. Despite these benefits, this segment also presents challenges. Negative impacts are noted for SDG targets 9.5, 9.a, 9.b, and 7.3. These negative influences arise from the high costs, technical complexities, and potential technological lock-ins associated with carbon capture systems [73, 74]. The resource-intensive nature of advanced capture technologies may also hinder broader accessibility and adaptation, particularly in developing regions [75–77].

The *transportation segment* plays a vital role in linking different elements of the BECCUS value chain, with a mix of indirect negative and direct positive impacts. With a total of 25 targets impacted, spread over 13 SDGs. The movement of biomass, captured carbon, and bioenergy products can result in indirect negative impacts on several SDG targets. SDG 3.9 may be affected due to emissions and pollution associated with transportation vehicles and pipelines, which contribute to environmental health risks [78, 79]. SDG 10.6 is implicated because BECCUS value chains are currently concentrated in countries of the Global North, limiting inclusive decision-making and representation for developing nations [26]. SDG targets 17.1, 17.6, and 17.7 are indirectly influenced by the substantial infrastructure costs and regulatory complexities involved in the transportation and broader BECCUS value chain, which pose challenges for domestic resource mobilization, international cooperation, and technology transfer [79–81]. This segment also often relies on trucks, trains, and ships that use fossil fuels, leading to greenhouse gas emissions and air pollution (SDG 3). For example, increased biomass transport in regions dependent on diesel-powered trucks may exacerbate respiratory illnesses, particularly in urban areas with pre-existing pollution issues [82–84]. A case study from Brazil's ethanol industry shows that emissions from transport fleets contribute to local air quality degradation, affecting vulnerable populations [85]. Transitioning to electric or hydrogen-powered transport fleets is identified in the literature as a potential mitigation strategy [82].

The transportation of BECCUS-related materials involves regulatory and economic challenges that disproportionately affect developing countries. Many nations lack the infrastructure for large-scale carbon transport, leading to unequal participation in carbon markets [86]. Additionally, cooperation on transport technologies (SDG target 17.6) is often hindered by intellectual property rights, preventing the widespread adoption of lower-carbon transport solutions [87, 88]. However, increased BECCUS transportation also has a direct positive impact on multiple SDG 12 targets by facilitating efficient resource use, minimizing waste, and enabling sustainable supply chains [89]. Additionally, it indirectly supports SDG target 9.1 by enhancing transport infrastructure critical for economic development and sustainability [90].

The *utilization segment* of BECCUS supports in maximizing the benefits of captured carbon by converting it into useful products, thereby significantly contributing to sustainability. This stage has direct positive impacts on SDGs 7, 9, and 12, with indirect positive effects mainly on SDG 4. By transforming captured CO_2 into valuable commodities, such as synthetic fuels, construction materials, or chemicals, the utilization process enhances industrial sustainability (SDG 9) and promotes responsible consumption and production (SDG 12) [17, 68, 72, 91]. Furthermore, innovative carbon utilization technologies contribute to energy security and renewable integration, supporting SDG 7 [17]. The only negative impact observed is on SDG target 17.1, as regulatory and economic challenges related to international taxation of carbon-based products may create barriers to widespread adoption [76]. Through these mechanisms, this segment contributes to circular economy strategies, reducing overall emissions while fostering industrial innovation.

The final segment of the BECCUS value chain, *storage of carbon dioxide*, is responsible for ensuring that captured CO_2 remains permanently removed from the atmosphere. This stage has a total impact on 24 SDG targets, with 13 positive and 11 negative effects. The impacts of storage are primarily linked to SDGs related to environmental protection, technological development, and governance. Storage of carbon dioxide contributes directly to SDG 13 by ensuring the long-term removal of CO_2 from the atmosphere, mitigating global warming and supporting SDG target 13.1 [30, 92]. By providing a large-scale carbon sequestration solution, BECCUS storage also supports SDG 9.4, as it encourages industrial investments in carbon management systems [35, 36].

Moreover, geological CO_2 storage helps protect ecosystems by reducing atmospheric CO_2 concentrations and SDG 14.3 [93]. Additionally, the development of CO_2 storage infrastructure can generate employment and economic benefits, positively influencing SDG 8.1 [60, 94]. Investments in storage facilities also drive progress toward SDG 7.a by stimulating cross-border agreements and technology exchanges [58]. Despite its climate benefits, BECCUS storage presents several challenges. A key challenge identified in the literature is the potential for CO_2 leakage from underground storage sites, which may undermine climate mitigation efforts and pose risks to local communities, negatively impacting SDG 3.9 [95]. Additionally, the high cost and energy intensity of CO_2 compression, transport, and injection make it difficult to achieve SDG 7.3 [4, 73]. Furthermore, reliance on carbon storage as a mitigation strategy could divert resources from direct emissions reductions, potentially slowing down the transition to renewables and affecting SDG 12.2 [96].

These results align with Möllersten and Gustavsson, who found that BECCS strongly supports SDG 7 (affordable and clean energy) and SDG 13 (climate action) but presents trade-offs with SDG 2 (zero hunger) and SDG 6 (clean water and sanitation) due to land and water competition [9]. Overall, the BECCUS value chain demonstrates clear synergies for climate and energy goals, while emphasizing the need for careful management of resource and environmental impacts.

4.3 Contrasting sustainability outcomes: technological inequality versus climate mitigation potential

While BECCUS presents as an innovative technology with the potential for decarbonizing the industry, it simultaneously reveals structural imbalances that hinder equitable progress toward SDG 9. The most significant direct negative impacts in our analysis stem from the unequal global distribution of technological capabilities and intellectual property rights. Patent data and innovation indicators show that the Global North strongly dominates BECCUS-related technological advancements and infrastructure deployment [26, 97]. This leads to a skewness in access, where developing countries face systemic barriers in establishing domestic R&D capacity, integrating new technologies, and accessing international carbon markets [22]. These disparities are particularly visible in SDG targets 9.5, 9.a, and 9.b, which highlight the need to enhance scientific research, support technological development, and foster resilient infrastructure in developing regions. The lack of inclusive innovation pathways not only perpetuates dependency on foreign technologies but also stifles the potential for localized BECCUS and job creation. Current evidence suggests that, in the absence of knowledge transfer mechanisms, capacity-building investments, and open-access technological systems, BECCUS may reinforce existing global disparities in infrastructure and innovation [75, 97].

In contrast, BECCUS demonstrates strong, consistent alignment with SDG 13, identified in recent literature as one of the few technologies capable of delivering net-negative emissions at large scale. Our results show that all identified influences on SDG 13 targets are positive, both directly and indirectly, across all five segments of the value chain. BECCUS contributes substantively to SDG target 13.1 by enabling long-term carbon removal from the atmosphere, thereby increasing climate resilience and reducing the severity of climate-related hazards [30, 75]. Moreover, the technology is featured prominently in all recent IPCC reports as a cornerstone of 1.5 °C-aligned scenarios, underscoring its strategic importance in achieving the Paris Agreement goals [3]. Unlike most mitigation technologies that focus on emission reduction, BECCUS actively removes CO_2 from the biosphere, positioning it as an essential tool in the climate policy arsenal [3]. Current trends in voluntary carbon markets, project pipelines, and infrastructure investments indicate its growing feasibility [98, 99]. While concerns remain about deployment scale and sustainability trade-offs, its climate benefits, particularly in the storage and capture phases, are consistently emphasized across the literature and make it a uniquely valuable component of global climate mitigation and energy transition strategies.

4.4 SDG 5 and 16: absent, but not irrelevant

While BECCUS value chain reveals direct and indirect influences across a wide range of SDG targets, it does not identify significant impacts on SDG 5 and SDG 16 This absence, however, does not imply that BECCUS is irrelevant to these goals, but rather that the current literature explored and empirical data do not establish clear or systematic connections at this stage. For SDG 5, the deployment of BECCUS infrastructure and its surrounding labour dynamics may, in theory, exacerbate or improve gender disparities in employment, decision-making, and access to technical education. However, such patterns are not yet documented within the context of BECCUS-specific projects, indicating that gender-disaggregated data remain limited and need further research. Similarly, SDG 16 may intersect with BECCUS indirectly through governance structures, transparency in carbon credit markets, land-use rights, or the enforcement of environmental regulation. Nevertheless, no consistent empirical linkages have emerged to date nor were any identified during the research.

This gap in the literature is not unique to BECCUS. Recent research on energy justice and gender, has shown that energy transition technologies often generate significant, but initially overlooked, impacts on equity, participation, and institutional inclusions [100, 101]. Given this, BECCUS may also carry such dimensions, although this has not yet been empirically demonstrated. As BECCUS matures and implementation scales globally, particularly in regions with complex institutional contexts, future research may uncover more concrete interactions with these goals. The current omission thus highlights both an inherent limitation of the VCA and the importance of incorporating justice-focused dimensions in future sustainable development analyses.

4.5 Temporal perspectives

In this study, we adopt the commonly used temporal framework to classify the impacts of BECCUS along short- and medium- to long-term horizons. The year 2030 marks the official target date for achieving the 17 SDGs, and thus defines the boundary for short-term impacts. Medium- to long-term effects are assessed from 2030 onwards, reflecting transitional developments, infrastructure scaling, and policy maturation expected in the decades following the initial SDG deadline. These temporal categories offer a structured lens to distinguish between immediate effects and those emerging as the technology matures, scales globally, and becomes embedded in broader socio-political and environmental systems.

A comprehensive analysis, considering short- and medium- to long-term perspectives, is essential for informed decision-making and effective public engagement. In the context of BECCUS, understanding its evolving impacts is crucial, as these effects vary based on regional socio-economic conditions, scale of implementation, and the specific phase of the value chain. Our analysis, as illustrated in Fig. 3, demonstrates that BECCUS impacts multiple SDG targets across different time horizons. In the short-term (≤ 2030), a significant portion of the SDGs experiences both direct and indirect effects, primarily positive. However, as BECCUS scales beyond 2030, the medium- to long-term outlook presents additional challenges, including trade-offs with land use, resource competition, and regional disparities in implementation capacity.

In the short-term, a few examples of BECCUS significantly contributing to the SDGs are related to affordable and clean energy (SDG 7), industry and innovation (SDG 9),

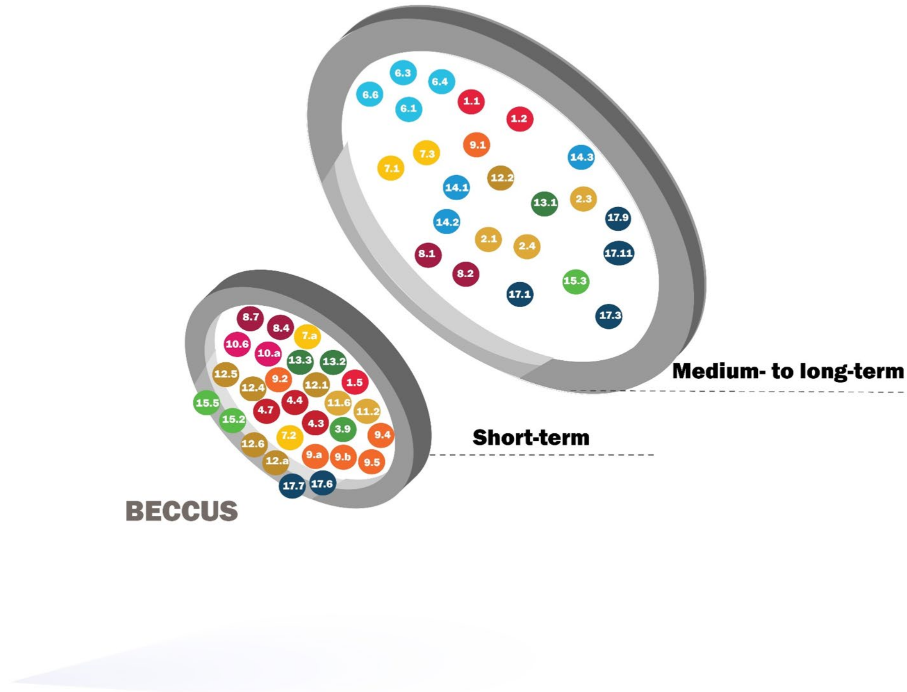

Fig. 3 Temporality of BECCUS value chain impacts on the SDG targets. The numbers correspond to specific SDG targets. Impacts expected in the short term (≤ 2030) are shown in the smaller circle, while impacts projected for the medium- to long-term (> 2030) are represented in the larger circle

responsible consumption and production (SDG 12), and partnerships for the goals (SDG 17). SDG target 7.2 is short-term, as according to a report from the Global CCS Institute, 56 BECCUS plants are planned to be operational by the end of 2025 globally [26]. More are planned to be operational before 2030, and therefore also promote industrial decarbonization before 2030 (SDG target 9.4) [34]. Additionally, the development of BECCUS infrastructure drives investment in sustainable technologies (SDG target 9.5) by adding substantial value to the voluntary carbon market [102]. BECCUS can also substantially reduce waste generation through prevention, reduction, recycling and reuse by 2030 (SDG target 12.5). Carbon is normally a waste flow in bio-energy creation and use, but in this case, it can be permanently stored, used for industrial processes or for the creation of sustainable aviation fuel (SAF) [103]. Lastly, a short-term impact is mentioned in SDG targets 17.6 and 17.7, where knowledge gaps between the Global North and South are already created on one side, and on the other side, knowledge is transferred through investments from companies in the Global North to the Global South [97, 104].

While the short-term impact is largely positive, early-stage deployment often prioritizes technical feasibility over broader sustainability objectives. This can lead to challenges such as high initial costs, regulatory uncertainty, and a lack of immediate economic incentives [105, 106]. However, strategic policy measures and financial mechanisms can mitigate these barriers, ensuring that BECCUS contributes to equitable and sustainable development.

After 2030, BECCUS expands its role to employment generation and economic growth (e.g., SDG target 8.1). Initially, investments need to be earned back, but positive impacts are expected from 2030 onwards [107]. At this stage, the increased deployment of BECCUS strengthens exports, as it requires a larger market presence to generate a meaningful impact on global trade (SDG target 17.11) [66, 94].

However, the expansion of BECCUS presents challenges. A key concern is the increased demand for water resources (SDG 6) and possible contamination in large-scale operations [31–109]. Without adequate water management strategies, BECCUS could exacerbate local water scarcity, particularly in arid regions [110]. Usually, natural groundwater has reserves for the short-term, but it is expected that this could impact SDG 6 negatively in the medium to long-term [42, 65, 111].

In the medium to long-term, BECCUS has the potential to achieve net-negative emissions, which could reduce natural disasters (SDG target 13.1) caused by global warming. By this stage, optimized BECCUS systems could play a transformative role in balancing atmospheric CO_2 levels, reinforcing climate resilience [3]. Additionally, sustained BECCUS development could develop quality, reliable, sustainable and resilient infrastructure in transportation (SDG target 9.1) [112]. Nevertheless, long-term deployment raises critical concerns regarding land competition and social equity. The large-scale cultivation of bioenergy crops may impact food security, depending on the form [113], driving up agricultural land costs and exacerbating poverty (SDG targets 1.1 and 1.2) [114]. This underscores the need for integrated land-use planning and sustainable agricultural policies [96, 115]. Additionally, the long-term feasibility of global BECCUS deployment depends on overcoming persistent infrastructure gaps in the global south, where limited financial and technical resources could hinder equitable implementation [116].

4.6 A PESTLE analysis

While BECCUS presents a promising pathway for deep decarbonization, its long-term success relies on policy coherence, technological advancements, and equitable distribution of resources. Addressing these challenges proactively will be crucial in ensuring that BECCUS contributes to a just and sustainable global energy transition. The integration of PESTLE analysis highlights the multidimensional nature of the challenges and opportunities present in each segment of the value chain. While the development of BECCUS may seem like a linear progression, the reality is far more complex, with each segment being shaped by distinct external forces [117].

Figure 4 provides a strategic framework that illustrates the strong interconnections between BECCUS value chain segments and the PESTLE dimensions, consistent with a previous report from IEA Bioenergy, which notes that deployment depends not only on technology readiness but also on business-model viability, coherent policy and regulatory systems, and robust carbon accounting methods [118]. This framework serves as a practical guide for stakeholders and policymakers, offering a structured roadmap for aligning BECCUS deployment with the SDGs. Unlike the *Deployment of BECCUS value chains* report from the IEA Bioenergy, which assesses deployment primarily through dimensions such as technology readiness, business model viability, policy measures, and carbon-accounting challenges [118]. It distinguishes six key dimensions and systematically links them to each of the five segments of the BECCUS value chain, providing a targeted tool for policy design and implementation.

Economic considerations have been the dominant driver in BECCUS deployment so far, often sidelining social and environmental aspects [2, 119]. For instance, investment

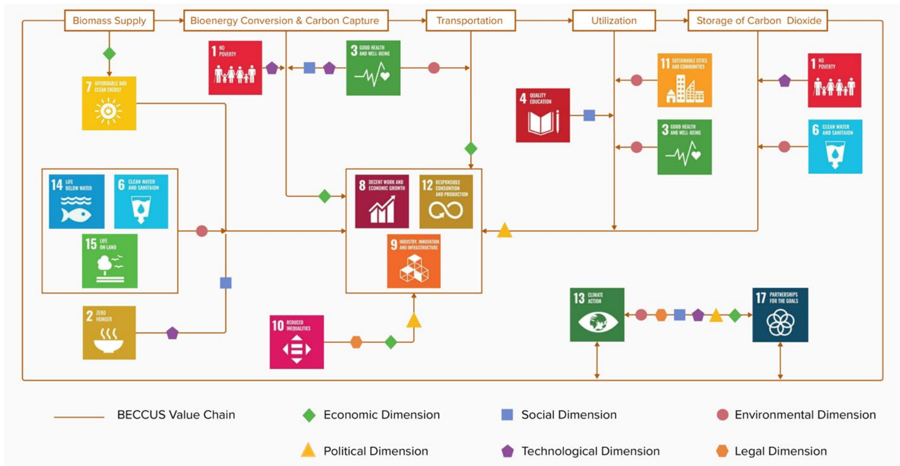

Fig. 4 This framework presents a strategic approach to maximizing the potential of the BECCUS value chain for sustainable development. It utilizes a color-coded system to illustrate the interconnected dimensions: economic (green), social (blue), environmental (red), political (yellow), technological (purple), and legal (orange). Dark yellow arrows visually represent the alignment between specific segments of the BECCUS value chain and the SDGs. Adapted from Peyerl and van der Zwaan [15]

flows primarily respond to cost-effectiveness and profitability, with less emphasis on long-term sustainability [2]. However, political and legal frameworks have the potential to shift these priorities by introducing incentives, regulations, and international agreements that promote sustainable practices [120]. Ensuring that BECCUS contributes to sustainable development requires balancing economic feasibility with social equity and environmental responsibility.

This research has shown that in the biomass supply stage, a key challenge lies in land use competition (SDG 15), where agricultural production, food security, and biodiversity conservation must be carefully managed. Policies that encourage sustainable sourcing, alongside technological advancements in biomass cultivation, can mitigate negative impacts. Meanwhile, economic factors such as subsidies and market demand significantly influence the viability of biomass as a feedstock for BECCUS [121].

Technological innovation and regulatory frameworks heavily shape the bioenergy conversion and carbon capture phase. The efficiency of capture technologies, energy input requirements, and policy support mechanisms all impact the sustainability of this segment. Social acceptance also plays a role, as concerns about land use changes, emissions from bioenergy plants, and local economic benefits influence public perception [122].

Transportation is a particularly intricate stage, given its geopolitical and environmental implications. International trade policies, infrastructure investments, and regulatory harmonization are crucial in ensuring that carbon transport and storage systems operate effectively. Environmental considerations, including potential leakage risks and the energy intensity of transportation, must be addressed to prevent unintended negative consequences [123, 124].

The final stages, carbon utilization and storage of carbon dioxide, raise critical questions regarding long-term environmental impact and legal accountability. Storage sites require careful assessment to ensure geological stability, and policies must clarify responsibilities regarding long-term monitoring and liability. Economic incentives, such as carbon pricing and offset mechanisms, can help integrate BECCUS into broader

Table 1 Policy recommendations for the deployment of BECCUS across the value chain using PESTLE analysis

Value Chain	Political	Economic	Social	Technological	Legal	Environmental
Biomass Supply	Develop subsidies for sustainable second-crop corn production, implementing approaches like BEFS (FAO)	Support the incentives BECCUS forms for farmers to increase yield and revenue	Raise awareness about sustainable agricultural practices and the debate of food versus fuel	Promote research on drought-resistant, high-yield fuel crops and second corn crops	Enforce regulations for land-use change and deforestation on local, national and international scale	Ensure sustainable farming and land management are the norm for fuel crops
Bioenergy Conversion & Carbon Capture	Integrate BECCUS into all national renewable energy policies and laws	Encourage investments in ethanol-BECCUS via voluntary and involuntary carbon markets	Ensure workforce training in bioenergy and CCS operations	Fund R&D for efficiency improvements in bio fermentation & CCS, and share knowledge with Global-South	Mandate emissions reductions for biofuel plants to stimulate the deployment of BECCUS	Use renewable energy in the fermentation process & enforce waste management by optimizing beneficial output
Transportation	Support infrastructure expansion for CO_2 pipeline networks	Offer tax credits for transport companies using BECCUS-related logistics	Develop community engagement strategies to address transport concerns	Invest in real-time monitoring and leak prevention for CO_2 pipelines	Implement strict safety regulations for CO_2 transport	Reduce transport emissions by incentivizing low-carbon logistics
Utilization	Encourage industries to integrate captured CO_2 in commercial applications	Provide financial incentives for CO_2 utilization in chemicals and construction	Educate the public on the benefits of carbon utilization	Support innovation in CO_2-based products globally	Set standards for CO_2 purity in industrial applications	Ensure CO_2 use contributes to net emission reductions
Storage of carbon dioxide	Establish long-term carbon pricing mechanisms to support storage	Create funding mechanisms for geological CO_2 storage projects, and implement incentives for completing storage period without leakage	Ensure local community acceptance of storage sites	Advance monitoring and verification technologies for long-term storage	Define clear liability frameworks for stored CO_2	Protect underground storage sites from environmental risks, especially water related

climate strategies [125], while social factors, including job creation and community involvement, will determine local support for these projects [126].

Ultimately, all dimensions of sustainable development are deeply interconnected. A holistic approach to the deployment of BECCUS will maximize synergies and minimize trade-offs across the value chain. By addressing the PESTLE factors at each stage, the development of BECCUS can be steered toward contributing positively to the SDGs, minimizing negative impacts and fostering economic growth while ensuring environmental and social sustainability.

Table 1 summarizes the key policy recommendations derived from this study's PESTLE analysis of the BECCUS value chain These recommendations reflect the integrated results of the research, combining insights from the literature review and value chain assessment. They emphasize the multi-dimensional nature of the deployment of BECCUS, highlighting that successful deployment depends on coherent political measures, stable economic incentives, social acceptance, continuous technological innovation, legal clarity, and environmental safeguards. Together, these factors form an interdependent system in which progress in one segment reinforces advances in others.

While the policy recommendations aim to support the deployment of BECCUS, it is essential to recognize the inherent limitations and challenges associated with translating these proposals into actionable governance. Many recommendations, particularly those tied to equitable technology transfer, infrastructure investment, and regulatory frameworks, exist within politically sensitive domains. National priorities, budget constraints, and competing interests may influence the political will and timing for adopting such measures. Moreover, in both the Global North and South, divergent perspectives on environmental responsibility, energy sovereignty, and market liberalization can create tension in multilateral discussions.

These complexities are further compounded by skewness in the global in technological capability, economic resources, and institutional capacity. For example, while carbon pricing mechanisms or cross-border CCS agreements might be technically sound and environmentally beneficial, their implementation may encounter resistance due to perceived risks of inequality, external dependency, or loss of competitiveness. Therefore, any policy pathway must be context-specific, guided by inclusive dialogue, adaptive governance structures, and a commitment to social and environmental justice. Future research and stakeholder engagement are critical to navigating these political uncertainties and refining recommendations in a manner that balances ambition with feasibility.

5 Conclusion

BECCUS has the potential to play a significant role in advancing the SDGs, particularly in accelerating energy transition and climate mitigation efforts. However, as with many emerging technologies, its long-term impact on sustainable development remains uncertain due to challenges such as resource consumption, regulatory barriers, and technological scalability. Directed investments, financial incentives, and well-aligned policies will be crucial in ensuring the responsible, sustainable and effective deployment of BECCUS across its value chain in both the short- and medium to long-term.

Each stage of the BECCUS value chain presents unique regional and sector-specific complexities in meeting the SDGs, requiring strategic planning to optimize its integration. Applying the VCA methodology highlights these complexities, offering insights to mitigate potential adverse effects and maximize benefits [15]. By aligning the deployment of BECCUS with sustainable development and following our policy recommendations, this approach can guide policymakers and stakeholders in addressing uncertainties in the global transition to a low-carbon economy.

Compared to previous assessments of BECCUS, this study advances the literature by applying the VCA that captures systemic, interactions across the entire BECCUS value chain [4, 9, 16]. While earlier works focused primarily on technological feasibility or environmental trade-offs, the present model incorporates temporal, socio-economic, and governance dimensions, allowing for a more holistic sustainable development evaluation. This approach enhances transparency and replicability while bridging the gap between technical climate mitigation analyses and the broader sustainable development framework.

Building on these insights, the PESTLE analysis developed in this study offers a practical tool for informing national and regional policy design. By identifying linkages and sustainable development trade-offs along the BECCUS value chain, it can help governments prioritize interventions that maximize climate and socio-economic co-benefits. Applying the methodology to regional contexts such as Brazil, the European Union, and the United States would enable comparative assessments of policy effectiveness, institutional readiness, and social acceptance. These applications could generate empirical evidence to guide the formulation of context-specific strategies and support the integration of BECCUS into broader decarbonization and sustainable development agendas.

Limitations exist, however, including those related to data gaps in long-term sustainable development outcomes and regional variability in the deployment of BECCUS. Future research should address these uncertainties through empirical case studies and scenario modelling. Applying these steps to regional BECCUS projects, one could make a fair and just assessment of their impacts on all SDGs. Despite these challenges, the present analysis reinforces the role of BECCUS as a viable climate mitigation tool, provided it is deployed responsibly.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s43937-025-00121-4.

Supplementary Material 1

Acknowledgements

J.H. was partially financed by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES). B. Z and D. P. acknowledge the support by the Energy Transition through the Lens of Sustainable Development Goals (ENLENS)—RPA (Proc. R.2322.0203), University of Amsterdam.

Author contributions

J.H: Wrote the main manuscript and created the figures. B.Z: Review D.P: Wrote the review and created the figures. Did the editing of the main manuscript and supervision of the entire research.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 5 September 2025 / Accepted: 29 December 2025

Published online: 06 January 2026

References

1. Haszeldine RS, Flude S, Johnson G, Scott V. Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. Philos Trans R Soc Lond A Math Phys Eng Sci. 2018;376(2119):20160447. https://doi.org/10.1098/rsta.2016.0447.
2. Fajardy M, Mac Dowell N. Can BECCS deliver sustainable and resource efficient negative emissions? Energy Environ Sci. 2017;10(6):1389–426. https://doi.org/10.1039/C7EE00465F.
3. Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne PW, Trisos C, Romero J, Aldunce P, Barret K, Blanco G, Cheung WWL, Connors SL, Denton F, Diongue-Niang A, Dodman D, Garschagen M, Geden O, Hayward B, Jones C, Ha M. IPCC, 2023:

Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero, editors]. IPCC, Geneva, Switzerland. 2023. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

4. Yeung FD, Sammarchi S, Wang E, Gao Q, Li J. Interdisciplinary challenges in bio-energy carbon capture utilization & storage deployment: a review. Carbon Capture Science & Technology. 2024;13:100283. https://doi.org/10.1016/j.ccst.2024.100283.
5. Ganeshan P, V S V, Gowd SC, Mishra R, Singh E, Kumar A, et al. Bioenergy with carbon capture, storage and utilization: potential technologies to mitigate climate change. Biomass Bioenergy. 2023;177:106941. https://doi.org/10.1016/j.biombioe.2023.106941.
6. Emas R. The concept of Sustainable Development: Definition and Defining Principles. Brief for GSDR 2015. Florida International University. United Nations Department of Economic and Social Affairs (UN DESA). 2015. https://doi.org/10.13140/RG.2.2.34980.22404
7. United Nations General Assembly. Transforming our world: The 2030 agenda for sustainable development. 2015.
8. Sachs JD, Lafortune G, Fuller G, Drumm E. Implementing the SDG stimulus. Sustain Dev Rep. 2023. https://doi.org/10.25546/102924.
9. Möllersten K, Gustavssona M. IImplementing Beccs in Swedish district Heating – An SDG assessment. SSRN Electron J. 2022. https://doi.org/10.2139/ssrn.4273306.
10. Negri V, Guillén-Gosálbez G. Implications of Optimal BECCS Supply Chains on Absolute Sustainability. In: 14th international symposium on process systems engineering. 2022. p. 619–24. https://doi.org/10.1016/B978-0-323-85159-6.50103-2.
11. Mascarenhas KL, Peyerl D, Weber N, Mouette D, Cuellar WOS, Meneghini JR, et al. Sustainable Development Goals as a Tool to Evaluate Multidimensional Clean Energy Initiatives. In: International business, trade and institutional sustainability. 2020. p. 645–57. https://doi.org/10.1007/978-3-030-26759-9_37.
12. Stoy PC, Ahmed S, Jarchow M, Rashford B, Swanson D, Albeke S, et al. Opportunities and trade-offs among BECCS and the food, water, energy, biodiversity, and social systems nexus at regional scales. Bioscience. 2018;68(2):100–11. https://doi.org/10.1093/biosci/bix145.
13. Hanssen SV, Daioglou V, Steinmann ZJN, Doelman JC, Van Vuuren DP, Huijbregts MAJ. The climate change mitigation potential of bioenergy with carbon capture and storage. Nat Clim Chang. 2020;10(11):1023–9. https://doi.org/10.1038/s41558-020-0885-y.
14. Fajardy M, Köberle A, Dowell N, Mac, Fantuzzi A. BECCS-deployment: a-reality-check. 2018. https://www.researchgate.net/publication/330774659
15. Peyerl D, van der Zwaan B. Analyzing the green hydrogen value chain against the sustainable development goals. Discover Sustain. 2024;5(1):199. https://doi.org/10.1007/s43621-024-00374-4.
16. Duval-Dachary S, Beauchet S, Lorne D, Salou T, Helias A, Pastor A. Life cycle assessment of bioenergy with carbon capture and storage systems: critical review of life cycle inventories. Renew Sustain Energy Rev. 2023;183:113415. https://doi.org/10.1016/j.rser.2023.113415.
17. Koytsoumpa EI, Magiri – Skouloudi D, Karellas S, Kakaras E. Bioenergy with carbon capture and utilization: a review on the potential deployment towards a European circular bioeconomy. Renew Sustain Energy Rev. 2021;152:111641. https://doi.org/10.1016/j.rser.2021.111641.
18. Schneider L. Fixing the climate? How geoengineering threatens to undermine the SDGs and climate justice. Development. 2019;62(1–4):29–36. https://doi.org/10.1057/s41301-019-00211-6.
19. Gough C, Mabon L, Mander S. Social and Ethical Dimensions of BECCS. In: Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions. John Wiley & Sons, Ltd; 2018. p. 251–76. https://doi.org/10.1002/9781119237716.ch12.
20. Apeaning R, Kamboj P, Hejazi MI. Bridging the divide: how unequal carbon dioxide removal deployment threatens climate equity and global mitigation feasibility. Sustainable Prod Consum. 2025;60:229–44. https://doi.org/10.1016/j.spc.2025.09.012.
21. Peter KY. Intellectual property, global inequality, and subnational policy variations. In: Intellectual property, innovation and economic inequality. 2024; pp. 81–105. Cambridge.
22. Schultz FC, Czyrnik V, Pies I. Is there a case for or against patents to incentivize green technologies? A critical evaluation of innovation incentives for the global North and global South. Sustain Nexus Forum. 2024;32(1):20. https://doi.org/10.1007/s00550-024-00558-6.
23. Pande R. Offsets, carbon markets, and climate and economic justice. Science. 2024. https://doi.org/10.1126/science.ads1902.
24. Holden E, Linnerud K, Rygg BJ. A review of dominant sustainable energy narratives. Renew Sustain Energy Rev. 2021;144:110955. https://doi.org/10.1016/j.rser.2021.110955.
25. Baker E, Goldstein AP, Azevedo IM. A perspective on equity implications of net zero energy systems. Energy and Climate Change. 2021;2:100047. https://doi.org/10.1016/j.egycc.2021.100047.
26. Global CCSI. The Global Status of CCS: 2024. 2024. https://www.globalccsinstitute.com/wp-content/uploads/2024/11/Global-Status-Report-6-November.pdf
27. Brazil. Federal Law No. 14,993, of October 8, 2024 (stemming from Bill No. 528/2020)BiobasedDieselDaily. 2024. https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/lei/l14993.htm
28. Kwakye JM, Ekechukwu DE, Ogundipe OB. Reviewing the role of bioenergy with carbon capture and storage (BECCS) in climate mitigation. Eng Sci Technol J. 2024;5(7):2323–33. https://doi.org/10.51594/estj.v5i7.1346.
29. Smith E, Morris J, Kheshgi H, Teletzke G, Herzog H, Paltsev S. The cost of CO2 transport and storage in global integrated assessment modeling. Int J Greenhouse Gas Control. 2021;109:103367. https://doi.org/10.1016/j.ijggc.2021.103367.
30. Rogieri Pelissari M, Gomes Relva S, Peyerl D. Possibilities for Carbon Capture, Utilization, and Storage in Brazil. In: <book-title update="added">Energy transition in Brazil. 2023. p. 141–57. https://doi.org/10.1007/978-3-031-21033-4_9.
31. Li Z, Fall M, Ghirian A. CCS risk assessment: groundwater contamination caused by CO2. Geosciences. 2018;8(11):397. https://doi.org/10.3390/geosciences8110397.
32. Cole IS, Corrigan P, Sim S, Birbilis N. Corrosion of pipelines used for CO2 transport in CCS: is it a real problem? Int J Greenhouse Gas Control. 2011;5(4):749–56. https://doi.org/10.1016/j.ijggc.2011.05.010.

33. Eldardiry H, Habib E. Carbon capture and sequestration in power generation: review of impacts and opportunities for water sustainability. Energy, Sustainability and Society. 2018;8(1):6. https://doi.org/10.1186/s13705-018-0146-3.
34. Patrizio P, Leduc S, Kraxner F, Fuss S, Kindermann G, Mesfun S, et al. Reducing US coal emissions can boost employment. Joule. 2018. https://doi.org/10.1016/j.joule.2018.10.004.
35. Cooper SJG, Hammond GP. Decarbonising' UK industry: towards a cleaner economy. Proc Institution Civil Eng - Energy. 2018;171(4):147–57. https://doi.org/10.1680/jener.18.00007.
36. Srivastav P, Schenkel M, Mir GUR, Berg T, Staats M. Carbon Capture, Utilisation and Storage, (CCUS): Decarbonisation Pathways for Singapore's Energy and Chemicals Sectors. 2021. https://file.go.gov.sg/carbon-capture-utilisation-and-storage-decarbonisation-pathway-for-singapore-energy-and-chemical-sectors-pdf.pdf
37. Achinas S, Horjus J, Achinas V, Euverink GJW. A PESTLE analysis of biofuels energy industry in Europe. Sustainability. 2019;11(21):5981. https://doi.org/10.3390/su11215981.
38. Christensen TH, Bisinella V. Climate change impacts of introducing carbon capture and utilisation (CCU) in waste incineration. Waste Manag. 2021;126:754–70. https://doi.org/10.1016/j.wasman.2021.03.046.
39. Peyerl D, Relva SG, Silva VOda. Energy Transition: Changing the Brazilian Landscape Over Time. In: <book-title update="added">Energy transition in Brazil. 2023. p. 1–15. https://doi.org/10.1007/978-3-031-21033-4_1.
40. Tatarewicz I, Lewarski M, Skwierz S, Krupin V, Jeszke R, Pyrka M, Szczepański K, Sekuła M. The role of BECCS in achieving climate neutrality in the European union. Energies. 2021;14(23):7842. https://doi.org/10.3390/en14237842.
41. Gerbens-Leenes W, Hoekstra AY, van der Meer TH. The water footprint of bioenergy. Proc Natl Acad Sci U S A. 2009;106(25):10219–23. https://doi.org/10.1073/pnas.0812619106.
42. Gerbens-Leenes PW. Green, blue and grey bioenergy water footprints, a comparison of feedstocks for bioenergy supply in 2040. Environ Process. 2018;5(S1):167–80. https://doi.org/10.1007/s40710-018-0311-x.
43. Fito J, Ahmed I, Nkambule TTI, Kefeni KK. Evaluation of water footprint in sugar industries and bioethanol distilleries in two different water basins toward water sustainability. Int J Environ Sci Technol. 2023;20(3):2427–40. https://doi.org/10.1007/s13762-022-04182-z.
44. Carvalho F, Müller-Casseres E, Poggio M, Nogueira T, Fonte C, Wei HK, et al. Prospects for carbon-neutral maritime fuels production in Brazil. J Clean Prod. 2021;326:129385. https://doi.org/10.1016/j.jclepro.2021.129385.
45. Rosa L, Sanchez DL, Mazzotti M. Assessment of carbon dioxide removal potential BECCS in a carbon-neutral Europe. Energy Environ Sci. 2021;14(5):3086–97. https://doi.org/10.1039/D1EE00642H.
46. Guntermann N, Franciò G, Leitner W. Hydrogenation of CO 2 to formic acid in biphasic systems using aqueous solutions of amino acids as the product phase. Green Chem. 2022;24(20):8069–75. https://doi.org/10.1039/D2GC02598A.
47. Hiloidhari M, Sharno MA, Baruah DC, Bezbaruah AN. Green and sustainable biomass supply chain for environmental, social and economic benefits. Biomass Bioenergy. 2023;175:106893. https://doi.org/10.1016/j.biombioe.2023.106893.
48. Hong BH, How BS, Lam HL. Overview of sustainable biomass supply chain: from concept to modelling. Clean Technol Environ Policy. 2016;18(7):2173–94. https://doi.org/10.1007/s10098-016-1155-6.
49. Fülöp L, Ecker J. An overview of biomass conversion: exploring new opportunities. PeerJ. 2020;8:e9586. https://doi.org/10.7717/peerj.9586.
50. Lee SY, Sankaran R, Chew KW, Tan CH, Krishnamoorthy R, Chu D-T, Show P-L. Waste to bioenergy: a review on the recent conversion technologies. BMC Energy. 2019;1(1):4. https://doi.org/10.1186/s42500-019-0004-7.
51. Bui M, Adjiman CS, Bardow A, Anthony EJ, Boston A, Brown S, et al. Carbon capture and storage (CCS): the way forward. Energy Environ Sci. 2018;11(5):1062–176. https://doi.org/10.1039/C7EE02342A.
52. Cuéllar-Franca RM, Azapagic A. Carbon capture, storage and utilisation technologies: a critical analysis and comparison of their life cycle environmental impacts. J CO2 Util. 2015;9:82–102. https://doi.org/10.1016/j.jcou.2014.12.001.
53. Hong WY. A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO2 emissions future. Carbon Capture Sci Technol. 2022;3: 100044. https://doi.org/10.1016/j.ccst.2022.100044.
54. Rasool MH, Ahmad M, Ayoub M. Selecting geological formations for CO2 storage: a comparative rating system. Sustainability. 2023;15(8):6599. https://doi.org/10.3390/su15086599.
55. Damen K, Faaij A, Turkenburg W. Health, safety and environmental risks of underground Co2 storage – overview of mechanisms and current knowledge. Clim Change. 2006;74(1–3):289–318. https://doi.org/10.1007/s10584-005-0425-9.
56. López-Bellido L, Wery J, López-Bellido RJ. Energy crops: prospects in the context of sustainable agriculture. Eur J Agron. 2014;60:1–12. https://doi.org/10.1016/j.eja.2014.07.001.
57. Jacobson RA, Jones S, Ugarte DDLT, Kline KL. Mapping and synthesis of international biomass supply assessments. 2025. https://biofutureplatform.org/wp-content/uploads/2025/02/Mapping-and-Synthesis-of-International-Biomass-Supply-Assessments.pdf
58. Torvanger A. Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement. Clim Policy. 2019;19(3):329–41. https://doi.org/10.1080/14693062.2018.1509044.
59. Fajardy M, Morris J, Gurgel A, Herzog H, Mac Dowell N, Paltsev S. The economics of bioenergy with carbon capture and storage (BECCS) deployment in a 1.5°C or 2°C world. Glob Environ Change. 2021;68:102262. https://doi.org/10.1016/j.gloenvcha.2021.102262.
60. Mersch M, Dejan R, Moustafa N, Sunny N, Dowell MN. The role and value of BECCS in the USA. 2024.
61. Gebrehiwot Y, Alemu S, Alemayehu G. Maximizing economic returns from sugarcane production through the optimization of a harvesting schedule: a case study of the Metahara sugar factory, Ethiopia. Discov Agric. 2025;3(1): 81. https://doi.org/10.1007/s44279-025-00239-y.
62. Pinheiro DT, Santos DMS, Martins ARR, da Silva WM, de Araújo CV, de Abreu DC, et al. Closing the gap: sustainable intensification implications of increased corn yields and quality for second-crop (safrinha) in Mato Grosso, Brazil. Sustainability. 2021;13(23):13325. https://doi.org/10.3390/su132313325.
63. Renzaho AMN, Kamara JK, Toole M. Biofuel production and its impact on food security in low and middle income countries: implications for the post-2015 sustainable development goals. Renew Sustain Energy Rev. 2017;78:503–16. https://doi.org/10.1016/j.rser.2017.04.072.
64. Muller A. Sustainable agriculture and the production of biomass for energy use. Clim Change. 2009;94(3–4):319–31. https://doi.org/10.1007/s10584-008-9501-2.
65. FAO. Bioenergy and Food Security The BEFS Analytical Framework (FAO). 2010. http://www.fao.org

66. Mutopo P, Beyene A, Haaland H, Boamah F, Widengård M, Skarstein R. Biofuels, land grabbing and food security in Africa. Bloomsbury Publishing; 2011.
67. Locke A, Henley G. The implications of land grabs and biofuel expansion for food and nutrition security in developing countries. In: Pritchard B, Ortiz R, Shekar M, editors. Routledge handbook of food and nutrition security. New York: Routledge; 2016. https://doi.org/10.4324/9781315745749.
68. Delgado Calvo MÁ. Decarbonizing industry by means of thermochemical conversion of biomass and CO2 capture & transport [Universidad de Salamanca]. 2024. https://doi.org/10.14201/gredos.159593
69. Martinez GE. Influence of carbon dioxide removal policies in carbon capture utilization and storage system development [Heat and Power Engineering, Aalto University]. 2023. https://urn.fi/URN:NBN:fi:aalto-202309035484
70. Stavrakas V, Spyridaki N-A, Flamos A. Striving towards the deployment of bio-energy with carbon capture and storage (beccs): a review of research priorities and assessment needs. Navigant. 2021. https://doi.org/10.3390/su10072206.
71. Donnison C, Holland RA, Hastings A, Armstrong L, Eigenbrod F, Taylor G. Bioenergy with carbon capture and storage (BECCS): finding the win–wins for energy, negative emissions and ecosystem services—size matters. GCB Bioenergy. 2020;12(8):586–604. https://doi.org/10.1111/gcbb.12695.
72. Ilinova A, Kuznetsova E. CC(U)S initiatives: prospects and economic efficiency in a circular economy. Energy Rep. 2022;8:1295–301. https://doi.org/10.1016/j.egyr.2021.11.243.
73. Wilberforce T, Olabi AG, Sayed ET, Elsaid K, Abdelkareem MA. Progress in carbon capture technologies. Sci Total Environ. 2021;761:143203. https://doi.org/10.1016/j.scitotenv.2020.143203.
74. Awasthi MK, Sarsaiya S, Patel A, Juneja A, Singh RP, Yan B, et al. Refining biomass residues for sustainable energy and bio-products: an assessment of technology, its importance, and strategic applications in circular bio-economy. Renew Sustain Energy Rev. 2020;127:109876. https://doi.org/10.1016/j.rser.2020.109876.
75. Kang J-N, Zhang Y-L, Chen W. Delivering negative emissions innovation on the right track: a patent analysis. Renew Sustain Energy Rev. 2022;158:112169. https://doi.org/10.1016/j.rser.2022.112169.
76. Sovacool BK. Expanding carbon removal to the Global South: thematic concerns on systems, justice, and climate governance. Energy Clim Change. 2023;4: 100103. https://doi.org/10.1016/j.egycc.2023.100103.
77. Qiu H-H, Yang J. An assessment of technological innovation capabilities of carbon capture and storage technology based on patent analysis: a comparative study between China and the United States. Sustainability. 2018;10(3):877. https://doi.org/10.3390/su10030877.
78. Solaymani S, Botero J. Reducing carbon emissions from transport sector: experience and policy design considerations. Sustainability. 2025;17(9):3762. https://doi.org/10.3390/su17093762.
79. Lee JS, Choi EC. CO2 leakage environmental damage cost – a CCS project in South Korea. Renew Sustain Energy Rev. 2018;93:753–8. https://doi.org/10.1016/j.rser.2018.04.074.
80. Gough C, Garcia-Freites S, Jones C, Mander S, Moore B, Pereira C, et al. <article-title update="added">Challenges to the use of BECCS as a keystone technology in pursuit of 1.5^{0}C. Glob Sustain. 2018;1:e5. https://doi.org/10.1017/sus.2018.3.
81. Baker E, Bosetti V, Anadon LD, Henrion M, Aleluia Reis L. Future costs of key low-carbon energy technologies: harmonization and aggregation of energy technology expert elicitation data. Energy Policy. 2015;80:219–32. https://doi.org/10.1016/j.enpol.2014.10.008.
82. Lao J, Song H, Wang C, Zhou Y. Research on atmospheric pollutant and greenhouse gas emission reductions of trucks by substituting fuel oil with green hydrogen: a case study. Int J Hydrog Energy. 2023;48(30):11555–66. https://doi.org/10.1016/j.ijhydene.2022.02.230.
83. Mahmudi H, Flynn PC. Rail vs truck transport of biomass. Appl Biochem Biotechnol. 2006;129(1–3):88–103. https://doi.org/10.1385/ABAB:129:1:88.
84. Lloyd AC, Cackette TA. Diesel engines: environmental impact and control. J Air Waste Manag Assoc. 2001;51(6):809–47. https://doi.org/10.1080/10473289.2001.10464315.
85. Pérez-Martínez PJ, de Fátima Andra M, de Miranda RM. Heavy truck restrictions and air quality implications in São Paulo, Brazil. J Environ Manage. 2017;202:55–68. https://doi.org/10.1016/j.jenvman.2017.07.022.
86. Fisher S, Bellinger DC, Cropper ML, Kumar P, Binagwaho A, Koudenoukpo JB, et al. Air pollution and development in Africa: impacts on health, the economy, and human capital. Lancet Planet Health. 2021;5(10):e681-8. https://doi.org/10.1016/S2542-5196(21)00201-1.
87. Abdel-Latif A. Intellectual property rights and the transfer of climate change technologies: issues, challenges, and way forward. Clim Policy. 2015;15(1):103–26. https://doi.org/10.1080/14693062.2014.951919.
88. Raiser K, Naims H, Bruhn T. Corporatization of the climate? Innovation, intellectual property rights, and patents for climate change mitigation. Energy Res Social Sci. 2017;27:1–8. https://doi.org/10.1016/j.erss.2017.01.020.
89. Wang Y, Cao Q, Liu L, Wu Y, Liu H, Gu Z, et al. A review of low and zero carbon fuel technologies: achieving ship carbon reduction targets. Sustain Energy Technol Assess. 2022;54:102762. https://doi.org/10.1016/j.seta.2022.102762.
90. Singh U, Loudermilk EM, Colosi LM. Accounting for the role of transport and storage infrastructure costs in carbon negative bioenergy deployment. Greenh Gases Sci Technol. 2021;11(1):144–64. https://doi.org/10.1002/ghg.2041.
91. Nass LL, Pereira PAA, Ellis D. Biofuels in brazil: an overview. Crop Sci. 2007;47(6):2228–37. https://doi.org/10.2135/cropsci2007.03.0166.
92. Heikkilä K. Towards carbon-negative future of the pulp and paper industry: possibilities of harnessing BECCUS in Finnish chemical pulp mills. LUT University. 2023. https://lutpub.lut.fi/bitstream/handle/10024/165810/Masters_thesis_Kasperi_Heikkila.pdf?sequence=1&isAllowed=y
93. Doney SC, Fabry VJ, Feely RA, Kleypas JA. Ocean acidification: the other CO 2 problem. Annu Rev Mar Sci. 2009;1(1):169–92. https://doi.org/10.1146/annurev.marine.010908.163834.
94. Muratori M, Calvin K, Wise M, Kyle P, Edmonds J. Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). Environ Res Lett. 2016;11(9):095004. https://doi.org/10.1088/1748-9326/11/9/095004.
95. Burant A, Lowry GV, Karamalidis AK. Partitioning behavior of organic contaminants in carbon storage environments: a critical review. Environ Sci Technol. 2013;47(1):37–54. https://doi.org/10.1021/es304262p.
96. Muscat A. The battle for biomass: Tackling tensions and tradeoffs at the science-policy interface [Wageningen University]. 2021. https://doi.org/10.18174/541657
97. Míguez JL, Porteiro J, Pérez-Orozco R, Patiño D, Gómez MÁ. Biological systems for CCS: patent review as a criterion for technological development. Appl Energy. 2020;257:114032. https://doi.org/10.1016/j.apenergy.2019.114032.

98. Michaelowa A, Honegger M, Poralla M, Winkler M, Dalfiume S, Nayak A. International carbon markets for carbon dioxide removal. PLoS Clim. 2023;2(5):e0000118. https://doi.org/10.1371/journal.pclm.0000118.
99. Fridahl M, Lehtveer M. Bioenergy with carbon capture and storage (BECCS): global potential, investment preferences, and deployment barriers. Energy Res Social Sci. 2018;42:155–65. https://doi.org/10.1016/j.erss.2018.03.019.
100. Raman R, Ustenko V, Filho WL, Nedungadi P. Energy justice and gender: bridging equity, access, and policy for sustainable development. Discov Sustainabil. 2025;6(1): 558. https://doi.org/10.1007/s43621-025-01375-7.
101. Johnson OW, Han JY-C, Knight A-L, Mortensen S, Aung MT, Boyland M, et al. Intersectionality and energy transitions: a review of gender, social equity and low-carbon energy. Energy Res Soc Sci. 2020;70:101774. https://doi.org/10.1016/j.erss.2020.101774.
102. Braccio S. The market of carbon credits and biofuels [Doctoral dissertation, Politecnico di Torino]. 2024. http://webthesis.biblio.polito.it/id/eprint/31130
103. Alvarez Sarró J. Assessing the Integration of Sustainable Aviation Fuels (SAFs): Balancing Environmental Impact, Economic Viability, and Aircraft Performance in the Aviation Industry. 2024.
104. Capaz S. Alternative aviation fuels in Brazil Environmental performance and economic feasibility. 2021. https://doi.org/10.4233/uuid:a2740d8c-f08c-4fdd-96b8-54dd5d6fee01
105. Sovacool BK, Rio D, Herman DF, Iskandarova K, Uratani M, J. M., Griffiths S. Reconfiguring European industry for net-zero: a qualitative review of hydrogen and carbon capture utilization and storage benefits and implementation challenges. Energy Environ Sci. 2024;17(10):3523–69. https://doi.org/10.1039/D3EE03270A.
106. Roh K, Bardow A, Bongartz D, Burre J, Chung W, Deutz S, Han D, Heßelmann M, Kohlhaas Y, König A, Lee JS, Meys R, Völker S, Wessling M, Lee JH, Mitsos A. Early-stage evaluation of emerging CO2 utilization technologies at low technology readiness levels. Green Chem. 2020;22(12):3842–59. https://doi.org/10.1039/C9GC04440J.
107. Abegg M, Clulow Z, Nava L, Reiner DM. Expert insights into future trajectories: assessing cost reductions and scalability of carbon dioxide removal technologies. Front Clim. 2024. https://doi.org/10.3389/fclim.2024.1331901.
108. Wu Z, Zhai H. Consumptive life cycle water use of biomass-to-power plants with carbon capture and sequestration. Appl Energy. 2021;303:117702. https://doi.org/10.1016/j.apenergy.2021.117702.
109. Rosa L, Sanchez DL, Realmonte G, Baldocchi D, D'Odorico P. The water footprint of carbon capture and storage technologies. Renew Sustain Energy Rev. 2021;138:110511. https://doi.org/10.1016/j.rser.2020.110511.
110. Nhamo L, Ndlela B, Nhemachena C, Mabhaudhi T, Mpandeli S, Matchaya G. The water-energy-food nexus: climate risks and opportunities in Southern Africa. Water. 2018;10(5):567. https://doi.org/10.3390/w10050567.
111. Picha MS. Carbon Capture Storage (CCS) Drilling & Completion Well Integrity Lifecycle Challenges & Mitigations. SPE/IADC Asia Pacific Drilling Technology Conference and Exhibition. 2024. https://doi.org/10.2118/219653-MS
112. Schippers EJ, Massol O. Unlocking CO2 infrastructure deployment: the impact of carbon removal accounting. Energy Policy. 2022;171:113265. https://doi.org/10.1016/j.enpol.2022.113265.
113. Gurgel AC, Seabra JEA, Arantes SM, Moreira MMR, Lynd LR, Galindo R. Contribution of double-cropped maize ethanol in Brazil to sustainable development. Nat Sustain. 2024;7(11):1429–40. https://doi.org/10.1038/s41893-024-01424-5.
114. IRENA, & AfDB. Renewable energy market analysis: Africa and its regions—a summary for policy makers. 2022
115. Muscat A, de Ol EM, de Boer IJM, Ripoll-Bosch R. The battle for biomass: a systematic review of food-feed-fuel competition. Glob Food Secur. 2020;25:100330. https://doi.org/10.1016/j.gfs.2019.100330.
116. Weko S, Goldthau A. Bridging the low-carbon technology gap? Assessing energy initiatives for the global South. Energy Policy. 2022;169:113192. https://doi.org/10.1016/j.enpol.2022.113192.
117. McLaughlin H, Littlefield AA, Menefee M, Kinzer A, Hull T, Sovacool BK, et al. Carbon capture utilization and storage in review: sociotechnical implications for a carbon reliant world. Renew Sustain Energy Rev. 2023;177:113215. https://doi.org/10.1016/j.rser.2023.113215.
118. Olle Olsson Michaël, Becidan C, Bang N, Abdalla S, Bürck H, Fehrenbach ZM, Harris. Daniela Thrän, Otavio Cavalett, Francesco Cherubini, & Christiane Hennig. Deployment of BECCUS value chains. 2022.
119. Cabello A, Abad A, de las Obras Loscertales M, Domingos Y, Mendiara T. Techno-economic analysis of chemical looping processes with biomass resources for energy production and CO2 utilization. Comparison of CLC and CLOU technologies. Energy Convers Manag. 2024;310:118476. https://doi.org/10.1016/j.enconman.2024.118476.
120. Clune WH, Zehnder AJB. The three pillars of sustainability framework: approaches for laws and governance. J Environ Prot. 2018;09(03):211–40. https://doi.org/10.4236/jep.2018.93015.
121. Knápek J, Vávrová K, Valentová M, Vašíček J, Králík T. Energy biomass competitiveness—three different views on biomass price. WIREs Energy Environ. 2017. https://doi.org/10.1002/wene.261.
122. Gough C, Mander S. Beyond social acceptability: applying lessons from CCS social science to support deployment of BECCS. Curr Sustain/Renewable Energy Rep. 2019;6(4):116–23. https://doi.org/10.1007/s40518-019-00137-0.
123. Deng H, Bielicki JM, Oppenheimer M, Fitts JP, Peters CA. Leakage risks of geologic CO2 storage and the impacts on the global energy system and climate change mitigation. Clim Change. 2017;144(2):151–63. https://doi.org/10.1007/s10584-017-2035-8.
124. Shang Y, Chen X, Yang M, Xing X, Jiao J, An G, Li X, Xiong X. Comprehensive review on leakage characteristics and diffusion laws of carbon dioxide pipelines. Energy Fuels. 2024;38(12):10456–93. https://doi.org/10.1021/acs.energyfuels.4c00715.
125. Palmer J, Carton W. Carbon removal as carbon revival? Bioenergy, negative emissions, and the politics of alternative energy futures. Front Clim. 2021. https://doi.org/10.3389/fclim.2021.678031.
126. Buck HJ. Challenges and opportunities of bioenergy with carbon capture and storage (BECCS) for communities. Curr Sustainable Renewable Energy Rep. 2019;6(4):124–30. https://doi.org/10.1007/s40518-019-00139-y.

Publisher's note