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Review

Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs

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Abstract: Assessing the performance or the implications of climate change mitigation options (CCMOs) is instrumental in achieving research and innovation efficiency in the field of climate change and becomes more imperative considering the Paris Agreement ('the Agreement'). Many climate scientists already believe that meeting the Agreement's goals and stabilizing "well-below 2 °C above pre-industrial levels" signals the deployment of currently undetermined and contentious mitigation technologies, such as bio-energy with carbon capture and storage (BECCS). BECCS is considered one of the most promising negative emissions technologies (NETs) with many scenarios already exhibiting its mitigation potential. However, stakeholders and policymakers remain skeptical about widespread reliance on BECCS questioning its unproven credibility. In this article, we aim at identifying research priorities and assessment needs to intensify the further deployment of BECCS, considering relevant technology associations' and platforms' perspectives and insights raised by scientific literature. The main outcome of our study is a list of 10 research priorities along with more specific assessment needs for each priority area. We also focus attention on several implications for potential end-users involved in the field of policy and practice. Overall, our work seeks to bridge the gap between market/industry and academia and to assist policymakers to make better-informed decisions.

Keywords: NETs; BECCS; Bio-CCS; assessment needs; research priorities; negative emissions technologies

1. Introduction

Climate change mitigation options (CCMOs) are essential when combating climate change, while their further development and transfer need to be accelerated in face of an imperative need to achieve a decrease in annual greenhouse gas emissions globally by 2020 and beyond [1]. The Paris Agreement ('the Agreement') came into force with an ambition of limiting global temperature to 1.5 °C above pre-industrial levels signaling the urgency for "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" [2]. Essentially, the Agreement serves as a national development incentive by retaining the issue of climate change on the agenda and urging policymakers worldwide to constantly review it [3]. With the emergence of the Paris Agreement, a new innovative system of nationally determined contributions (NDCs) by nations around the world has been established reflecting countries' highest ambitions to take climate measures beyond what has been previously implemented [2,4,5]. To ensure countries' efforts to meet with the Agreement's objectives, it becomes imperative to identify dynamic challenges to guide future research on key mitigation technologies to enable their further deployment [2,6].

With the attention now on the implementation of the Paris Agreement, the energy sector should maintain momentum and lead international efforts towards decarbonization to ensure long-term sustainability for the years to come [4,7,8]. In addition, the term decarbonization has been recently replaced by the much vaguer term of "emissions neutrality", leading many climate scientists in the field to support the idea of rapidly declining global emissions' levels towards zero by 2050. This latter suggests that negative CO_2 emissions are essential in a global scale, by the second half of the century, to get rid of gas from the atmosphere and store it on land, underground, or in the oceans. Achieving negative emissions signals the deployment of currently undetermined and contentious technologies, as bio-energy with carbon capture and storage (BECCS) [9–12].

Biomass derived through sustainable growing and harvesting practices is considered an alternative to fossil fuels, which absorbs CO_2 from the atmosphere (i.e., through the process of photosynthesis) and releases it during transformation or combustion, producing electrical energy. The capture and storage of the released CO_2 in geological formations enables the permanent removal of the CO_2 from the atmosphere. This option is referred to as 'bio-energy with carbon capture and storage' (BECCS) and, when carefully deployed, it is expected to provide low-carbon energy products and to achieve negative CO_2 balance [13–15].

BECCS is considered as one of the most promising negative emissions technologies (NETs). Even though demonstration at a commercial scale has not yet been achieved, BECCS is now included by many climate scientists in the majority of modelling "pathways" showing how the 1.5 °C goal could be achieved [13,16]. BECCS is considered "carbon negative", since bioenergy is theoretically "carbon neutral" based on the idea that biomass plants will regrow to sequester about as much CO_2 emitted during the combustion process [10,17]. However, many critics argue that emissions from land-use change and life-cycle emissions are not thoroughly considered [14,18]. Although large BECCS deployment facilitates reaching the 1.5 °C target in scenarios, the large reliance on BECCS has raised uneasiness amongst policymakers and scientists, with sustainability risks highlighted as the prime concern. For example, large-scale deployment of BECCS would require vast areas of land for the cultivation of biomass, which raises competing interests with the conservation of ecosystem and food security in the face of a still growing population. Political implications are further enhanced by the fact that suitable area for growing biomass is not distributed evenly across the globe [10,17–19]. It becomes apparent that further research to assess BECCS potential and regional opportunities is essential at this point and should be routed to address existing risks and concerns.

The work presented in this article considers relevant technology associations' and platforms' perspectives on 10 main research priorities that merit further attention by the research community for BECCS to be successfully deployed. These insights are supplemented by an extensive academic review extracting more specific assessment needs for each priority area, as raised by scientific and grey literature. The main goal is to explore whether these research priorities, as highlighted by the respective technology associations/platforms, are also supported by recent assessment and feasibility studies on BECCS, to bridge the gap between market needs and industrial know-how and scientific research inquiries. Finally, a number of implications for end-users involved in the field of policy and practice are suggested to enable better-informed decisions and to shape directions for further development and deployment.

The rest of this paper is organized as follows: Section 2 presents an overview of the methodological approach used for the identification of the key research priorities and specific up-to-date assessment needs for CCMOs of interest. Section 3 presents the application of our methodological approach for the case of BECCS. More specifically, Section 3.1 presents the key research priorities, for the case of BECCS, as reflected in the positions papers, of relevant technology associations/platforms, reviewed. These research priorities guided the scientific literature review, presented in Section 3.2, with the goal of acknowledging additional, specific, and up-to-date assessment needs per each priority area, raised by the scientific literature. Finally, in Section 4, we discuss key implications of our findings for policy and practice; while, in Section 5, we present the conclusions of our work and the main lessons learned.

2. Identifying Research Priorities and Assessment Needs for Climate Change Mitigation Options (CCMOs)—A Methodological Framework

There is already a large body of academic studies (i.e., scientific articles, literature reviews, etc.) analyzing demonstration programmes and industry pilots, and assessing the feasibility or the performance of different CCMOs. In addition to scientific literature, position papers are being published regularly from relevant technology associations/platforms presenting key priority areas to bridge the gap between basic research and market needs. Such position papers have been considered in the framework of the H2020 project CARISMA (Coordination and Assessment of Research and Innovation in Support of climate Mitigation Actions, http://carisma-project.eu/) to provide a good basis for prioritizing future research on CCMOs of interest. Experts' knowledge and concerns were also incorporated as a supplementary source of input.

Figure 1 below illustrates the methodological framework suggested for the identification of research priorities and assessment needs for CCMOs of interest.

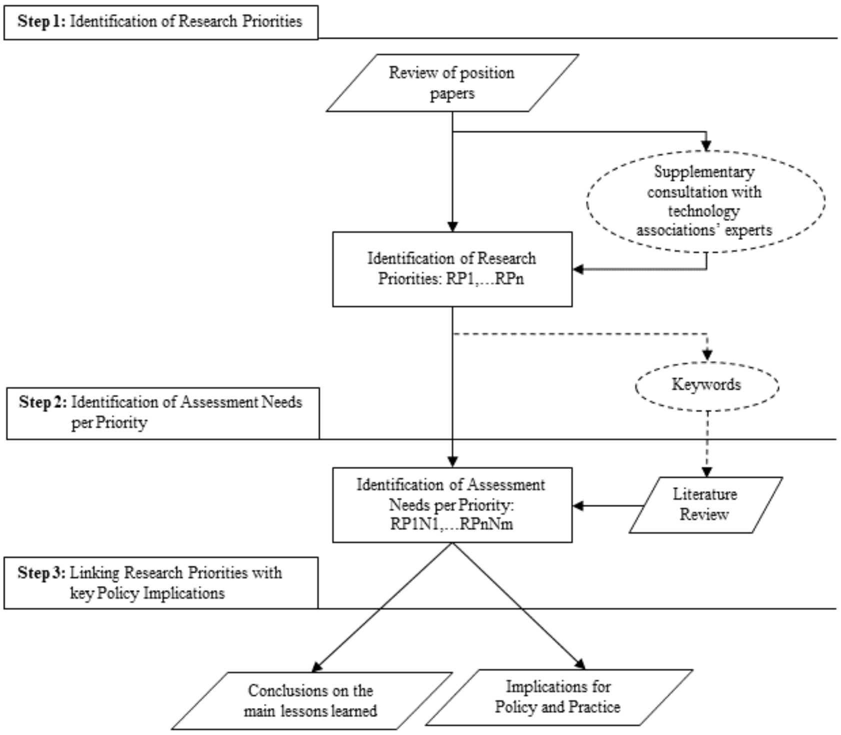

Figure 1. Methodological framework for identifying research priorities and assessment needs for CCMOs under study.

2.1. Step 1: Identification of Research Priorities (RPs)

Typically, during the development of the position papers published by the respective technology associations/platforms, an extensive stakeholder consultation process (i.e., round tables, surveys, open discussions, meetings-events, etc.) takes place. Step 1 takes advantage of that and builds on accumulated knowledge from a wide representation of market experts, technology providers, and other relevant stakeholders in the field, that has been recently synthesized and further communicated by the technology associations in the form of research priorities (RPs).

To select the position papers relevant to our study, the following criteria have been used:

1. Specialization of technology associations/platforms for the CCMO of interest (mainly on European level),
2. Legal status and overall activity/duration of the technology associations/platforms,

3. Technology associations'/platforms' members and network in Europe and worldwide,
4. Clear statement of the technology associations'/platforms' positions,
5. Date of publishing,
6. Methodology used to support the positions expressed,
7. List of references.

Furthermore, the outcomes of the position papers were supplemented by direct contacts with associations'/platforms' experts, to validate the key research challenges extracted and to receive additional feedback on extra insights and updates, through semi-structured questionnaires. This process highlighted recurrent knowledge gaps that were further distilled into key research priorities.

2.2. Step 2: Identification of Assessment Needs per Priority (RPNs)

Step 2 consists of reviewing literature studies, covering one or more of the research priorities extracted by Step 1 above. The main goal was to ensure that literature research was done in a structured way, in order to minimize the probability of missing out important and information-rich contributions.

The rationale on the literature review was hybrid, incorporating existing knowledge from both scientific articles (i.e., peer-reviewed articles in scientific journals, proceedings and book chapters) and "grey literature" (i.e., technical/scientific reports, project deliverables, etc.).

1. For the case of scientific articles, the literature search was structured in two rounds:
    - In the first round, generic keywords were used to identify literature sources of interest. For the purpose of broad thematic inclusion, keywords related to the assessment of different aspects of the CCMO under study were used. Indicative keywords that guided the initial literature search were: "cost–benefit analysis", "research challenges", "innovation", "assessment framework", "sustainability issues", "regulatory framework", "life-cycle analysis", "environmental impacts", etc.
    - In the second round, the initial search was expanded, using some additional keywords, to account for more specific themes, as extracted from the research priorities identified in Step 1.
    - In both rounds, the search results were limited to the period of 2000 till 2017, selecting studies from 2010 onwards. However, older studies were evaluated according to their relevance and impact and few of them considered appropriate to be included.
2. For the case of grey literature, the search process was focused on the inclusion of relevant state-of-the-art scientific studies (e.g., research work published by IEA, IPCC, etc.) and technical reports/deliverables from EC funded projects or other research programmes, to build on existing knowledge and experience. Search results were also limited to the period of 2000–2017 for this case, selecting studies from 2010 onwards.

The analysis of evidence from the literature was based on a randomized sample, due to a large number of relevant search results. Our literature review was not exhaustive, rather it served to cross reference the key research priorities expressed by the technology associations, and to provide evidence on whether additional, more specific, and up-to-date assessment needs have already been raised from the academic community.

2.3. Step 3: Linking Research Priorities with Key Policy Implications

Step 3 provides the main lessons of the previous two steps, by synthesizing findings in a way that: (i) shapes specific directions for future research to update experts in the field about the prerequisites of further development and deployment of the CCMO under study, and (ii) encourages the design of new policy instruments or the revision of the existing ones, to support policymakers in making better-informed decisions.

3. Application for the Case of BECCS

In this section, the methodological framework presented above is being applied for the case of BECCS, to extract research priorities, as expressed in position papers published by relevant technology associations/platforms, and to validate if these priorities are, also, reflected in recent studies in the scientific literature. Specific up-to-date assessment needs per each priority area, are, also, identified by the literature review, to bridge the gap between market/industry needs and scientific research inquiries.

3.1. Identification of Research Priorities for the Case of BECCS

The position papers identified and reviewed incorporate knowledge and viewpoints expressed by: (1) the Joint Task Force of the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) (the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) is a unique coalition of stakeholders united in their support for CO_2 capture and storage (CCS) as a key technology for combating climate change) and the European Biofuels Technology Platform (EBTP, now ETIP Bioenergy) (European Technology and Innovation Platforms (ETIPs) are industry-led stakeholders recognized by the European Commission as key actors in driving innovation, knowledge transfer and European competitiveness in the energy sector), and (2) the Bellona Foundation (the Bellona Foundation is an independent non-profit organization with the aim of meeting and fighting climate challenges, through the identification and the implementation of sustainable environmental solutions).

These position papers used in the context of our study are listed below:

I. "Biomass with CO_2 Capture and Storage (Bio-CCS). The Way Forward for Europe" [17],
II. "The Carbon-Negative Solution: Incentivizing BIO-CCS in Europe" [20].

To supplement our analysis, direct contacts with SINTEF (SINTEF is the largest independent research organization in Scandinavia and member of the ZEP) were made, to validate on existing knowledge (as extracted from the review of the position papers above) or provide additional feedback on key research priorities.

The outcome of Step 1 of the methodological framework presented in Section 2 above is Table 1, which outlines 10 key research priorities that merit further attention from the research community, for BECCS to be further developed and deployed in the future.

Table 1. Ten key research priorities for the case of BECCS according to technology associations/platforms.

Research Priority (RP)	Why is this Research Priority Required?	Section
RP1: Evidence of pilot and demonstration projects.	Pilot and demonstration projects to provide evidence on progressive technologies and close knowledge gaps.	3.2.1
RP2: Detailed cost analysis and Life-Cycle Analysis (LCA) of BECCS value chains for the different technology routes.	Cost and life-cycle impacts for the large-scale deployment of BECCS have not yet been thoroughly evaluated, either in a European or a global scale. Considering the significant differences between the various technology routes, a general reporting would not be sufficient and a more exhaustive assessment is required.	3.2.2
RP3: Improving public perception and awareness.	Public perception and attitude towards BECCS projects differs as compared to fossil CCS projects.	3.2.3
RP4: Up-scaling biomass conversion processes for improved economies of scale for CCS deployment.	To make the most promising biomass conversion technologies combined with CCS commercially available by 2020 and enable wide-scale deployment of BECCS.	3.2.4
RP5: Accelerating research into sustainable advanced biofuels.	Enhance advanced biofuel technology routes, to ensure economic viability and ameliorate the performance and reliability of conversion processes.	3.2.5

Table 1. *Cont.*

Research Priority (RP)	Why is this Research Priority Required?	Section
RP6: Improving data accuracy on sustainably available land.	The effects of direct and indirect land exploitation are considered key determinants for the feasibility of a BECCS project, considering that vast areas of land will be needed if BECCS are to contribute to future mitigation strategies.	3.2.6
RP7: Assessing the potential for biogas co-firing in gas power plants–Opportunities for hydrogen production.	A wide variety of biomass feedstocks could be potentially used to release energy through conversion to other vectors (e.g., biogas) and thus, work is still needed to estimate the opportunities for BECCS when biogas is combined with CCS.	3.2.7
RP8: Determining the effect of the composition of biogenic CO_2 on the CCS value chain in power plants.	The composition of biomass fuels is variable, and their generally high alkaline content can lead to ash deposition and corrosion when co-firing in existing boilers, which will lead to soaring costs.	3.2.8
RP9: Identifying any specific storage properties for biogenic CO_2 (i.e., biogenic impurities in the CO_2 stream).	Because of (geo-)physical variations, there is a need to explore specific storage properties that will provide storage site operators with a clearer view of the existing suitable storage sites.	3.2.9
RP10: Studying algal (macro/micro) biomass feedstock in terms of fuel properties and CO_2 capture.	Because of the high uncertainty and limited accessible data, marine biomass has not yet been evaluated as an option that highlights and supports the full potential of BECCS. Thorough research is required worldwide to discover new ways to take advantage of the energy potential of these promising marine types of biomass.	3.2.10

3.2. Identification of Assessment Needs per Priority for the Case of BECCS

Applying Step 2 of our methodological approach, more than 100 literature studies went through review. Following the hybrid rationale of our review:

1. For the case of the scientific literature:
    - in the first round of the literature search, we attempted to identify literature sources using several combinations of "BECCS" and indicative, generic keywords, as presented in Step 2 in Section 2 (e.g., "BECCS" AND "cost-benefit analysis", "BECCS" AND "regulatory framework", etc.).
    - in the second round, our initial search was expanded, searching for combinations of "BECCS" with specific keywords extracted from the Research Priorities identified in Step 1 and presented in Table 1 (e.g., "BECCS" AND "projects", "BECCS" AND "life-cycle analysis (LCA)". "BECCS" AND "land-use", etc.).
2. For the case of grey literature, we made sure to include knowledge from important scientific reports, as the "Technology Roadmap, Carbon Capture and Storage" or the "Technology Roadmap Bioenergy for Heat and Power" published by IEA [21,22] or reports from relevant research programmes, as the "AVOID 2" research programme (AVOID 2 is a UK government funded climate change research programme) [23,24].

Figure 2 below presents an overview of the literature sources reviewed, across five key dimensions of interest (i.e., economic, social, environmental, regulatory, and technological) for the case of BECCS. Literature findings indicated a plethora of studies focusing on the economic, environmental, regulatory, and technological dimensions of BECCS, while they also highlighted a lack of studies for the social dimension.

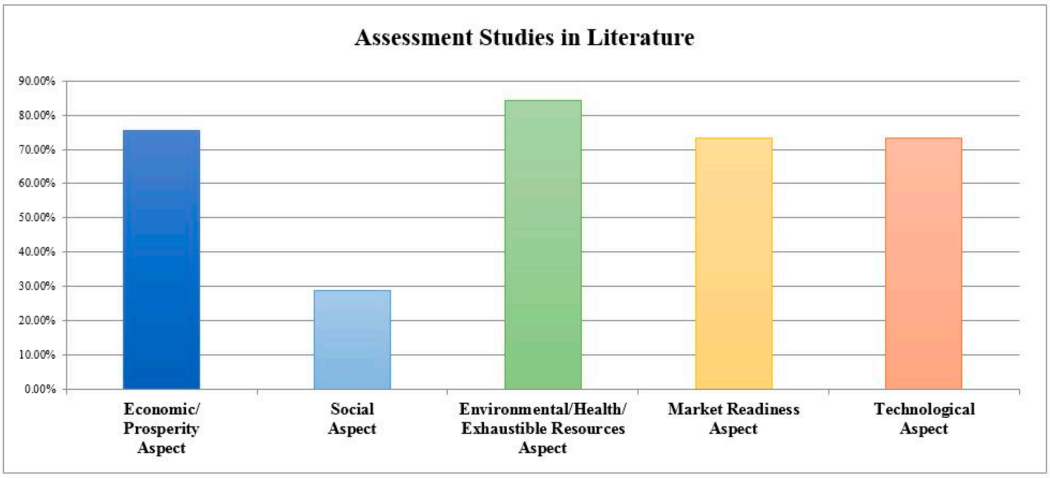

Figure 2. Dimensions under assessment in the ensemble of the literature studies reviewed.

The research priorities identified during Step 1 and presented in Table 1, are further analyzed and discussed based on findings from recent scientific literature in the field. The aim is to explore whether these research priorities are also raised by recent assessment and feasibility studies on BECCS, and whether additional assessment needs can be identified, to communicate existing research knowledge to the interested parties in the market. The sections below present a discussion for each research priority, followed by a set of more specific assessment needs, when and where identified through the academic review.

3.2.1. RP1: Evidence of Pilot and Demonstration Projects

Development of CCS technologies provides a new suite of opportunities for BECCS [23,25–28]. Although biomass is already extensively used in power generation applications utilizing a variety of feedstocks, CCS is still in its early stage and as a result, BECCS is still a far-future prospect which first requires CCS demonstration at scale [23,26–32]. The connection between BECCS and CCS is still obscure. BECCS is already established on solid knowledge foundations and will benefit from the further diffusion of CCS and from the fact that some CCS demonstration projects will perform BECCS [30,31]. However, policy measures to reduce the risk that CCS obstructs BECCS progress will be essential [30,33]. Over the decade 2020 to 2030, CCS can be deployed on one out of eight gas- or biomass-fired power plants, primarily in OECD member countries and China [21]. BECCS could be easily applied into pulp and paper industry sectors, but growth opportunities are also valid in cement, iron, and steel industry; and oil/gas refineries [34–36].

One of the main problems for BECCS demonstration is scale [26,31,32,37]. CO_2 flows are expected to be of a smaller scale, as compared to those used in commercial fossil fuel power plants, raising both capture and transportation costs. Location also constitutes another barrier, defined by the necessity to be close to biomass resources (to reduce cost and energy requirements for biomass transportation), rather than to CO_2 transport routes and storage facilities [23,37]. The main idea is to develop structures around the already existing sources of energy, including specialized CO_2 pipelines leading to storage sites. In fact, lack of infrastructure could become the most crucial economic obstacle to dedicated BECCS unless located near a storage site, landing point or existing large point source equipped with CCS. [29,31]. The suitability of BECCS will differ across countries; some of them will be more well-suited to extensive BECCS applications than others [26,27,29–32], as there are many potential obstacles for large scale implementation [29–31].

Smaller-scale BECCS applications, such as co-location of dedicated or co-combusted biomass on fossil CCS CO_2 transport pipeline pathways, would be potentially less problematic and much easier to envisage. Thus, BECCS potential must not be exaggerated, considering the small number of existing studies on the costs of connecting bio-processing (e.g., combustion, gasification, etc.) infrastructure with CO_2 storage sites and the current controversial scenarios of global bioenergy potential [29]. On the other hand, economies of scale could increase the transport and storage costs from larger fossil or co-fired plants, compared to smaller-scale biomass plants [29,31,37]. Once a CO_2 transport and storage system is developed, there may be the potential to set up smaller-scale bioenergy power plants with capture adjoining to the large CCS stations [26,29,31]. The full potential of BECCS will be implemented only to regions with developed infrastructure and favorable (i.e., high) CO_2/natural gas prices in place [19].

The IEA bioenergy roadmap suggests that the first commercial-scale BECCS project should happen between 2020 and 2025 [22]. Even if they are in their infancy, demonstration projects can provide a chance to acquire knowledge, reach a consensus and establish support around BECCS [30,31,36]. BECCS encounters big challenges in financing and as a result, no such plants have been currently constructed and tested at scale [19,38]. Capital expenses of BECCS could be alleviated by investment subsidies and thus, financial support is an essential part of future success [39]. Currently, BECCS are mainly deployed in the United States, Western Europe, Eastern Europe, Japan, and Canada [40] and overall, there are around 20 BECCS projects globally in different stages, ranging from evaluation over operation to cancellation [19,26,41].

Table S1 in Supplementary Materials summarizes these projects and their main characteristics.

It is crucial that the number of BECCS projects established in all phases is expanded [26]. However, only a few actors are aware of the BECCS potential, since no governments, international organizations, multinational companies, or other resource-rich associations have so far committed to BECCS deployment. Surprisingly, biomass actors have not yet been actively engaged in developing and implementing BECCS, even if it might be claimed that BECCS could be used to boost and reinforce the biomass niche. Supporters of BECCS so far, come mainly from academia, including researchers working with long-term climate modelling scenarios (i.e., IPCC and IIASA), and only a few NGOs (i.e., Norwegian Bellona and ZERO) and a limited number of companies (i.e., Norwegian Tel-Tek and Swedish Biorecro) are currently proactive in this field [30].

The relevant assessment needs identified are:

RP1N1	Investigating the synergies and advantages of linking BECCS with existing European CCS strategies.
RP1N2	Further insight into the economic and infrastructure boundary conditions for CO_2 capture from bio-ethanol production, using detailed case studies.
RP1N3	Further assessment of biomass uses in industrial sector in combination with CCS (e.g., steel, cement production), biomethane production with CCS and CCS in the pulp and paper sector.
RP1N4	Further assessment of the impact of (co-) firing biomass on the performance of CO_2 capture options in pilot/demonstration plants, especially regarding potential effects of increasing biomass output.
RP1N5	Further consideration of the co-utilization of biomass and coal in current and new Fischer–Tropsch facilities, which are planned or operate worldwide in combination with CO_2 capture from bio-ethanol production.
RP1N6	Assessing the performance of a biomass energy infrastructure that enables BECCS, including adjustment in optimal plant size for biomass combustion and conversion systems, to respond to the economies of scale required to implement BECCS.

3.2.2. RP2: Detailed Cost Analysis and Life-Cycle Analysis (LCA) of BECCS Value Chains for the Different Technology Routes

The Need for Further Cost Assessment

There is a high uncertainty in cost estimates for BECCS as they are defined by many variables and assumptions coupled with the additional doubt of limited commercial experience of a full-scale CCS plant [26,27,29,31,32,42]. Given that there is an absence of constant and thorough assessment studies of current and expected cost of CCS, literature indicates that CCS technologies deficiency is the most important cost barrier for BECCS. According to literature, costs for BECCS could be compared to conventional CCS technologies, with costs ranging from 60 to 250 USD/tCO_2 [18].

Regarding CO_2 transport, the biggest barriers are the technical feasibility and cost-effectiveness based on the transportation distance [40,43]. Transportation costs are determined based on whether existing pipelines can be re-used, or there is a need to construct new infrastructure, whether transport is onshore or offshore, whether there is a CO_2 transport network, or point to point transport is required [26,29–31,44]. Large-scale transportation alternatives could not be easily predicted, since pilot plants require large investments. However, storage remains the key determinant of BECCS success and economic viability [40]. The storage costs depend on the capacity of storage properties and the number of injections [26,29,31]. CCS costs will be reduced, only if the storage sites are placed near big CO_2 emitters from biomass operations [40]. The costs related to CO_2 capture and transport are probably higher at a BECCS plant compared to a fossil-only CCS plant, as dedicated bioenergy power or heat plants are generally smaller [29,30,32].

Literature highlights many potential BECCS technology routes. According to IEAGHG, six of the most promising routes are: (1) pulverized coal power plant with biomass co-firing (PC-CCS co-firing); (2) circulating fluidized bed combustion power plant, with a 100% biomass share (CFB-CCS dedicated); (3) integrated gasification combined cycle with co-firing of biomass (IGCC-CCS co-firing); (4) biomass integrated gasification combined cycle (BIGCC-CCS dedicated); (5) bio-ethanol advanced generation; and (6) biodiesel based on gasification and Fischer–Tropsch synthesis [45].

From an economical perspective, BIGCC-CCS and IGCC-CCS seem to be the most attractive routes [19,43]. Comparatively, biomethane production alternatives present an insignificant potential, with some limited interest in anaerobic digestion [18]. Klein et al. showed the long-term potential of BIGCC with CCS as the principle bioenergy conversion technology [46]. BECCS would easily compete with coal or gas (without capture) at a carbon price of around \$100/tC, and cheaper at around \$160/tC, considering a biomass gasification combined cycle plant with CO_2 capture. Referring to the EU Emissions Trading Scheme (EU ETS), an ETS certificate price of €48–55/tCO_2 (€176–202/tC) could be essential for a biomass co-fired plant with capture to reach the advantage of an equivalent plant without capture, and €65–76/tCO_2 (€238–278/tC) for dedicated biomass plant with capture [29,31]. For large biomass-based substitute natural gas (BioSNG) production plants, Carbo et al., claim that the CO_2 avoidance cost amount to 62 €/ton CO_2, under the assumption that these negative emissions are recognized in the emissions trading [47]. Finally, co-firing biomass with coal in bigger plants indicates a rather reduced incremental cost providing that CCS has already been included [42].

Table S2 in Supplementary Materials summarizes a collection of techno-economic assessment studies in literature, presenting key assumptions and findings, concerning various technology routes for the principal value chains of BECCS.

Literature acknowledges that BECCS costs could be minimized if large biomass conversion plants are used, in which the improvement of profitable and low-emitting large-scale feedstock and supply logistics would be required [48]. However, there are only a few studies available looking into the cost of connecting bio-processing (e.g., combustion, gasification or other) infrastructure with CO_2 storage sites [29].

The relevant assessment needs identified are:

RP2N1	Examining the economic trade-offs of different alternatives for CO_2 capture from biomass electricity or poly-generation systems.
RP2N2	More studies on the cost of bio-processing (e.g., combustion, gasification, etc.) infrastructure connection with CO_2 storage sites to accelerate BECCS demonstration.
RP2N3	Assessing the BECCS potential in a regional scale and more thoroughly using specific cost supply curves for CO_2 transport and storage, including source ink matching.
RP2N4	Further research on the role of BECCS in IAM scenarios of future emissions. IAM assumptions need to become more transparent regarding the future availability of BECCS.
RP2N5	Detailed investigation and quantification of the key determinants of the trade volume and price of biomass, enabling a more robust evaluation of the economic benefits of BECCS technologies.

The Need for Environmental Assessment from a Life-Cycle Perspective

A life-cycle approach is necessary once negative emissions are to be claimed. To date, only few LCA studies of BECCS exist, mainly indicating that it constitutes an effective option to generate electricity with negative net CO_2 emissions, which increases with a growing share of biomass in the fuel [26,29–31].

Some literature studies [30,31,49,50] agree with the viewpoint, also expressed by the respective technology associations/platforms, that EU ETS regulation is not yet prepared to recognize negative emissions. From the climate change perspective, captured and stored biogenic CO_2 is as valuable as fossil CO_2, and as a result, acceptable CO_2 emission reductions should be similar for both cases. On other hand, the required adjustments in the existing ETS framework to account for negative emissions may not be feasible to be adopted, since it includes uncertainties due to land-use change (LUC) results that might emerge from deploying BECCS, especially on the magnitude that is potentially needed to meet challenging emissions reduction targets beyond 2050 [23,51]. Additionally, there is still uncertainty whether BECCS yields net negative emissions during the full life-cycle [23]. Despite the specific technology pathway, the capacity of BECCS to produce negative emissions could become critical in achieving deep emissions decrease by offering a mechanism to balance emissions in the world economy [25–27,32]. However, BECCS must not be perceived as a reason to promote higher overall cumulative emissions, even with an equivalent stabilization target, as BECCS does not entail the undermining of the further development of renewable energy sources or the relaxation of mitigation efforts [29].

It is obvious that biomass use represents the most prominent aspect of BECCS from a life-cycle point of view [26]. Evidence from literature shows that up to 66% of emissions from a particular bioenergy life-cycle are emitted in the biomass production chain [52], and that an amendment in management strategy focus could easily turn emissions from positive to negative or vice versa. It is true that any biomass refining or utilizing process, involving CO_2 emissions, could deploy CCS technologies. The CO_2 footprint of a procedure could also be eliminated if carbon was removed from the process in other forms than CO_2 [31,36]. This results in a totally different life-cycle perspective for carbon cycles with aspects also relating to the declining biomass use [26,36]. Direct anthropogenic CO_2 emissions are not derived by biomass combustion; thus, its capture contributes to CO_2 emissions reduction during the entire lifetime. It is claimed that the co-firing of biomass results in a decline of emissions of CO, SOx, NOx, and flue dust by about 12–16%, as compared to boilers fired only with coal. It is evident that a lower impact on the depletion of non-renewable natural resources stems from the application of biomass co-firing with CCS technologies. This fact demonstrates that the biomass co-firing is considered to be a sustainable solution [53].

According to LCA results in the literature co-firing 30% biomass in combination with 90% CO_2 capture leads to negative net CO_2 emissions of 67–85 g/kWh [33]. Although so far studies have investigated the effects of co-firing on the power plant's efficiency and CO_2 balance, none of them have yet managed to conduct a thorough research of the impact of co-firing on the performance of the CO_2 capture unit. It is essential that the effects of co-firing on CO_2 capture performance are examined, since the different components in biomass modify the flue gas properties, and thus the behavior of chemicals and catalysts in the capture procedure could be affected. As such, both the performance of the capture unit and the distribution of inputs and outputs of the power plant, might exhibit differences [33]. The majority of the persistent life-cycle emissions of BECCS derive from fossil fuels use (e.g., for planting and harvesting) and LUC [24,48]. The intensity of these emissions is also influenced by several factors such as the specific type of biomass, location, scale, and biomass production–land management systems.

Finally, global warming potential (GWP) is solely investigated by most of the LCA studies in literature, whereas effects on other environmental features are merely examined in the study of Carpentieri et al., where 100% biomass-fired BIGCC is the notable electricity generation technology and pre-combustion chemical absorption, the CO_2 capture strategy [54]. It is important to underline that there are some restrictions, uncertainties, variabilities, and lack of similarity in LCA studies [19]. Literature studies acknowledge restrictions in the availability and reliability of data that could have an effect on the environmental performance of BECCS [19,24]. Such limitations comprise the existing experimental data on the impact of co-firing biomass on the CO_2 capture procedure and the life-cycle inventory (LCI) data on the construction and dismantling of an IGCC, and on the use or treatment processes of by-products and waste streams [33]. Although BECCS routes could favor the reduction of human health impacts, the net effect might remarkably differ in various cases [19].

Table S3 in Supplementary Materials summarizes a collection of LCA studies in literature, presenting key assumptions and findings, concerning various technology routes for the principal value chains of BECCS.

The relevant assessment needs identified are:

RP2N6	Optimization of supply, conversion, and storage systems, assessing life-cycle risks.
RP2N7	Evaluating the impacts of co-firing on CO_2 capture performance from a life-cycle perspective.
RP2N8	Quantifying the effect different BECCS technology routes have on human health.
RP2N9	Follow-up work on the interactions and ambiguities in the carbon-cycle response to negative emissions.
RP2N10	Investigating the possible carbon debt that comes from the time span between biomass production and usage.
RP2N11	Assessing the potential of novel carbon storage and/or utilization technologies (e.g., augmented ocean disposal) from a life-cycle perspective.
RP2N12	Investigating the best method to exploit biomass (e.g., use agricultural residues and push down into more marginal fuels, contaminated material/waste, and un-harvested biomass), from a life-cycle perspective.
RP2N13	Maximizing and optimizing yields, through bioengineering, for biomass supply with negative emissions (considering the whole bioenergy life-cycle, from supply and harvesting to processing and conversion).

3.2.3. RP3: Improving Public Perception and Awareness

Although a plethora of studies have already been conducted on the public perception of CCS (see e.g., [55–66]), literature acknowledges that studies focusing merely on the public opinion of BECCS are limited so far [19]. A lot of research conducted to date regarding public opinion of CCS with fossil fuel has provided meaningful insights in order to figure out risk perceptions that affect public acceptance of the technology. However, the degree to which risk perceptions of BECCS can affect the technology's deployment or cause other issues of acceptability, has not yet been defined [26,35,67]. The presentation of CCS as a standalone technology does not favor its acceptance [67]. However, it is more likely to be appreciated if approached from a social perspective and demonstrated as a portfolio of low-carbon energy technologies [58]. It is commonly believed that public opinion will have an effect on the success of BECCS, while negative viewpoints of CCS and/or biomass are considered likely to undermine the technology's uptake. However, it is expected that biomass combined with CCS could be supported to a greater extent by public, than each of the technologies individually [29,67].

The reduction of carbon through conventional CCS (with fossil fuels) is more recognizable than BECCS, which seems to have a far less public profile despite its mitigation potential [67]. Vergragt and Markusson et al., declare that the predominant problem for BECCS is cultural, due to a deficiency in a 'community of support', lacking awareness and reliability amongst its own key stakeholders, and the wider public [30]. Although our review identified several studies focusing on bioenergy, little evidence exists in the literature concerning public perceptions of BECCS. To this end, key actions to increase public awareness of BECCS include: (1) an EU roadmap towards 2050; (2) formation of research groups that focus on BECCS; (3) BECCS specific centers and networks; (4) the organization of seminars and workshops that will benefit scientists, the public, and potential stakeholders; (5) directing dedicated BECCS research and development; (6) the provision of demonstration support, along with specific incentive programmes [25,67]. Despite the expansion of both CCS and bioenergy communities, the connection between them remains relatively weak. The main challenge will be to establish a BECCS actor networks and a BECCS technology system, by bringing different components together (e.g., ideas, key individuals, organizations, etc.) [29].

Literature also suggests that, in order to better understand the industry's current public perception on BECCS, social acceptance of bioenergy should also be considered [67]. Bioenergy is a technologically heterogeneous niche and thus, actor-networks are fragmented, with each sub-niche having distinctive principal actors and actor constellations. Disputes about the sustainability of different types of biomass could compromise socio-political legitimacy, leading to anti 'big-biomass' campaigns that might grow in the future [28,68–70]. Additionally, biomass production is usually presented in the public eye relating to the construction of waste plants, and as a result, social acceptance of bioenergy should conform with education and marketing [38]. Finally, in the public eye, the key concerns stated about bioenergy crops are associated with competition between bioenergy and food crops for the deployment of productive land. These concerns refer to the effect on biodiversity and deforestation, underestimation of greenhouse gas benefits, if biomass crops are grown on land with existing high carbon stock, and to the possible negative effects on communities (e.g., land rights, poverty, etc.) [23,29,56].

Finally, our findings acknowledge that to increase public awareness on BECCS, the industry should be actively engage with the media [26,67]. Since there are no previous studies exploring how BECCS is perceived by the media, there is a lack of knowledge, especially when it comes to the public image of the technology in comparison with fossil fuel-based CCS projects. It is necessary for the BECCS industry to monitor and take advantage of media, as new technologies and the possibility of becoming the center of public and political attention in the future could bring up existing risks and uncertainty. This fact could generate further awareness of BECCS, as well as interest about its wider application, use, and impact [67].

The relevant assessment needs identified are:

RP3N1	Investigating how BECCS is perceived by the media (also compared to fossil fuel-based CCS projects) to increase empirical knowledge and awareness.
RP3N2	Explore in more details how the human factor (e.g., different actors/components from different fields, positions, motives, etc.) can influence the further deployment of BECCS.

3.2.4. RP4: Up-Scaling Biomass Conversion Processes for Improved Economies of Scale for CCS Deployment

Literature has recently pointed out several changes in favor of biomass conversion, as a consequence of the cost-effectiveness of conversion processes, in comparison with new build dedicated biomass, and to the fact that conversion processes will enable further biomass applications by 2020, in sectors other than electricity generation (i.e., heat, transport, etc.). Coal-to-biomass conversion fits very well with the existing electricity regime, usually because of governmental preferences for working with incumbents on established large-scale technologies (e.g., co-firing and coal plant conversions), rather than new entrants (e.g., dedicated biomass) and smaller-scale solutions. Furthermore, it is also easy for operators to switch from coal to biomass and it provides a reliable and constant level of electricity generation. Nevertheless, even if the efficiency of conversion processes will probably increase in the future, due to the introduction of enhanced steam cycles for dedicated biomass power plants, fossil-fired power plants are expected to be above them, since on-site pre-treatment and operation require a higher amount of energy, and also the feedstock presents lower heating values [43].

Biomass can be converted in various ways in a BECCS system and a few studies have investigated which conversions are most effective, technically feasible, and can be integrated to carbon capture and storage systems [21,26,35,41]. There are a number of factors defining a specific conversion route, such as: the nature of the biomass feedstock, the availability of a given technology and the demand for a particular energy product, and more specifically electricity, heat, or fuels [71–74]. Biomass conversion technologies are characterized by diversity and a wide range of development and deployment stages [34,35,37–39]. Also, many of them have the ability to adapt to different feedstocks and to produce different energy products [34,38]. Literature acknowledges that capture systems are applicable to biomass energy systems [21,25,26,29,35,37,50,75,76]. Post-combustion capture (PCC) or oxy-fuel capture systems can be combined with modern biomass boiler technologies or retrofitted to existing plants, however the small-scale and low efficacy of existing biomass boilers (due to design limitations) would result in low efficiency [25,34]. Alternatively, coal-fired power plants can be retrofitted to co-fire biomass and incorporate CCS [21,25,26,33–35,77], while modern biomass gasification technologies can also incorporate pre-combustion separation (PCS). Finally, oxygen-blown biomass gasification offers higher energy efficiency and carbon capture and has already been demonstrated. However, there is still a lack of operating experience and economic data [25,34,35,75].

The four major biomass conversion routes are biochemical conversion (e.g., fermentation and hydrolysis), thermochemical conversion (e.g., gasification), power production (e.g., combustion), and industrial processes [34,36,37,75]. Thermochemical biomass conversion processes, along with ethanol fermentation, constitute the first-phase objectives for applying CO_2 capture, both from a logistic and cost aspect [34,36]. Experts suggest that R&D is needed for CCS and for both thermochemical and biochemical conversion processes, highlighting in parallel the need for demonstration activities [38] and further costs reduction, especially for the case of biochemical conversion, where current projections for 2020 seem pessimistic [38,78]. Thermochemical conversion processes—such as combustion and co-combustion of biomass with coal—are well-developed, including mature technologies (e.g., steam turbines and gas turbines), while other thermochemical paths, as pyrolysis, are less-developed, including emerging technologies (i.e., biomass integrated-gasifier/integrated gasification combined cycle, BIG/IGCC) [35,38]. Particularly, integrated biomass gasification combined cycle (BIGCC) is a promising conversion technology, especially suitable for CCS with a high capture rate [38,43]. Finally, another upcoming and promising option is the technology used to sugar cane-based energy, which converts part of the primary energy to ethanol via fermentation [39].

Overall, there is an urgent need to ensure the commercial availability (by committing to a clear R&D programme beyond 2020) of these new biomass conversion technologies, to achieve further diffusion and deployment of BECCS [79]. Significant advances are in need when it comes to large-scale biomass conversion, addressing issues of transport and intermediate storage of large amounts of biomass, as well as, improving pre-treatment processes to decrease moisture content and increase specific heat content of large-scale biomass supply chains [26,34,41,75]. In order to establish a stable investment environment and promote commercialization of new conversion technologies, it is urgent that strong and balanced policy efforts are put in place [22], while achieving competitiveness comparable to fossil fuels (e.g., dedicated carbon policies) [34,38].

The relevant assessment needs identified are:

RP4N1	Further research on improving boilers' design, materials, and combustion technologies.
RP4N2	Substantial advances on increasing conversion efficiency, in both the thermochemical and the biochemical pathway.
RP4N3	Further research on oxygen-blown biomass gasification, due to a lack of operating experience and economic data.
RP4N4	Further research on biological processes (e.g., bio-ethanol fermentation), as they offer further CCS opportunities.
RP4N5	More research on biomass integrated gasification combined cycle (BIGCC), as a very promising biomass conversion technology.
RP4N6	Assessing the potential of technology routes that combine bio-methane production with CCS on country or local level, where conditions are favorable.

3.2.5. RP5: Accelerating Research into Sustainable Advanced Biofuels

Accelerating research into sustainable advanced biofuels is vital for the case of BECCS, as future deployment depends on understanding the feasibility of CCS applications to different biofuel plants [22]. Sustainable biofuels, right now, have a rather low momentum, mainly for their high costs and little cost reduction potential [80]. Recent innovation trajectories appear to have very low momentum, with coal-to-biomass now dominating in terms of both deployment and support from powerful energy companies and governments. With the current demand for sustainable biofuels, it is essential to develop a variety of resources, as the combined mix will be a critical step to replace fossil fuels. Still, limited policy commitments exist for additional extension of this niche, as well as for broader concerns on sustainability and competing uses of biomass for the decarbonization of other sectors [28].

Although advanced biofuel deployment is still in an early stage and lots of developing countries have not yet explored new technologies, one significant question to answer is whether there are sufficient feedstock supplies to fulfill future biofuel demand, thereby, the investment in the necessary R&D and infrastructure is perceived to be imperative for the following two decades. Findings from literature acknowledge that, while in some emerging economies sufficient financing and R&D opportunities are available, for other developing countries the promotion of sustainable growth in the next years has merely restricted potential by advanced biofuels. As a result, until commercial availability of new technologies is achieved, developing countries should focus on investments in rural infrastructure, agricultural production, and improved energy supply. Another point of consideration, for the case of the developing countries, is to develop alliance both with developed countries and other emerging economies, to build infrastructure and to ensure technology access [81].

Advanced biofuels could offer a true supplement to fossil fuels, if high producing algae species could be recognized, advanced production and harvesting practices are utilized and innovative drying and oil extraction processes are employed. Finally, the IEA notes that the full assessment of the potential social, economic, and environmental effects of advanced sustainable biofuel production in practice is still at an early stage. However, to better understand these issues in developing countries and emerging economies, further research on specific areas of interest should be conducted [81].

The relevant assessment needs identified are:

RP5N1	Further research on the development of supply chain concepts, the assessment of feedstock features and the analysis of production costs worldwide.
RP5N2	Investigating how collaboration between developed and developing countries could assist in building capacities for advanced biofuels and in ensuring technology access.
RP5N3	Gathering field data from commercial advanced biofuel production from residues to better figure out effects on rural markets and on the overall economic conditions.
RP5N4	Continuous enhancement of technologies to deploy micro-algae production; oil extraction; and biomass processing-pre-treatment, logistics, and conversion technologies for flexibility, reliability, and scale.

3.2.6. RP6: Improving Data Accuracy on Sustainably Available Land

Numerous studies indicate that technical barriers related to the development of sustainable farming practices and socio-political barriers, such as competing uses of agricultural land to produce crops, biofuels and bio-based materials—along with the further development of agricultural regime—are of key importance for the future of BECCS [10,18,22–24,26,38,46,81,82]. Key concerns relate to: (i) the competition for use of the available productive land between bioenergy and food crops, (ii) the effects on biodiversity and deforestation, and (iii) the denial of greenhouse gas benefits, in case that bioenergy crops are raised on land with existing high carbon stock, as net avoided GHG emissions definitely depend on the method in which feedstock is procured [22,23,29,32].

Another important issue associated with sustainable bioenergy production for BECCS is land-use change (LUC) [19,24,48,83]. Direct LUC appears every time additional biomass feedstock demand results in the cultivation of new districts for biomass production and indirect LUC, when existing production areas cover the additional feedstock demand, replacing the previous production function of the land and provoking enlargement of land to new territories [19,23]. However, only a few studies have explored the land requirements of BECCS [84]. BECCS also faces quite a few challenges, since the sourcing of biomass from sustainable resources is not always guaranteed, leading to possible net positive CO_2 emissions outcomes, instead of a decrease of emissions [22,23,26,27,40,43,67]. The sustainability of land has already raised concerns to experts, because of biomass stock and impacts of increased biomass use on global lands, biodiversity, and also water use [26,38,41,43]. Thus, when assessing the potential for BECCS technologies, sustainability criteria should also be considered [19,38,43,45].

In addition, BECCS might lead to carbon stock loss and reduce or neutralize net positive GHG mitigation outcomes because of direct and indirect LUC [24,32,67,81]. Recent studies demonstrate that land-use and land cover changes derived by biomass production for energy objectives might affect the life-cycle GHG emissions balance in a negative way [19,32]. Policies (e.g., certification schemes) need to be implemented to promote biomass sustainable use and to avoid biomass infringing on food security and other environmental goals given that large areas of land will be required, if BECCS is to be included in the future mitigation strategies [10,26,32,38,81,85]. Accordingly, impact assessment of LUC should redefine the understanding of absolute CO_2 emissions avoided [32,67,81].

Finally, to better understand the impact of BECCS, it is important to improve the accuracy of the existing data regarding the sustainability of the available land, in order to determine the potential for dedicated energy crops, especially for the case of developing countries [23,24,81]. Particularly in emerging economies, important potential for the cultivation of dedicated energy crops is indicated by global estimations, with the highest potential assigned to countries with good climatic conditions or with the capacity to intensify their agricultural activities to large available areas of land. However, some of the existing assumptions are very promising, taking into consideration the high proportion of currently cultivated land, and the steadily rising population of some areas. Consequently, there may be a limitation on the availability of land used for energy crops for the production of advanced biofuels, requiring careful assessment [23,81].

The relevant assessment needs identified are:

RP6N1	Impact assessment of land-use change (LUC) on food production for the case of BECCS.
RP6N2	Thorough examination of factors that limit sustainable biomass storage at a regional level, and of actions required for the supply expansion.
RP6N3	Research on available land resources and land requirements of BECCS, through detailed case studies, to enable a detailed analysis of local rural markets; material flows; and specific social, economic, and environmental benefits and risks.

3.2.7. RP7: Assessing the Potential for Biogas Co-Firing in Gas Power Plants—Opportunities for Hydrogen Production

Producing biomass-based substitute natural gas (BioSNG) with CCS offers new opportunities for net CO_2 uptake from the atmosphere [47]. Various studies demonstrate that the incorporation of BECCS in the production of SNG has been thoroughly examined [86] and that BECCS is not limited only to production of electricity or heat, as it may also be used to produce biofuel units, like biogas and hydrogen [19]. Fossil fuel-fired power plants and CCS are not the only efficient methods to produce energy, as BECCS through BioSNG production, can be a competitive alternative. Due to the fact that CO_2 needs to be separated continually, so as to fulfill certain product specifications, BECCS technologies characterized by fuel synthesis offer relatively straightforward opportunities for retrofit application of CCS [47].

The Skåne area in southern Sweden is a region with multiple facilities to upgrade biogas. Since the upgrading process derives a high purity stream of CO_2 as a by-product, it has been suggested that CO_2 from various gas upgrading facilities in Skåne could be introduced to a BECCS project, reserving CO_2 in geological formations below ground in the south west parts of the region [26]. There has already been 20 years of experience in upgrading biogas and different upgrading technologies are available in the market. The option for an upgrading technology, and thus CO_2 removal, depends on various factors, such as the costs, composition, and characteristics (e.g., temperature, pressure, etc.) of the gas flow that must be treated, the required purity of the CO_2 stream, and the capacity (i.e., total gas flow) [44].

It is expected that over the decade 2020 to 2030, almost one-third of global biogas processing capacity will be CCS-equipped, along with large amounts of hydrogen production capacity [21]. Evidence from literature indicates that converting biomass into gas has the potential to become available for a wider variety of energy appliances. Biomass-sourced gas can be converted to electricity or mechanical work (via a secondary conversion device, such as an internal combustion engine) or used as a synthetic gas for generating fuels of a higher quality, or chemical elements (e.g., hydrogen). Other state-of-the-art alternatives incorporate dual fuel engines, in which biogas can be co-fired with a usually very small share of e.g., bio-diesel or bio-ethanol. In cases where cheap or waste sorbents are available at a local level, effective hydrogen production from biogas can be achieved, particularly via sorption enhanced reforming [87]. However, it has been proven that from a life-cycle perspective, the environmental and energy performance of hydrogen from biofuel reforming depends on the biogenic feedstock selected at a large scale [88].

Several potential process innovations for biogas technology have been thoroughly suggested and examined during the last few years. For example, fast internally circulating fluidized bed (FICFB) and MILENA are considered key promising gasification technologies, with both being in the demonstration phase and it is believed that, as soon as these two technologies are developed towards commercial-scale demonstration plant, they will permit full-scale commercial biogas power plants of 500 MW [43]. However, it is required that more review reports systematically compare, analyze, and evaluate the suitability of these emerging methods, focusing on realistic commercial potential. Innovations are also needed in biogas production, conditioning, and utilization and R&D efforts should be mainly headed to areas where disruptive innovations could be yielded relatively quickly. Finally, policy options will be necessary, since they form directions of innovation in biogas technology and need to be in place before biogas technology is selected to play a crucial role in the economy of any country [87].

The relevant assessment needs identified are:

RP7N1	Further research on novel biogas feedstocks.
RP7N2	Further research on novel biomass to biogas conversion routes.
RP7N3	Investigating industrial symbiosis of biogas with conventional emissions/energy intensive industries.
RP7N4	Further research on novel biogas upgrading methods, using CO_2 removal, through additional energy efficient pathways.
RP7N5	Further assessment of fast internally circulating fluidized bed (FICFB) and MILENA gasification technologies.

3.2.8. RP8: Determining the Effect of the Composition of Biogenic CO_2 on the CCS Value Chain in Power Plants

Biogenic CO_2 emissions are defined as CO_2 emissions related to the natural carbon cycle, as well as, those caused by the production, harvest, combustion, digestion, fermentation, decomposition, and processing of biologically based materials [26,49]. They are thought to be balanced with the CO_2 uptake from air during the growth of the plants. Biogenic CO_2 emissions are accounted as fossil emissions [26,47] and are captured just as them [26,89]. There are not any dominant technical limitations with biogenic CO_2 capture. Even if fluidized bed technology presents high flexibility regarding the fuels, with biomass combustion some difficulties arise with emphasis given in utilization of CCS. For instance, in the case of oxy-fired fluidized bed boilers, even small concentrations of chlorine in the fuel can result in deposits of harmful alkaline and chlorine compounds on boiler heat transfer surfaces, due to the enrichment of components in the flue gas because of a lack of nitrogen in furnace and flue gas re-circulation [49].

Literature indicates that significant issues need to be overcome to characterize the composition of biogenic CO_2 on the CCS value chain, in both dedicated and co-fired biomass installations [41].

Such issues are pollutant formation, carbon conversion, ash management, and balance-of-process issues (e.g., fuel supply and storage, fuel preparation and ash utilization). Another problem of boilers is the corrosion triggered by the formation of potassium chloride. A lot of fast-growing plant species—considered capable of supplying large quantities of sustainable biomass—have high levels of potassium, which can result in the formation of the corrosive potassium chloride. Nevertheless, corrosive species and harmful emissions could be decreased, in some cases, by using a blend of biomass with coal. In such cases, the biomass captures sulfur from coal and forms potassium sulfate, which is less corrosive than potassium chloride. Even if there are existing solutions to all of these challenges, further attention from the research community is needed to avoid the effects of corrosion [41,43].

The relevant assessment needs identified are:

RP8N1	Assessing the consequences of corrosion in boilers and fast-growing plant species that provide large quantities of sustainable biomass.

3.2.9. RP9: Identifying Any Specific Storage Properties for Biogenic CO_2 (i.e., Biogenic Impurities in the CO_2 Stream)

The storage of biogenic CO_2 is defined as the capture, compression and transport of a biogenic CO_2-rich stream to an onshore/offshore geological storage facility (sequestration) [86]. The introduction of BECCS to the storage stages of CCS does not cause any specific technical consequences, since the CO_2 stream produced by the capture process does not depend on the plant feedstock. For the case of biomass co-firing, developing the necessary infrastructure (i.e., specialized CO_2 pipelines routing to storage sites), will be constructed around existing large point sources [42]. Stored biogenic CO_2 offer the same value as stored fossil CO_2 and as a result, there should not be a difference between acceptable CO_2 emission reductions in the plant whether the stored CO_2 is fossil fuel derived or biogenic [49].

A previous IPCC assessment anticipates storage capacity in geological formations of at least 550 Gt of biogenic CO_2. The study underlines uncertainties concerning storage capacities in saline formations and focuses on the fact that the storage capability can be significantly larger, in the order of 1000 s of Gt CO_2 [90]. Stored biogenic CO_2 during the course of the century varies between 350 and 500 Gt CO_2, which conforms with the global capacity of 1000 s of Gt CO_2 [91]. Nevertheless, the application of biogenic storage at large scales requires further research. Also, it should not be taken for granted that this option could work widely, if there are not sufficient and safe geological storage options, as well as sufficient political acceptability [18,91].

Even if biogenic storage on its own could degrease atmospheric CO_2, there is a risk that the biosphere might cease to be a net sink and turn into a net source of atmospheric carbon. Advances in CCS technologies (i.e., in terms of CO_2 capture and storage in underground geological formations) could further contribute to the capture of CO_2 derived by bioenergy combustion for the production of electricity [67]. An important benefit of geological storage, as compared to other forms of carbon sinks (e.g., oceans, forests, etc.), is that it is not affected by temperature changes, tree logging, or other circumstances that could endanger these other types of carbon sequestration. In fact, in the case of other carbon sinks, there is the risk of negative feedback loops at high temperatures, potentially causing excessive releases of stored CO_2. The compression and geological storage of biogenic CO_2 requires its separation into a pure stream. As there is a great amount of CO_2 in biomass flue gas, CO_2 capture is definitely easier in the flue stream. This fact partly counterbalances the smaller scale of the biomass sites [26].

The relevant assessment needs identified are:

RP9N1	Further LCA of long-term storage properties of biogenic CO_2.
RP9N2	Determining the impacts of the existing biogenic geological storage options in terms of safety.
RP9N3	Exploring the political acceptability for application of sufficient and safe biogenic storage at large scale.
RP9N4	Investigating the impact of CO_2 leakage from the reservoir on the overall environmental performance of BECCS.
RP9N5	Further assessment of the potential of non-traditional biomass processes (e.g., algae, biochar, etc.), as new opportunities for storing biogenic CO_2.

3.2.10. RP10: Studying Algal (Macro/Micro) Biomass Feedstock in Terms of Fuel Properties and CO_2 Capture

New opportunities for the capture of biogenic CO_2 could arise from non-traditional biomass processes [36,92–94], as BECCS are closely related to biological sequestration, as a feedstock to derive algal biomass [29]. However, literature indicates that the use of micro-algal biomass for cost-efficient BECCS will continue to be limited in the short to medium term, as, in order to provide a competitive cost, it still requires technological breakthroughs, such as maximization of algal lipid content and growth rate [19]. For micro-algae capturing CO_2 directly from air, the low atmospheric CO_2 concentration and land availability are often pointed as the main limitations [40].

Conversion of algal biomass to energy includes various processes, ordinarily followed for the case of terrestrial biomass, and which are highly dependent on the type of biomass and sources, as well as on conservation options. The conversion methods for deploying micro-algae biomass could be divided into the two basic categories of thermochemical and biochemical conversion. Both thermochemical liquefaction and pyrolysis are considered the most technically feasible processes for conversion of algal biomass to biofuels, after the extraction of oils from algae [75,93,94]. Cost reduction of both small-scale and large-scale systems should be the predominant target of micro-algae production. This could be managed, for instance, by utilizing cost-effective CO_2 sources for culture enrichment, using nutrient-rich wastewaters or inexpensive fertilizers, deploying cheaper design culture systems with automated process control, and using greenhouses and heated effluents to increase algal yields [93,95].

Our findings acknowledge that third generation biofuels produced from micro-algae appear to be a practically feasible alternative energy resource that lacks of the most vital disadvantages related to first and second-generation biofuels [75,92–94]. Although micro-algae are highly capable to produce biofuels, replacing fossil fuel in power generation in parallel, challenges regarding the wide commercialization of their production need to be addressed. Such challenges are: (a) their limited demand due to fossil fuels' lower market price; (b) their high cost when produced from microalgae; and (c) the optimal energy balance between demand and cost-of-production [94]. Another obstacle faced by the existing stages of micro-algae cultivation is low cost with high efficient and low contamination harvesting methods [93,94]. Biofuel production from algal biomass is considered high-priced and the returns of investment are quite slow and low [93]. However, micro-algae biofuels are expected to become soon economic viable with the development of advanced technologies and possible government incentives. In this way, they could be compared to fossil fuels from a cost-of-production perspective [93,94]. At present, research focus on identifying the algae species that could be produced massively to make biomass production commercially feasible. Current harvesting processes using centrifugation (mechanical), chemical flocculation, biological, or electrical methods trigger challenges for recovering the suspended algae. All of the above procedures are still relatively high-cost [93].

The relevant assessment needs identified are:

RP10N1	Assessing the potential of other biomass supply options, such as aquatic biomass from algae.
RP10N2	Assessing the potential of phagotrophic micro-algae (phagotrophic algae is a microalgae species that can eat particles and other small bacteria (e.g. Ochromonas danica). There is not much research carried out yet on phagotrophic microalgae but, according to Milano et al., it could result in a sustainable biofuel feedstock in the near future [94]) as a sustainable solution for the near future,
RP10N3	Investigating the economic and commercial viability of novel technologies for cultivation of (micro-)algae,
RP10N4	Further research on the economic and environmental sustainability of algal biomass production methods.
RP10N5	Further research on the heat and mass transfer phenomena to ensure the best environment for (micro-)algae growth.
RP10N6	Bringing down the current costs for the commercialization of the production of biofuels from (micro-)algae at large scale.
RP10N7	Further research on the synthesis of the natural flocculants to decrease the time needed and costs of (micro-)algae harvesting systems.
RP10N8	Optimizing the logistical value chain of biomass, while studying the negative effects (e.g., due to water availability and soil quality) of algal biomass production.

4. Discussion

A critical challenge is often how to enable and improve relationships between academia and research with those involved in policy and practice. Challenges for climate change mitigation in Europe from policymakers' perspective include concerns about: (1) embedding of CCMOs in socio-economic planning in central and local governments, (2) the fact that mitigation technologies are not often mature enough for market and thus, they do not make it to diffusion phases, (3) lack of knowledge of relevant technologies and policies in different parts of Europe.

Considering these points, our outcomes on the main research priorities for the further development and deployment of BECCS, entail a set of implications for police and practice, which we summarize below.

4.1. Establishing Synergies between CCS and BECCS Market Strategies

CCS strategies must be investigated in conjunction with BECCS opportunities to avoid a BECCS lock out. Government interventions should be coordinated on an attempt to:

- Improve R&D and market opportunities for both CCS and BECCS,
- Promote cooperation between CCS, biomass and BECCS stakeholders,
- Legitimate BECCS,
- Address existing localized differences between countries growing biomass and countries with experience and know-how on power generation based on CCS.

4.2. Establishing Policy Consensus

- Promoting the continuous interaction between research and industry to bridge knowledge gaps between market needs and scientific research inquiries,
- Interpreting the necessary technological and innovation breakthroughs and optimizations in policy terms, so that national and European policymakers can understand the relevance to the further BECCS deployment and shape necessary actions forward,
- Promoting national and international regulatory frameworks and standards to accommodate regional differences across the BECCS supply chain,
- Defining the safety degree of betting on negative emissions, in terms of adapting existing mechanisms and the impact on the energy markets, as policymakers will require a much clearer picture of negative emissions,
- Investigating carbon reporting and accounting systems under the EU ETS, UNFCCC, and Kyoto Protocol,

- Accounting and verification frameworks to verify that BECCS lead to net negative emissions during the full life-cycle,
- Promoting investment stability and predictability: typically, policymakers want flexibility in terms of adapting and modifying policies, as technology changes or new information comes to light. The perception of changing policy, in terms of altering long-term policy signals will damage investment prospects for BECCS, as private investors are typically attracted by stability and predictability.

4.3. Dedicated R&D Funding Programmes

- Make the various BECCS technology routes more efficient and decrease their costs during their first diffusion steps. Efforts should focus on the commercialization of the most promising biomass conversion technological routes beyond 2020,
- Establish the necessary CCS and biomass infrastructure, as only regions/countries with the appropriate structures in place will be capable of benefiting from the full potential of BECCS,
- Accelerate progress (i.e., innovation, technological breakthroughs, infrastructure) in advanced sustainable biofuels in order to ensure sufficient feedstock quantities to meet future biofuel demand.

4.4. Innovative Financing Mechanisms and Processes—Incentives Provision

- If global mitigation strategies conclude that negative emissions are imperative to meet the 1.5 °C target, BECCS needs to be rewarded by accounting for negative emissions in the EU Emissions Trading System (ETS). This could be achieved through the modification of the ETS Directive (Directive 2003/87/EC) to recognize emissions from biogenic sources and the establishment of a mechanism in the ETS for the issuing of European Union Allowances (EUAs) on the basis of such emissions,
- Provision of direct monetary incentives by encouraging operators who achieve negative emissions, to sell EUAs to the market (or surrender for any fossil emissions if relevant),
- Engaging the public sector to finance a portion of the necessary investments,
- Attracting private sector investors and energy companies: Public purse cannot solely meet the full investment needs and entrepreneurial initiative is highly recommended. It is important to create viable environments that provide security and reasonable risk mitigation. This relates mostly to streamlining high revenues through effective long-term carbon pricing, as one of the main reasons that investors currently show no interest in supporting BECCS, is the lack of proper government support to bridge the first non-profitable years of deployment,
- Learning from previous experience: A specific government effort has already been put in place in Netherlands, where BECCS is already eligible for support under the SDE+ programme. This support system is still considered insufficient, as it does not still compensate the costs associated with CO_2 capture and storage,
- Establishing a monitoring process to engage investors who demand not only a high return on investments, but also an environmental and social added value.

4.5. Promoting Collaboration

- Between components (i.e., key individuals, organizations, ideas) from different fields and with different motives and interests, to establish BECCS actor networks and technology systems, both at a national, as well as, at a cross-country level,
- Between CCS, biomass, and BECCCS actors (i.e., agencies, industry, academia, research community, NGOs, etc.) to shape future decisions jointly,
- Between countries that grow biomass and countries with CCS know-how,

- Between countries (developed and/or developing) with high advanced sustainable biofuels capacity, but limited funding capabilities, to build capacities and to ensure technology access.

4.6. Increasing Public Awareness and Acceptance

Social acceptance will not be ensured just from the bilateral relationship between a host community and a BECCS project, but from a much broader set of social norms, social and political structures, and actors that will need to be engaged. Negative perceptions of CCS and/or biomass should not prevent BECCS uptake and thus, policy-making should focus on:

- Encouraging CCS, biomass and BECCCS actors to shape the suitable circumstances in the future that will encourage public acceptance through their responsibilities for legislation, financial incentives, and regulatory settings,
- Establishing an EU roadmap for BECCS deployment towards 2050,
- Establishing research groups, centers, and networks with a BECCS focus,
- Organizing seminars and workshops that will enable public and potential stakeholders promoting dialogue,
- Promoting the active engagement of BECCS actors with the media, to address concerns and perceived risks.

4.7. Revision/Streamlining of Policy Measures

- Better use of existing biomass feedstock is required to ensure sustainable supply, while the improvement of land-use will help to overcome technical barriers related to the development of sustainable farming practices and socio-political barriers (i.e., competing uses of agricultural land),
- Aligning policy targets with sustainability criteria (e.g., certification schemes) that promote sustainable use of biomass (e.g., Report COM(2010)11 of the European Commission), to avoid biomass infringing on food security and other environmental targets,
- Revising the issue of biomass sustainability in the context of the Kyoto Protocol,
- Considering co-benefits (e.g., improving soil fertility, preventing ocean acidification, etc.) of sustainable biomass use during policy impact assessment,
- Establishing a coherent EU Agricultural Policy framework that promotes NETs (e.g., biochar) resulting in such co-benefits (e.g., soil fertility),
- If negative emissions are to be included in EU ETS, policy revisions should consider uncertainties due to LUC deriving from BECCS implementation.

5. Conclusions

Many scientists argue that to reach the climate goals set by the Paris Agreement, it is crucial to achieve globally negative CO_2 emissions by the second half of the century, in order to remove the greenhouse gas from the atmosphere and store it on land, underground, or in the oceans. These negative emissions signal the deployment of uncertain and currently controversial technologies, such as bio-energy with carbon capture and storage (BECCS). BECCS is considered as one of the most promising negative emissions technologies (NETs), with many modeling scenarios already exhibiting its potential. However, demonstration at a commercial scale has yet to be achieved and large reliance on BECCS has raised uneasiness amongst policymakers and experts in the field, with sustainability risks highlighted as the prime concern (i.e., competing interests with the conservation of ecosystem and food security). Political implications are further enhanced by the fact that suitable area for growing biomass is not distributed evenly across the globe.

Our study builds on the premise that further research to assess potential and regional opportunities of BECCS is essential and should be routed addressing existing risks and concerns. To do so, we considered relevant technology associations'/platform's perspectives on the main research priorities that merit further attention by the research community. These insights were supplemented by an extensive academic review extracting specific assessment needs for each priority area, as raised by scientific and grey literature. The main goal of our study was to explore whether these research priorities, as highlighted by the respective technology associations/platforms, were also supported by recent assessment and feasibility studies on BECCS, to bridge the gap between market needs, industrial know-how, and scientific research inquiries.

The main lessons learned on research priorities and assessment needs, as raised by position papers, published by relevant technology associations, and recent studies in the scientific literature, are summarized below.

5.1. Need for Further Cost Assessment

The main obstacles for BECCS demonstration relate to scale, location (since it is required to be close to biomass resources) and the lack of infrastructure. Infrastructure is very important when predicting the costs of CO_2 transport and storage. There is an absence of constant and thorough assessment of current and expected costs of BECCS. Future research should focus on investigating the BECCS potential per region by using specific cost supply curves for CO_2 transport and storage and for biomass availability.

5.2. BECCS from a Life-Cycle Perspective

To date, only a number of studies are engaged with the life-cycle assessment of BECCS. Experts point out that emissions differ depending on the specific application and the location of each project and thus, it would be necessary to evaluate life-cycle emissions for each specific BECCS project. Further research is important to focus on optimization of supply, conversion, and storage systems, assessing life-cycle risks and investigating the best use of biomass. Further quantification of the effects of different BECCS technology pathways on human health is also an important area for future research from a life-cycle perspective.

5.3. Land Requirements of BECCS

Few studies so far have investigated the land requirements for BECCS. Given that vast land areas will be needed if BECCS is to be integrated in the future climate change mitigation strategies, future research on impact assessment of land-use changes, due to BECCS application, should receive attention to avoid negative consequences (e.g., carbon stock loss, decrease/neutralize net positive GHG mitigation outcomes, etc.).

5.4. Potential for Pitfalls

BECCS is not without the potential for pitfalls, since the sourcing of biomass from sustainable resources is not always guaranteed. Thus, it is necessary to investigate the sustainability factors, when exploring the potential of BECCS technologies, and further research should confirm these results with more comprehensive assessment of factors that limit sustainable supply of biomass resources at a regional level.

5.5. Enabling the Necessary Economies of Scale

Several routes to convert biomass to energy are already existing and applicable, but still need to be adapted to BECCS. Several studies have already looked at a few methods to convert biomass in a BECCS system, examining which conversions are most effective, practically viable, and could be integrated to CCS. Future research should account for optimal plant size for biomass combustion and conversion systems, to enable the economies of scale required for BECCS implementation.

5.6. Increasing Public Awareness and Social Acceptance

One of the major problems of BECCS is the deficiency of a ‘community of support’, awareness and reliability amongst its own key stakeholders and the wider public. The key supporters of BECCS so far are mainly academics and NGOs. Further research should explore how the human factor (e.g., different actors/components from different fields, positions, motives, etc.) can influence the further deployment of BECCS. Further research should also be oriented towards how BECCS is perceived in comparison, also, with fossil fuel-based CCS projects by the media, to increase empirical knowledge.

5.7. Accelerating Research into Advanced Sustainable Biofuels

Understanding the viability of CCS application among various biofuel plants is crucial for the future deployment of BECCS. Thus, further research on infrastructure and new technological breakthroughs is important for the future of this option.

5.8. Biogas (Co-)Firing with CCS

BECCS can be integrated to biofuel production units, such as biogas and hydrogen production plants, making a competitive alternative, compared to fossil fuel-fired power plants with CCS. To enable future CCS-equipped gas processing capacity, along with large amounts of hydrogen production capacity, further research should focus on: (i) assessing the opportunities for biogas co-firing in gas power plants, (ii) evaluating novel biomass-to-biogas conversion routes, (iii) novel biogas upgrading techniques using CO_2 removal, while (iv) analyzing in parallel realistic commercial potential.

5.9. Case of Algal Biomass

The use of micro-algal biomass for cost-efficient BECCS will continue to be limited in the short-to-medium term, as to achieve competitive costs, technological breakthroughs are still required. Future research should focus more on studying algal (macro/micro) biomass feedstock in terms of fuel and CO_2 capture properties.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/7/2206/s1, Table S1: An overview of BECCS projects; Table S2: Key assumptions and findings from cost assessment studies on BECCS; Table S3: Key assumptions and findings from LCA literature studies on BECCS.

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