The BECCS Doughnut

A Strong Sustainability Framework for Assessing Implementation Strategies for Bioenergy with Carbon Capture and Storage (BECCS)

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LUCSUS
Lund University Centre for Sustainability Studies

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Abstract:

Bioenergy with Carbon Capture and Storage (BECCS) is a largely promoted, but also heavily contested solution to the problem of climate change. Whilst removing carbon from the atmosphere, it potentially leads to detrimental side effects. This thesis provides guidance for NGOs, industry and policymakers in Germany and the wider EU context on how to assess the sustainability of BECCS implementation proposals. Based on a systematic literature review and semi-structured interviews, a new conceptual model, the BECCS-Doughnut, with a comprehensive set of social and ecological sustainability assessment dimensions has been developed. Furthermore, implementation trade-offs and coping strategies are evaluated. A decision tree for sustainability assessments is presented in accordance with the suggested principle of limited and targeted BECCS implementation. This implementation principle can structure the urgently needed democratic debate on if and how to implement BECCS from a strong sustainability perspective with a focus on critical ecological thresholds and social justice.

Keywords: sustainability assessment, bioenergy, carbon capture and storage, negative emissions, planetary boundaries, doughnut economics

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List of Abbreviations

AR	Assessment Report
BECCS	Bioenergy with Carbon Capture and Storage
BII	Biodiversity Intactness Index
CCS / CCU	Carbon Capture and Storage / Carbon Capture and Usage
CDR	Carbon Dioxide Removal
DACCS	Direct Air Carbon Capture and Storage
E/MSY	Extinctions per Million Species-Years
EU	European Union
GHG	Greenhouse Gas
IAM	Integrated Assessment Models
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-Cycle Assessment
LUC	Land Use Change
MRV	Monitoring, Reporting and Verification
N	Nitrogen
NET	Negative Emissions Technologies
NGO	Non-Governmental Organization
NIMBY	Not In My Backyard
P	Phosphorus
ROSES	Reporting Standards for Systematic Evidence Syntheses

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1. Introduction and Background

Climate Change is one of the most pressing issues of our time, caused by greenhouse gas (GHG) emissions from human activities such as burning fossil fuels, deforestation, and land use change (IPCC, 2023). The recent synthesis report of the Intergovernmental Panel on Climate Change (IPCC) has made very clear that despite global efforts to reduce emissions, the world is on a path towards dangerous levels of global warming. Current trends suggest that humanity is still not on a mitigation pathway in accordance with the Paris Agreement (stabilize global temperatures below 2°C, ideally below 1.5°C). Overshoot scenarios, where temperatures exceed 1.5°C and 2°C at least temporarily in the second half of this century, are therefore becoming increasingly probable as emissions are not reduced at the necessary speed (IPCC, 2023). Moreover, even with the most ambitious emissions reduction efforts, there will still be unavoidable residual emissions (i.e. agriculture) that need to be addressed (van Vuuren et al., 2017).

This is where negative emission technologies (NET) come in. NET are defined as "intentional human efforts to remove CO_2 emissions from the atmosphere" (Minx et al., 2018, p. 3). This concept is now increasingly discussed under the name of Carbon Dioxide Removal (CDR), defined as "capturing CO_2 from the atmosphere and storing it away for decades to millennia" (S. M. Smith et al., 2023, p. 13). Both concepts will be used in this thesis interchangeably. The basic idea behind NET is that they remove at least as much carbon from the atmosphere as remaining sources keep emitting (Allen et al., 2022). As a result, net zero or even net negative emissions would stabilize global temperatures – and possibly even reduce them (IPCC, 2023).

Thus, there is a double role for negative emission technologies, especially in the second half of this century: a) balancing residual emissions and b) compensating for GHG emission overshoot if mitigation efforts fail to deliver the necessary speed of emission reductions (S. M. Smith et al., 2023). This compensatory role of NET is often translated into the rule of thumb, that with every year emissions are not significantly reduced, the dependence on negative emissions for reaching the Paris Agreement increases (Minx et al., 2018). Yet, we are still in a very early testing phase for most NET, and it is still entirely unknown whether these technologies will actually deliver what is hoped for (Vaughan & Gough, 2016). Therefore, it must be emphasized that negative emissions are no alternative to short-term deep cuts in emissions for the upcoming years, but that they are complementary to compensate for unavoidable residual emissions and for stabilizing or even reducing global temperatures in the long-term (Fuss et al., 2016). It is also important to note that for Climate Change other GHG emissions such as CH_4 or N_2O must be reduced as well, but are not addressed through CDR, which only removes CO_2 (Minx et al., 2018; Popp et al., 2011).

Bioenergy with Carbon Capture and Storage (BECCS) is one of the many technologies with potential to deliver negative emissions, but is the only one that co-produces energy (Minx et al., 2018). This makes BECCS particularly attractive. Briefly, this is how the technology works: Trees or other plants naturally remove carbon from the atmosphere via photosynthesis. This carbon is normally released as CO_2 emissions when biofuels are combusted for producing energy. But with carbon capture and storage, a high share of these CO_2 emissions can be captured (post-combustion CCS) and stored away in subsurface geological formations such as saline aquifers or depleted natural gas fields (Negri et al., 2021; Chiquier et al., 2022). Another route is the application of CCS to biofuel production processes such as gasification, fermentation, or hydrogen production (pre-combustion) (Jeswani et al., 2022). As the captured CO_2 initially had been taken from the atmosphere by plants and is then stored away, the result should ideally be negative emissions (Jeswani et al., 2022). However, there are still CO_2 emissions along the supply chain and therefore the actual amount of negative emissions is only a fraction of the captured emissions, even in the ideal case or cannot be achieved at all in the worst case (Fajardy & Mac Dowell, 2017). The alternative case with CCU (carbon capture and usage) instead of CCS is not within the scope of this thesis.

Both, bioenergy (BE) and CCS are technologies with many years of experience and therefore technologically feasible (Fuss et al., 2018). As BECCS produces energy in a diverse set of applications and negative emissions at a relatively low price, the implementation seems economically and technologically attractive (Fuss et al., 2018; Jeswani et al., 2022). Thus, many global Integrated Assessment Models (IAM), especially around the fifth IPCC Assessment Report (AR5) in 2014/15, have calculated mitigation pathways that include large amounts of BECCS employment around the year 2050 as a cost-effective possibility for reaching net zero emissions (Gambhir et al., 2019; Minx et al., 2018). However, it remains highly contested if the modelled scale of negative emissions can realistically be reached (Fuss et al., 2018). Furthermore, the role of bioenergy in the global energy system is contested, because the rapid upscaling of energy crop plantations has caused large ecological destruction and social conflicts through land use change and deforestation with negative impacts (for example on biodiversity, water systems, and soil health) in the past decades (Creutzig et al., 2015). Many scientists raised concerns that BECCS implementation at scale could exacerbate detrimental ecological and social negative side effects of bioenergy (Burns, 2016; P. Smith et al., 2016; van Vuuren et al., 2017). Furthermore, CCS technologies are deeply entangled with fossil fuel industries trying to prolong business as usual (Palmer & Carton, 2021). According to Shue (2017), there are concerns that BECCS constitutes a risk of mitigation deterrence, because it can be used as an argument for less ambitious emission reductions, since they can be compensated for via BECCS in the future. This would be a considerable risk in the case that BECCS does not deliver according to this expectation (Shue, 2017).

Policymakers, industry, and civil society actors are now confronted with a tension between the need for negative emissions (IPCC, 2023) and an increasing body of evidence pointing out social and ecological risks of BECCS (Heck et al., 2018). On the one hand, it seems to be imperative from a precautious point of view to start developing CDR from now on as fast as possible for reaching the necessary scale of negative emissions in about two decades – especially to guard against the case of not decarbonizing fast enough globally (S. M. Smith et al., 2023). On the other hand, it can be argued that it seems equally precautious to proceed slowly or even restrictive with a technology such as BECCS to avoid the potential risks that have been pointed out (Creutzig et al., 2021). This conundrum around BECCS as an attractive, but also very contested solution to the sustainability problem of continued CO_2 emissions makes it difficult for environmentally concerned organizations, industries, or policymakers to form a position on how to proceed, and which strategy to embrace regarding the implementation of BECCS (Boettcher et al., 2023). Thus, the big question remains: Can we or can't we rely on BECCS for the upcoming decades?

The answer can be different depending on the geographical context (Asibor et al., 2022). The chosen context for this thesis is Germany and the wider context of the European Union (EU), because the debate on if and how to implement BECCS is on the political agenda right now (Boettcher et al., 2023). The EU is currently on the way to establishing a certification framework for carbon dioxide removal that potentially will give strong incentives for BECCS (European Commission, 2022). The German government has recently put negative emissions on the agenda in the key negotiation agreement *Modernization package for climate action and planning acceleration* (Modernisierungspaket für Klimaschutz und Planungsbeschleunigung) between the three governing parties that was published in March 2023 (Table Media, 2023). Here, the German national government set the timeline to develop a long-term strategy for handling unavoidable residual emissions until 2024 including a commitment for national CDR-targets. In this announcement, BECCS is explicitly given a role together with Direct Air Capture with Carbon Storage (DACCS) and natural carbon sinks (Table Media, 2023).

Thus, in the German and wider EU context there is an emerging CDR policy space in its *formative phase* (Boettcher et al., 2023). Proposals for BECCS implementation are soon to be expected and these will need to be assessed from a sustainability perspective. Scientific input for well-informed positioning is therefore required – not only for policymakers and industry, but particularly for civil society actors with potentially less access to technological and scientific assessments.

The academic literature on the topic contains many technical articles, often specific to the field of interest such as feasibility studies, life cycle assessments, and global modelling discussions, but also some reviews and overview articles (Minx et al., 2018). However, this dynamically growing and disparate body of scientific literature mostly refers to future scenarios and is quite difficult to translate into practice when it comes to assessing the sustainability of BECCS implementation proposals. Therefore, there is a translation gap from science to practice.

This thesis aims to add value to this body of research by putting the different scientific perspectives together into one coherent framework that NGOs, industries, and policymakers can use in practice. By doing so, it addresses two knowledge gaps regarding: a) how to navigate the tension between BECCS as a solution for achieving negative emissions and BECCS as a risk to sustainability more broadly; and b) which dimensions of coupled social and environmental systems should be assessed for evaluating the sustainability of BECCS implementation. The geographical focus is on Germany and the wider EU-context.

Thus, the aim of this thesis is to provide hands on knowledge and guidance to inform the ongoing democratic deliberation regarding the complex and contentious issue of implementing bioenergy with carbon capture and storage (BECCS) as a strategy for mitigating climate change. This will be achieved by systematically reviewing the sustainability dimensions that are relevant for assessing the value of BECCS for the transition to sustainability, and by engaging with experts through interviews to explore the expected trade-offs associated with the implementation of BECCS and the question of how to navigate them. Against this background, the first research question (RQ1) is: *Which dimensions have been assessed to evaluate the sustainability of BECCS?* The objective is to make sure that a sustainability assessment includes all relevant dimensions.

The second research question (RQ2) is*: Which trade-offs potentially result from BECCS implementation and how can they be navigated?* The objective is to make sure that a sustainability assessment is able to recognize and weigh potential trade-offs which should also facilitate the democratic debate about the contested question if and how to implement BECCS.

The thesis is structured as follows: Section 2 gives a succinct overview of the underlying understanding of strong sustainability and introduces the planetary boundaries and the Doughnut-framework as guiding frameworks of this thesis. Section 3 describes the methodology. Section 4 presents the results to each research question and section 5 discusses the most important findings synthesizing them in a way that structures and facilitates the debate on if and how to implement BECCS. Finally, section 6 discusses contributions to sustainability science, limitations, and further research before reaching conclusions in section 7.

2. Theoretical and Normative Foundations

2.1 Strong Sustainability

The sustainability assessment in this thesis has its theoretical and normative foundation in following a ‘strong’ sustainability approach. Strong sustainability acknowledges that key ecological resources, qualities, or contributions (in this context often called natural capital) cannot be substituted, but must be sustained (Daly, 2005). Strong sustainability acknowledges critical thresholds beyond which environmental degradation can cause irreversible harm. As human welfare depends on the functioning of ecological systems, (critical) natural capital is a limiting factor to social and economic development (Pelenc & Ballet, 2015). Therefore, strong sustainability does not weigh social, ecological and economic dimensions equally, but prioritizes sustaining (critical) natural capital as the precondition for long-term social and economic development (Pelenc & Ballet, 2015). This understanding of strong sustainability has been operationalized by two important – and interrelated – frameworks: The Planetary Boundaries (Steffen et al., 2015) and the Doughnut Framework (Raworth, 2022). I employ and build on both frameworks in this thesis.

2.2 The Planetary Boundaries Framework

In the planetary boundaries framework, Steffen et al. (2015) seek to define the safe operating space for humanity within the constraints of the Earth's ecological systems. The basic rationale is that the stability of essential ecological systems is disturbed through human activity at a planetary scale. The nine planetary boundaries are critical ecological thresholds beyond which the Earth System is destabilized to such an extent that the Earth's ability to support human life is threatened (Steffen et al., 2015) (Figure 1).

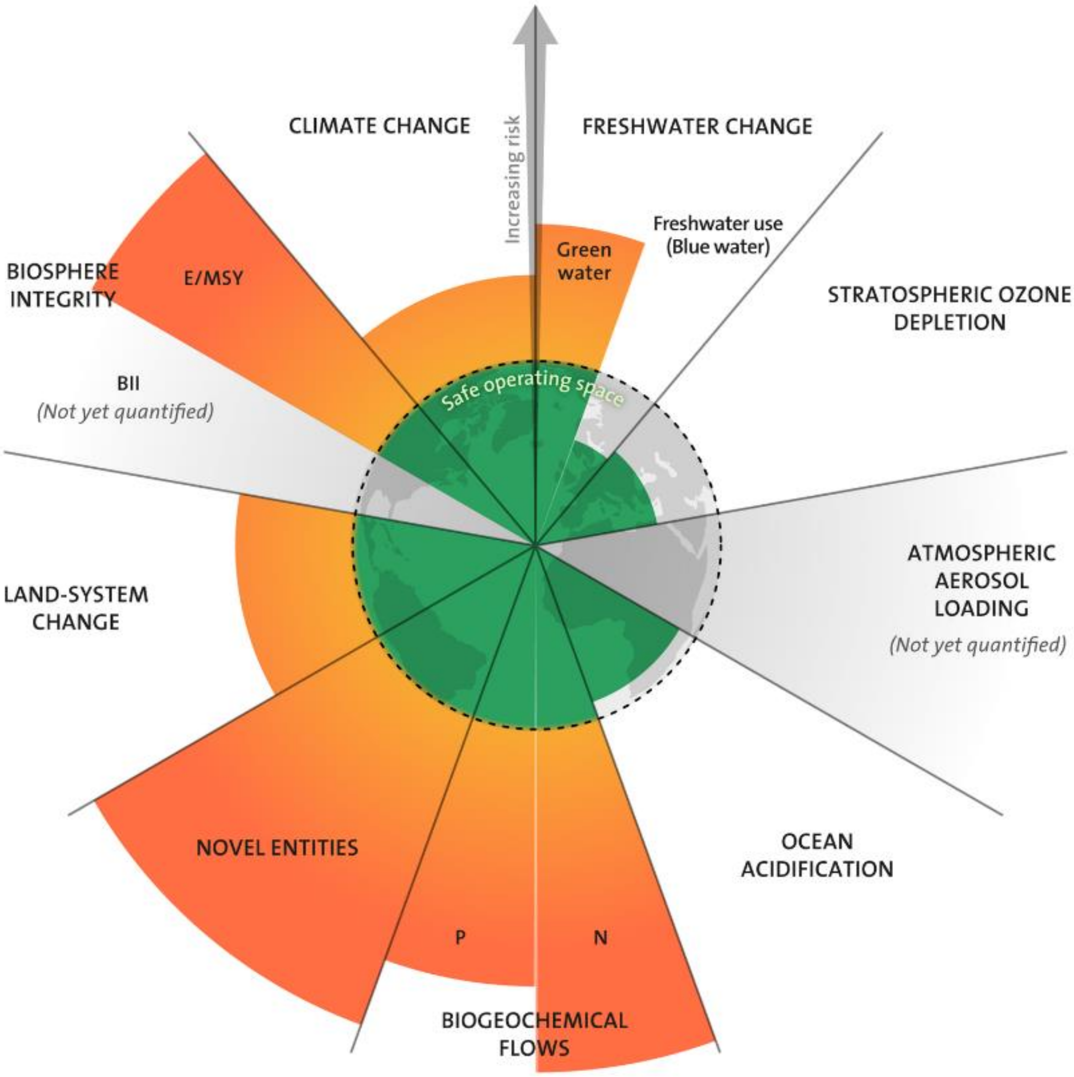

Figure 1. The Planetary Boundaries. Each of the wedges represents a critical ecological threshold for the stability of the Earth System. The inner ring in green represents the safe operating space for humanity. Orange wedges highlight transgressions of the threshold. Source: Azote for Stockholm Resilience Centre (Steffen et al., 2015, Wang-Erlandsson et al., 2022). Licensed as Creative Commons. Abbreviations: P = Phosphorus, N = Nitrogen, BII = Biodiversity Intactness Index, E/MSY = Extinctions per million species-years.

Figure 1 depicts the planetary boundary concept. The safe operating space for human development is highlighted in green, the transgressions of each critical threshold are highlighted in orange. According to some scholars, five out of nine planetary boundaries have already been transgressed which implies that the Earth System is facing an increasing risk of destabilization (Wang-Erlandsson et al., 2022). The framework recognizes that the Earth's natural systems are interconnected and interdependent and highlights that climate change is only one out of several ecological dimensions regarding which the current impact of human activities on ecosystems is far from sustainable (Steffen et al., 2015). If a stable and resilient earth system is to be maintained in the sense that it can sustain human development over the long term (a safe operating space), the drivers of each dimension’s transgression must be addressed (Steffen et al., 2015).

2.3 The Doughnut Framework

The doughnut framework builds upon the planetary boundaries framework by incorporating social and economic dimensions of sustainability – representing a way of achieving social justice within ecological limits. According to the doughnut framework, societies should develop within a safe *and just* space for humanity that ensures well-being while staying within the planetary boundaries (Raworth, 2022) (Figure 2).

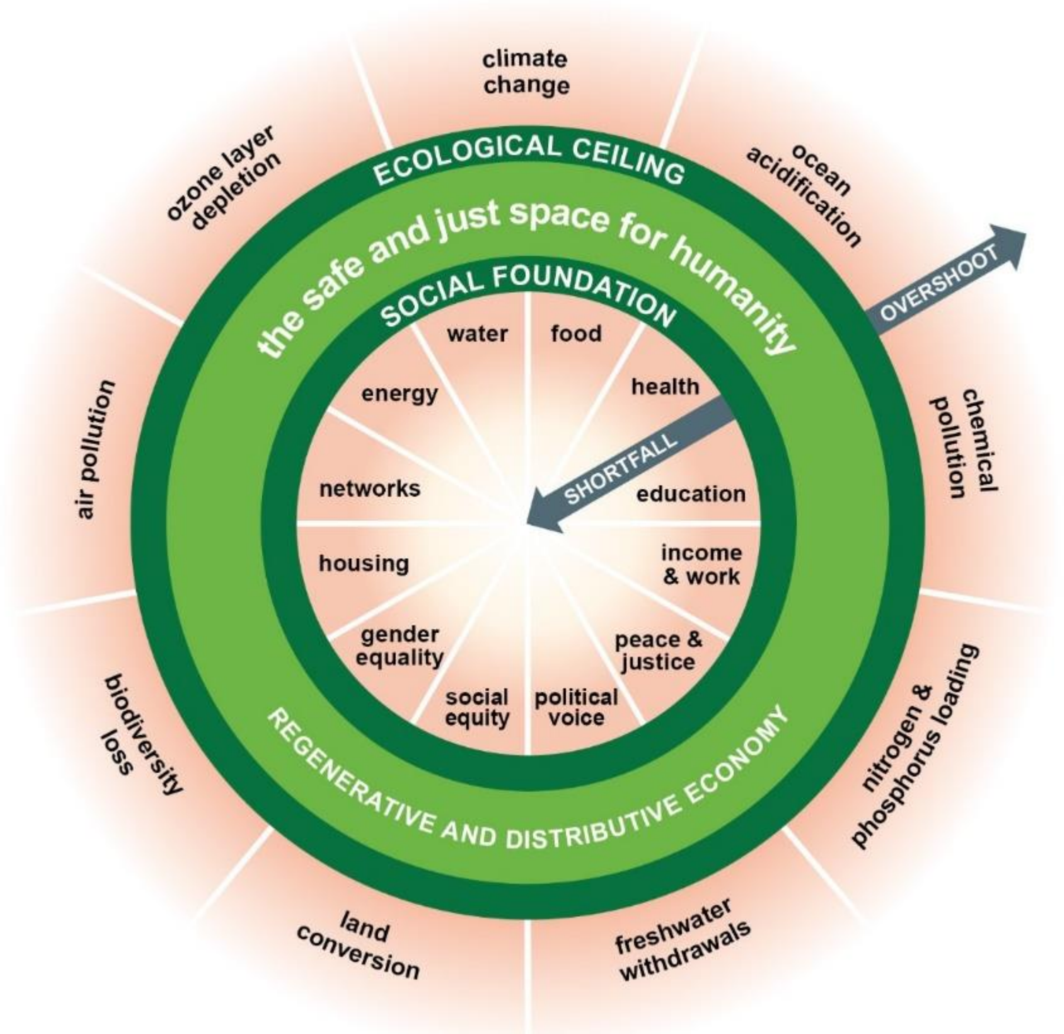

Figure 2. The Doughnut Framework. The inner ring represents social minimum standards of well-being, the outer ring the planetary boundaries (Raworth, 2017), licensed as Creative Commons.

In Figure 2, the inner ring of the doughnut represents minimum standards of well-being that every human being should be entitled to, such as access to food, water, and healthcare. The outer ring of Figure 2 represents the planetary boundaries that we must stay within to prevent ecological collapse (Raworth, 2017). The area between the two rings represents the safe *and just* operating space – the optimum of sustainable development, where social and ecological goals are achieved simultaneously

(Raworth, 2017). As this optimum should be reached within the planetary boundaries, which therefore constitute a limiting factor for socioeconomic development, Raworth relates to the principles of strong sustainability.

The doughnut framework emphasizes the need to achieve a fair distribution of resources and opportunities, both within and between societies, to ensure that everyone has the chance to live a fulfilling life (Raworth, 2022). The doughnut model is a powerful framework for guiding policy decisions, as it provides a clear visual representation of the complex interplay between social, economic, and ecological factors. It has been applied to different contexts such as cross-country comparisons (O'Neill et al., 2018) and Amsterdam's city vision (Raworth, 2020; Turner & Wills, 2022). In this thesis, I apply the Doughnut framework for representing the sustainability dimensions relevant for BECCS implementation in a new *BECCS-Doughnut*.

3. Methodology

3.1 Research Design

To achieve the aim of the thesis and answer the research questions, I employ a mixed methods approach (Figure 3). The research design combines a systematic literature review with expert interviews. The results are presented as narrative synthesis. The systematic literature review process ensures replicability when synthesizing a comprehensive scope of literature (M. J. Grant & Booth, 2009). Through the process of a systematic review the risk of an individual selection bias is reduced when it comes to literature choice compared to generic literature research via typical search engines (M. J. Grant & Booth, 2009). The expert interviews were chosen as a complementary research method, because a) they provide additional qualitative insights from practitioners' perspectives in the sustainability assessment process itself; especially when it comes to complex issues involving ethical judgments such as weighting trade-offs, and b) they further reduce biases by bringing in additional perspectives (Galletta & Cross, 2013). Thus, whilst the systematic review makes the results of this replicable and depicts the academic perspective, the interviews add the practitioners' perspective. The interviews were especially valuable for the trade-off discussion (second research question) and helped improve the usefulness and relevance of the results for stakeholders outside of academia. This resulted in the development of a conceptual model – the BECCS Doughnut – (see section 4) and the sustainability assessment decision tree (see section 5). The latter is designed as a practical tool for sustainability assessments and for structuring the democratic debate on sustainable BECCS implementation. The conceptual model and the decision tree were then presented in a stakeholder workshop to improve the usefulness and relevance for practice.

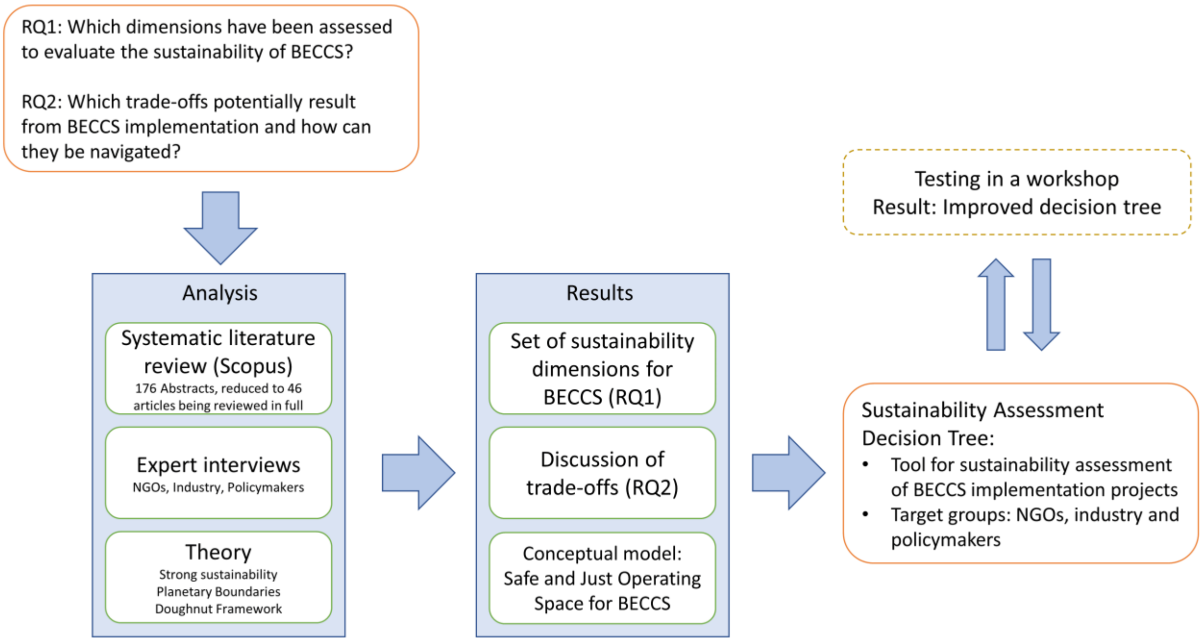

Figure 3. Research Design. Visualization of the most important elements of the research process for this thesis.

3.2 Systematic Review

Useful standards for conducting a systematic review in environmental studies are defined by ROSES (*RepOrting standards for Systematic Evidence Syntheses*) (Haddaway et al., 2018b). These standards help report transparently each step of the systematic review so that especially the early and middle stages of the review process are replicable. A protocol, written before starting the review process, is at the core of ROSES (Haddaway et al., 2018b). My review protocol is available in appendix B and written according to the ROSES checklist (Haddaway et al., 2018a).

A set of 176 articles was retrieved from the Scopus database with the following search string: TITLE-ABS-KEY ((((bioenergy OR biomass) AND "negative emissions") OR (beccs OR (bioenergy AND (ccs OR "carbon capture and storage")))) AND (trade-off* OR (sustainab* AND (criteria OR eval* OR assess*)))).

The resulting set of articles was successfully trialled by benchmarking; that is, already known papers of relevance were found within the list (Haddaway et al., 2020). Forward and backward tracking of citations was used to find additional sources helpful for answering the research questions and the discussion. Aiming at reducing publication bias, I searched for so-called grey literature via Google and recommendations from the expert interviews and stakeholder dialogues (Haddaway et al., 2020).

After screening titles and abstracts, the scope of potentially relevant articles was reduced to 81. This number was further reduced to 45 articles included in the analysis after engaging more deeply with the literature. Decisions to include or exclude articles were documented and followed a set of criteria defined in the protocol (see Appendix B). Inclusion criteria considered that the article provides social or ecological assessment dimensions or discusses sustainability-related trade-offs, exclusion criteria were most importantly a purely technical focus, no sustainability focus, not relating to BECCS or a context outside Europe

3.3 Semi-Structured Expert Interviews

Six semi-structured interviews of around 45 to 60 minutes were conducted online in English and German. All interviewees are currently working on the implementation of BECCS and can therefore be considered experts. The sampling was purposive to ensure a variety of perspectives (Döring & Bortz, 2016). The experts' background is either in the EU or the German policy space with affiliations in environmental NGOs, private and public think tanks, industry, or policymaking. Following standard research ethics, they were provided with information about the study, its purpose and process so that informed consent for participation could be obtained (Döring & Bortz, 2016).

The interview guide is available in the appendix (see appendix C) and was developed according to the framework developed by Kallio et al. (2016). The first two parts are framed around the two research questions while the third part contains questions about how to ensure the usefulness of a sustainability assessment framework for practitioners. The resulting transcripts were then coded and analyzed with the software *NVivo 12 Plus* with a focus on a) social, b) ecological sustainability dimensions, and c) trade-offs when implementing BECCS. Further coding dimensions (nodes) were d) biomass hierarchy/cascade, e) decision/weighting, and f) useful result translation – in accordance with the research questions and the aim of producing knowledge for practice. The main goal of the interviews was not to conduct an extensive qualitative interpretation, but to test the literature review results against what practitioners mention as relevant dimensions and to include their perspectives in the development of the conceptual model, the trade-off discussion, and the decision tree.

3.4 BECCS-Doughnut Development

The results of the literature review and interviews were used to initially catalogue the many subdimensions relevant to assessing the sustainability of BECCS. These subdimensions were then clustered, guided by the dimensions given through the doughnut-framework and the planetary boundaries. Some modifications were made to depict the specific impacts of BECCS more adequately (explained in section 4.1). The modifications were partially made because the Doughnut-framework was intended to depict global development of humanity as a whole (*safe and just space for humanity*)

(Raworth, 2022) whilst I now apply this concept to depict the social-ecological implications of the implementation of a certain technology.

Each sustainability dimension consists of a set of subdimensions which can be quantitatively or qualitatively assessed. How these subdimensions are assessed is highly context-specific, thus I do not provide an exhaustive list on how to assess each dimension, but rather an overview to ensure complete coverage when assessing the sustainability of BECCS. The resulting conceptual model and the subdimensions are now presented in the following section.

4. Results

4.1 The BECCS-Doughnut: A Safe and Just Operating Space for BECCS

The literature review and the interviews revealed more than one hundred sustainability categories which were reduced to 59 by grouping those that were similar. These 59 sustainability assessment categories which were grouped into seven social dimensions (with 22 subdimensions) and seven ecological dimensions (37 subdimensions) should be covered when comprehensively assessing the sustainability of BECCS. The "BECCS-Doughnut" was developed as a conceptual model (see Figure 4). It conceptualizes *a safe and just operating space for BECCS* which is *limited* by the seven ecological dimensions (the ecological ceiling) and the seven social ones (the social foundation). Many of the 14 sustainability dimensions retrieved from the literature review and interviews are similar or even the same when comparing the BECCS-Doughnut to the original planetary boundaries (Steffen et al., 2015) and the "Doughnut framework" (Raworth, 2022).

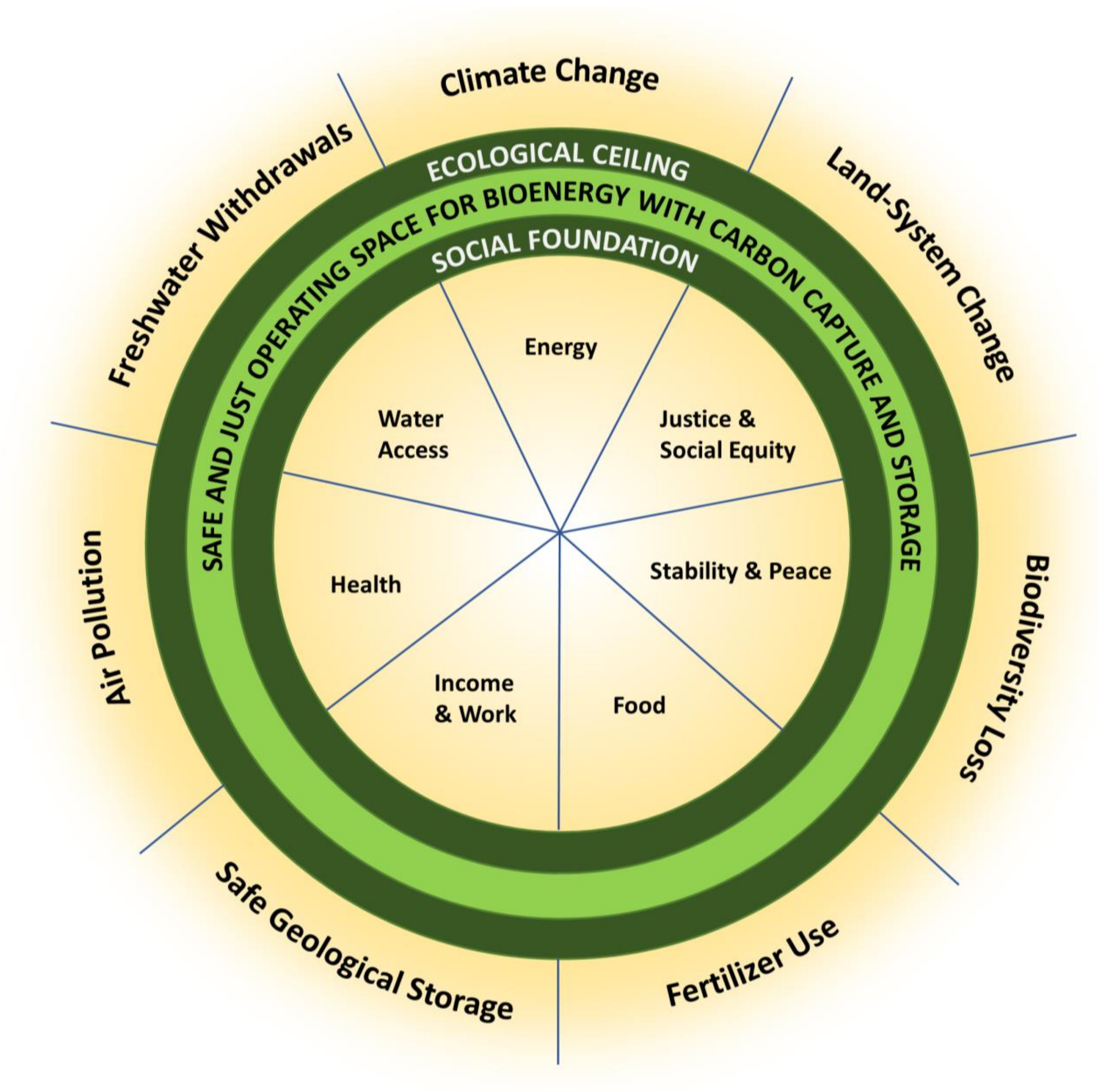

Figure 4. The BECCS-Doughnut. Own creation based on Raworth (2022) and Steffen et al. (2015), but adjusted according the literature review. The wedges in the outer ring represent ecological and in the inner ring social limiting factors for a safe and just operating space for Bioenergy with Carbon Capture and Storage (BECCS).

Compared with the planetary boundaries, *climate change, land-system change, biodiversity loss, air pollution* and *freshwater withdrawals* remain unchanged. A slightly modified category is *fertilizer use* (nitrogen and phosphorus loading in the original doughnut). The reviewed literature was quite explicit in mentioning excessive nitrogen fertilization as the main driver for transgressing this planetary boundary whilst remaining silent about phosphorus. Thus, *fertilizer use* depicts more adequately the review results. The following categories have been excluded from the original framework: ozone layer depletion, chemical pollution, and ocean acidification (Steffen et al., 2015). The first two categories were not in the focus of the reviewed literature. By contrast, ocean acidification was excluded, because it is not directly affected by BECCS. However, it should be emphasized that indirectly, BECCS has a positive effect on ocean acidification: Carbon removal from the atmosphere at large scale can help reducing ocean acidification, because it decreases the ocean's uptake of atmospheric CO_2 (McElwee et al., 2020; P. Smith et al., 2019). Nonetheless, this is directly linked to reducing atmospheric CO_2 emissions and concentrations, which is already fully covered by the Climate Change dimension. Thus, I decided to keep only the latter as it is directly impacted by BECCS. One new category specifically related to BECCS in the literature that is not in the original planetary boundaries framework is *safe geological storage*. It was included because total safe storage availability can constitute a biophysical limit to a sustainable implementation of BECCS even though it does not seem to be an ecological threshold on a planetary boundary scale (see 4.3.4).

Compared to the original Doughnut, the following social dimensions remain the same: *Energy, Food, Income & Work, Health,* and *Water*. The categories *justice & social equity* and *stability & peace* were modified, because they cover a broader range of dimensions than the underlying variables in the original Doughnut-Framework (Raworth, 2022). Whilst *social equity* in the Doughnut framework is referring only to income inequality and therefore only distributional justice, I added other justice dimensions such as procedural justice, autonomy, and labour rights. Furthermore, the category *peace and justice* from the original Doughnut only referred to homicides and corruption, whilst *stability & peace* in this BECCS-Doughnut refers to conflicts generally and a broader range of dimensions that influence the stability of the environment and living conditions. The following categories were excluded, because they did not appear as relevant categories in the reviewed BECCS literature: *networks, housing, gender equality, political voice, and education*.

Each of the dimensions of the BECCS-Doughnut with its subdimensions will be explained in the following sections. A complete table of the sustainability dimensions will be given for all social and all ecological dimensions at the beginning of each section (Tables 1 and 2).

4.2 The Social Dimensions of the BECCS-Doughnut

The literature review and the interviews resulted in seven social dimensions of the BECCS-Doughnut. The table in the beginning gives an overview, then each dimension is explained in a narrative synthesis.

Table 1. Social subdimensions of the BECCS-Doughnut. Numbered sources can be found in appendix A.

	Subdimension	Explanation	Sources
Justice & Social Equity	Land use rights & ownership	Land grabbing, displacement, large scale plantations replacing small scale farming, especially where land tenure is not clear[7]	1,2,3,4,5,6,7,8
	Equitable profit and income distribution	Who benefits to what degree from the bioeconomy's profits and the generated income?	3,5,8,9,10
	Procedural Justice	Transparent process of regional/national planning and quality of participation procedures, stakeholders' risk assessment	5,9,10
	Autonomy	"Degree of energy self-sufficiency, which is reflected in the potential for regional self-sufficiency or individual self-sufficiency"[9]	9
	Labour rights	Assess if labour rights are guaranteed across the whole biofuel value chain[3]	3
	Gender impacts	Impacts on livelihoods can be different according to gender	3
Stability & Peace	Social conflicts (e.g. land grabbing)	Existing conflicts can increase or decrease, farmers can be displaced, but also empowered[3]	3,4,5,7,8
	Loss of livelihood through loss of tropical forests	Loss of cultural ecosystem services[12], local communities depend on their forests for most basic needs[11]	11,12
	Traditional practices	Local knowledge and practice can be used/encouraged or displaced/discouraged	3
	Visual impacts / landscape aesthetics	Very heterogeneous, context-specific category, difficult to assess opposition or support[13]	1,9,13,14
	Social acceptance	Public support, "NIMBY" (not in my backyard), level of opposition	1,2,9,13,15
Food	Marginal land used	"Marginal land is considered to be at the intersection of under-utilised lands and neglected unused land"[17] This land type does not directly compete with food. Contested classification (could still be biodiversity-rich or of other social value)[19]	3,9,16,17,18, 19,20,21
	Use of residues, waste as biofuels	Biomass not primarily grown for energy and without land/food/feed competition such as straw, branches, biogenic waste	9,10,17,18,19, 21,22,23,24
	Lignocellulosic biofuels	This feedstock type does not directly compete with food in terms of yield. A risk of land use competition and thus indirect competition for food production remains.	8,9,12,13,16, 17,18,20,21
Income & Work	Jobs created by BECCS	Jobs created along the supply chain[3]. Engineers and planners from the fossil industry needed for CCS implementation (just transition opportunity)[23]	3,23
	Income diversification for farmers	Additional economic value for yield, residues, and by-products.	1,2,3,7,8,10, 12,23,25

	Subdimension	Explanation	Sources
Health	Particle emissions (respiratory inorganics)	Particulate matter emitted through pelleting, refinery processing, transportation, and combustion[16]	1, 2, 9, 13, 23, 25, 26, 27
	Smog (photochemical oxidant formation potential)	Standard category in life cycle assessments	26
	Proximity to human population	Also for noise and odours, but mostly related to particle emissions	2,27
Water access	Water stress, access, and quality	Here understood as water quality and access of the local population to water. Correspondingly, assess local water stress levels and water access of local populations. For related assessment subdimensions, see 4.3.6 (freshwater).	10,28
Energy	Energy access and security	Rather positive effect through BECCS as versatile allrounder for energy production can be expected.	26,23
	Competition with local biomass for energy	Relevant category in poor rural areas with local biomass as only available energy source.	2,3

4.2.1 Justice and Social Equity

BECCS implementation can involve issues of distributional, but also procedural justice, especially if vulnerable regions in the Global South are involved (for example through biomass imports). Distributional justice can be negatively affected through highly unequal profit and income distribution and unequal land use or ownership rights (P. Smith et al., 2019). In the past, large agribusinesses were often favoured at the expense of family or community-based farming, resulting in large income inequalities (Creutzig et al., 2015). By contrast, procedural justice is related to transparency, autonomy and participation in decision making (Thrän et al., 2020). However, these categories are intertwined, for example procedural injustices (like top-down implementation with weak governance) can lead to distributional injustice such as the marginalization of local populations (Honegger et al., 2021). Furthermore, labour rights are an essential social sustainability category that should be evaluated along the whole supply chain (Creutzig et al., 2015).

4.2.2 Stability & Peace

The global demand for bioenergy crops is riddled with social conflicts and has destroyed the living conditions of many communities, especially in the tropical zones (Fuss et al., 2018; P. Smith et al., 2019). Hansson et al. (2020, p. 6851) argue in the case of sugarcane or jatropha in Sub-Saharan Africa that "conflicts over access to land and mismanagement have been more of a rule than an exception." Yet, if done right, there is a potential for the empowerment of farmers through bioenergy production (Creutzig et al., 2015). However, this is put into question at the scale of global BECCS deployment as global IPCC models suggest (Creutzig et al., 2021). It is therefore crucial to assess a feedstock's conflict potential, especially when imported from the Global South (Hansson et al., 2020). Furthermore, if whole landscapes are converted into biomass plantations, there is also a risk that important ecosystem services are lost, and with them the livelihoods of local communities (Yamagata et al., 2018). Local traditional knowledge and practice can be displaced, and with it a sense of belonging and stability, even though there can also be ways of integrating traditional knowledge and practice into bioenergy production (Creutzig et al., 2015).

Two subdimensions rather stem from literature from the Global North: Biomass plantations can change the landscape to a large extent and thus local populations can be quite affected in how the landscape looks like (Donnison et al., 2021). If the environment changes in a scale that your home does not look the same anymore, this can also be considered a loss of stability, even though in a less existential way than the examples above. This can also influence public acceptance and local protests in more privileged regions (Thrän et al., 2020).

4.2.3 Food

The first generation of biofuels (also called conventional biofuels) uses feedstocks grown on arable land such as oil seeds, corn, or sugar and therefore directly competes with food, feed, and animal products (Creutzig et al., 2015; Stoy et al., 2018). When crops and arable land are diverted to energy production, this can have detrimental effects on food prices and lead to food insecurity (Doelman et al., 2018; P. Smith et al., 2019). If agricultural residues, waste, or by-products are used for bioenergy, these effects can be limited (Creutzig et al., 2015; Wu et al., 2023). On the other hand, Calvin et al. (2021) point out that food production and market stability could benefit in the long run from increased bioenergy demand, because of increased agriculture investments and biomass for energy as an additional income source. If bioenergy production is integrated into food production systems instead of displacing them, there is a certain complementary role for bioenergy which can be seen as sustainable (Creutzig et al., 2015). Another important subdimension is the use of 'marginal land', defined as land that is not in use or under-utilised and can be activated for bioenergy production (Fajardy et al., 2018). This land could be used for growing lignocellulosic biomass such as short rotation coppice, miscanthus, or switchgrass which are non-food products and therefore pose no food insecurity problems (see 4.5.1) (Fuss et al., 2018).

4.2.4 Income and Work

The impacts of BECCS implementation on income and work are rather positive throughout the literature, even though some impacts on livelihoods described before have to be kept in mind. CCS is design-intensive, requires new infrastructure and is therefore expected to provide high quality jobs. This contributes to a just transition by reducing job losses especially for people who are currently employed in the fossil industry (N. Grant et al., 2021). On the bioenergy side, there are also many jobs created along the supply chain. Furthermore, residues and by-products are new income sources and biomass demand from the energy sector contributes to income diversification (Calvin et al., 2021; Clery et al., 2021; Creutzig et al., 2015; Fuss et al., 2018; Minx et al., 2018; Pour et al., 2017; Stoy et al., 2018).

4.2.5 Health

The health effects of BECCS depend largely on the type of application and its proximity to populated areas. Most health impacts, such as cancer, arise through emissions of particulate matter (respiratory inorganics). These impacts are therefore closely related to the ecological dimension of air pollution, also because these emissions increase the risk for smog (photochemical oxidant formation potential) (Jeswani et al., 2022). Hotspots for particle emissions are pelleting, refinery processing, transportation, and the combustion itself (Negri & Guillén-Gosálbez, 2022). Using BECCS for the production of car biofuels results in more health impacts than other BECCS applications. This is partially due to health impacts from refinery processing (not only particle emissions, but also noise and odours), but especially because cars will emit the particles from combustion directly where people live and breathe (Lask et al., 2021; Pour et al., 2017). This is aggravated by the fact that biofuel combustion in cars actually leads to more emissions of particulate matter than fossil petrol (Lask et al., 2021). This seems to outweigh the health benefit of preventing climate change in this category (Fuss et al., 2018; Negri & Guillén-Gosálbez, 2022; P. Smith et al., 2019).

4.2.6 Water Access

Due to climate change, the number of people exposed to water stress will increase (Stenzel et al., 2021). Expanded biomass production for BECCS can result in even more water stress than through climate change itself, because of the required scale of irrigation and resulting water depletion (Stenzel et al., 2021). This could lead to further negative impacts on water quality, availability, and access to drinking water and sanitation. Furthermore, CCS requires water during the capture process (Rosa et al., 2020). Generally, from a social point of view, water demand should be minimized and regional vulnerabilities to water stress need to be assessed regarding a) where the biomass is grown, b) at the BECCS plant and c) at the storage site (if onshore) (Stenzel et al., 2021). As this is highly related to the planetary boundary of freshwater withdrawal, more information is given in chapter 4.3.6. Both water dimensions are kept to emphasize that water is an important social basic need and an important ecological threshold at the same time – as Raworth (2022) has argued for the doughnut framework.

4.2.7 Energy

In the original Doughnut-framework, this category is defined as access to electricity and clean cooking facilities mostly referring to the Global South (Raworth, 2022). In the reviewed literature, the only risk mentioned is that an increased demand for biomass could compete with local biomass availability in poor rural areas (Creutzig et al., 2015; Pour et al., 2017). Otherwise, BECCS is expected to contribute positively to energy security and therefore energy provision and access (in a broader sense), because of its versatility providing energy in its various forms where other renewable energy carriers fail to do so (Jeswani et al., 2022).

4.3 The Ecological Dimensions of the BECCS-Doughnut

Seven ecological dimensions of the BECCS-Doughnut emerged from the literature review and the interviews. As with the social dimensions, the table in the beginning first gives an overview, then each dimension is explained in a narrative synthesis.

Table 2. Ecological subdimensions of the BECCS-Doughnut Numbered sources can be found in appendix A.

	Subdimension	Explanation	Sources
Land System Change	Land use change (LUC)	Direct land-use change (LUC) occurs when bioenergy crops displace other crops, pastures or forests, while ILUC results from bioenergy deployment triggering the conversion to cropland or pasture of lands, somewhere on the globe, to replace a fraction of the displaced crops[3]	7, 8, 9, 10, 11, 16, 17, 18, 19, 20, 21, 23, 24, 25, 27, 29, 30
	Soil degradation and erosion	Effect can be positive[8], but negative if land use change leads to vegetation loss, mostly in the tropical zones[11]	8, 9, 11, 14, 16, 17, 18, 25
	Deforestation / Forest degradation	Can also be understood as a natural carbon sink being depleted. However, deforestation is more than biological carbon, for example biodiversity loss, livelihood loss, etc. and was often mentioned separately in the review.	4, 7, 9, 10, 11, 16, 17, 18, 20, 24, 25, 29,
	Local biogeophysical impacts through LUC	Large-scale changes in vegetation can modify the local climate (e.g., evapotranspiration, precipitation, albedo, temperature)	6, 7, 8, 9, 10, 16, 17, 18, 19, 25
	Land use efficiency	Ratio of land use to energy yield[9], use of carbon dense lignocellulosic energy crops such as Miscanthus (for Europe)	9, 13, 16, 17, 18, 20, 21, 23, 24
	Second generation biofuels	Source of biomass that has no direct competition with food markets (cellulosic or woody biomass, algae, food waste or forest and agricultural residues). As these are mostly by-products, many sustainability assessments assume no LUC for this type of biofuel.	8, 9, 10, 12, 16, 17, 18, 19, 20, 21, 22, 23, 24, 31, 32
	Regional land and feedstock availability & suitability	Geographical, context-specific dimension. How much land and feedstock are available in the source region? Which feedstock is suitable?	9, 15, 16, 17, 18, 19, 20, 21
Biodiversity loss	Biomass cultivation in regions with lowest biodiversity	If biodiversity-rich areas are avoided for biomass cultivation, biodiversity loss is not linear with an increase in negative emissions through BECCS[18]	9, 17, 18
	Crop type choice and heterogeneity	Increased crop type heterogeneity is good for biodiversity as well as replacing annual with perennial crops[13]	6, 13
	Intensity of cultivation and pesticide use	Intensified farming practice and pesticide use decrease biodiversity	9
	Biodiversity impacts	Distinguish natural habitat loss (through land conversion) and species richness/abundance/diversity in general[12,13]	4, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 25, 29
Fertilizer use	Fertilizer minimization and efficiency	Some studies suggest efficiency (optimal input-yield ratio) whilst some suggest minimization (reduce nitrogen input generally, even at the expense of reduced yield)	1, 7, 8, 9, 17, 18, 19, 20, 21, 23, 29
	Carbon footprint of agricultural chemicals	Assess life cycle emissions from fertilizers (and other agricultural chemicals)	21

	Subdimension	Explanation	Sources
Safe geological storage	Carefully selected storage site / Permanence	The storage site should be well suited according to geological criteria depending on the subsurface geology to ensure permanence (in other words: avoid carbon leakage). Other environmental aspects: Seismic activities and risks for local groundwater.	1, 8, 33
	MRV (Monitoring, Reporting, Verification)	MRV of the storage site, especially the wells for injection, should help ensuring permanence and minimizing risks. There should be a long-term obligation for high-quality MRV.	8, 34, 35
Air pollution	Air pollution	Can be assessed through the dimensions 'fertilizer use' and 'health' as these are directly linked to air pollution.	1, 2, 9, 13, 16, 23, 25, 26, 27
Freshwater withdrawal	Regional water scarcity	Assessing the general level of water scarcity / water stress in the cultivation area that could be aggravated by additional irrigation or water withdrawal	10, 11, 28, 29
	Irrigation and evapotranspiration (blue and green water)	Water footprint of biomass cultivation[28]	2, 7, 8, 10, 11, 12, 14, 15, 16, 17, 19, 21, 23, 27, 28, 29, 36
	CCS water withdrawal (blue water)	Water footprint of the BECCS plant	23 37
	Water quality / Eutrophication	"Deterioration of water quality"[11], mostly due to land conversion and agriculture, eutrophication caused by fertilizer runoff, thus linked to the sustainability dimension 'fertilizer use'[10]	1, 2, 6, 7, 8, 9, 10, 11, 12, 15, 16, 17, 19, 25, 26, 27
	Freshwater Ecotoxicity	Life Cycle Assessment category for water quality (chemicals)	2, 7, 16, 26, 27
Climate Change	Life cycle CO_2 emissions	CO_2 emissions should be accounted for along the whole supply chain including direct and indirect land use change to determine if total emissions are actually negative[38].	1, 2, 8, 9, 12, 16, 27, 29, 38, 39
	Methane (CH_4) emissions	CH_4 emissions from fertilizer use and manure. If BECCS is combined with biomethane (anaerobic fermentation), there is a risk of CH_4 leakage[9]	3, 9
	Nitrous oxide (N_2O) emissions	N_2O emissions from fertilization are a key variable. As N_2O is a long-lasting greenhouse gas, its effects can offset all CO_2 savings from a BECCS project[41]	3, 11, 20, 25, 39, 40, 41
	Soil carbon loss/sequestration	Soil carbon loss from land conversion or tillage (positive or negative). Perennial crops improve soil carbon sequestration substantially[27]	7, 27, 36, 41
	Depleted natural carbon sinks	Soil carbon and biological carbon before land use change plus biomass carbon debt (difference from C that could have been accumulated over the years by the existing ecosystem)	11, 12, 42

	Subdimension	Explanation	Sources
Climate Change	Agricultural greenhouse gas emissions	Partial calculation of supply chain emissions after land use change and before transportation. Include all GHG such as CO_2, CH_4 and N_2O. Tillage practices, crop residue management, the use of cover crops, manure applications and chemical fertilizer application rates[19], energy use for farming such as power and fuels[21]	3, 7, 9, 15, 19, 21
	Forestry greenhouse gas emissions	Clear cuts cause high emissions. For sustainable woody biomass, harvesting whilst increasing maintaining carbon sequestration minimizes emissions (e.g. continuous cover forestry). Or harvest of mature forest with high disturbance potential (e.g. plantations, monocultures)[3]. Also avoid forest fertilization[6].	6, 9, 10, 16, 17, 18
	Feedstock production life cycle emissions	Sugarcane, perennial grasses, crop residues, waste cooking oil and many forest products result in lower life cycle emissions than other biofuels[3] - if they do not replace forests, but cropland or marginal land[19].	7, 9, 13, 15, 16, 17, 18, 19, 43
	Transport emissions	Emissions from biomass transport to the BECCS plant and from captured CO_2 transport to the storage site.	3, 9, 15, 16, 17, 24, 43
	Energy source and efficiency for biomass processing (conversion)	Biomass processing/conversion often based on fossil fuels (natural gas). Switch to carbon neutral electricity, natural drying or torrefaction[21].	21
	Energy efficiency of the BECCS plant	Depends on the energy product (power has a higher share of captured emissions than biofuels production which still emit later when combusted), but also on the conversion process[19] and if the heat is used.	9, 16, 17, 18, 19, 43
	Energy demand of capture and liquefaction process	Capturing and liquifying CO_2 is energy-intensive, posing an energy penalty in a range of 20-30% on energy production in a BECCS plant[10]. Values can be different depending on the production process.	9, 10, 16, 17, 18, 42
	Emissions of the energy carriers being displaced	Emissions savings also depend on the displaced energy carrier.	19
	CO_2 capture rate	The CO2 capture rate can vary depending on the product and process. A higher capture rate means less CO_2 released into the atmosphere.	9, 12, 16, 17, 18, 42, 43
	CO_2 leakage	Especially relevant after CO_2 capture. CO_2 leakage in transport and storage.	25
	Remaining emissions from combustion	Depend on the process and CO_2 capture rate. Especially relevant for pre-combustion CCS. For example, biofuels (produced for shipping, aviation) still cause emissions when combusted and biorefineries cause further emissions, e.g. through chemicals and waste water treatment[27]	2, 8, 16, 19, 26, 27

4.3.1 Land-System Change

Bioenergy production requires more land for the same amount of energy than other renewable energies such as solar, wind, or geothermal energy (Scheidel & Sorman, 2012). If bioenergy is to be produced at large scales for BECCS, this also means an increasing need for land use change for growing energy crops or harvesting forest biomass (Heck et al., 2018). From a sustainability perspective, it is decisive which type of land is converted into biomass production. First, because of the emissions of land use change: Converting a carbon-rich forest, wetland, or grassland into agricultural or forest plantations releases so much carbon that negative emissions through BECCS are almost impossible (Fajardy & Mac Dowell, 2017). Second, the planetary boundary of biodiversity loss is put under pressure with deforestation and land use change (Creutzig et al., 2021; Stoy et al., 2018). Third, the local climate can change with vegetation interventions at large scales (P. Smith et al., 2019), which can be positive or negative (Honegger et al., 2021). And fourth, land-system change can lead to soil degradation and erosion, even though this depends on the initial and final land conditions (Fuss et al., 2018; Yamagata et al., 2018). As land constitutes a limiting factor for BECCS deployment, land use efficiency is therefore of high importance (see section 4.5.2) (Fajardy et al., 2018; Wu et al., 2023).

4.3.2 Biodiversity Loss

The planetary boundary of biodiversity loss is highly related to land conversion. Most land use change (for food, feed, bioenergy, or fast-growing carbon stock afforestation) impacts biodiversity (Doelman et al., 2018). Some studies conclude that the scale of BECCS implementation that was suggested by the IPCC pushes the biodiversity planetary boundary far outside the safe zone (Creutzig et al., 2021; Heck et al., 2018). However, if the cultivation of biomass happens in regions with low biodiversity under optimal allocation, the benefit for biodiversity of reducing climate change through BECCS could be greater than the negative impacts from biomass cultivation (Hanssen et al., 2022). Nevertheless, this argument is contested (Creutzig et al., 2021). Generally, there are ways to reduce biodiversity loss, such as increasing landscape and crop type heterogeneity, converting annual into perennial crops and reducing farming intensity and pesticide use (Donnison et al., 2021; Krause et al., 2020; Thrän et al., 2020). But overall, the tendency within the literature underlines that the impact of BECCS on biodiversity is quite high – depending on the scale of implementation.

4.3.3 Fertilizer Use

This category was named “fertilizer use” instead of “biogeochemical cycles” (Steffen et al., 2015) to make this key driver of unsustainable biomass production more explicit. The planetary boundaries refer to nitrogen and phosphorus use, stating that, globally, the boundary has already been transgressed (Steffen et al., 2015). Interestingly, the reviewed literature does not refer to phosphorus, but mostly to nitrogen and to fertilizers as the main driver for nitrogen pollution. The consequences of excessive fertilizer use are manifold. Freshwater and ocean eutrophication affect biodiversity and water quality. Nitrogen is also problematic in its reactive forms (e.g. air pollution through nitrous oxides and climate change acceleration through the greenhouse gas N_2O) (Doelman et al., 2018; Fuss et al., 2018; Heck et al., 2018; P. Smith et al., 2019). Furthermore, the carbon footprint of agricultural chemicals such as fertilizers is considered substantial (Fajardy & Mac Dowell, 2017). Therefore, minimizing fertilizer use is a key improvement area for sustainable bioenergy production (Fajardy & Mac Dowell, 2017).

4.3.4 Safe Geological Storage

The main reason for adding this dimension is ensuring permanence of the CO_2 storage not only for decades but for centuries (Clery et al., 2021; Krevor et al., 2023). To reach this goal, the storage site should be carefully selected (different criteria for different geologies such as sandstone or basalt) and monitored (Furre et al., 2017). Geological storage does not seem to be the bottleneck for large-scale BECCS until 2100 and is therefore probably not a very limiting factor for a safe and just operating space for BECCS in the upcoming decades (Krevor et al., 2023). However, there might be limits of the human ability of ensuring *Monitoring, Reporting, Verification* (MRV) at an increasing number of storage sites and also geological availability limits in centuries after 2100. As permanence of storage is key for the success of BECCS (and a permanent task that needs attention) over centuries, this category was added as one potential biophysical limiting factor to be carefully monitored and assessed (Interviews 1, 4, 5).

4.3.5 Air Pollution

Even when the emitted CO_2 from biofuel combustion is captured, other particle emissions remain (Clery et al., 2021; Jeswani et al., 2022; Lask et al., 2021). Additional air pollution stems from excessive fertilizer use (nitrogen oxides) and biomass processing such as pelleting, conversion, or refining (Creutzig et al., 2015; Negri & Guillén-Gosálbez, 2022). Throughout the reviewed literature, air pollution has rather been highlighted as a negative side-effect for human health than in the sense of the transgression of the planetary boundary with its effects on the Earth System. The dimension 'air pollution' in the context of BECCS is directly interlinked with 'fertilizer use' and 'health' and can therefore be assessed through these two categories.

4.3.6 Freshwater Withdrawals

Implementing BECCS at scale would result in highly increased water demand. Additional biomass cultivation for BECCS requires water, especially when so-called marginal or degraded land is converted into energy crops (as this often requires irrigation) (Fajardy et al., 2018; Yamagata et al., 2018). The scale of water demand through BECCS implementation is projected to be very high (Stenzel et al., 2021) – to a degree that the planetary boundary for freshwater withdrawal would be transgressed (Heck et al., 2018). Further water demand is caused by the CCS technology at the power or production plant level, even though not to the same extent as water demand by biomass cultivation (N. Grant et al., 2021; Rosa et al., 2020). Thus, freshwater availability is a key social and ecological limiting factor for the sustainability of BECCS, depending on the regional level of water availability or water stress (Heck et al., 2018). But not only quantity matters – water quality can also be negatively affected, especially through agricultural chemicals (Honegger et al., 2021). Excessive fertilizer use can lead to eutrophication and water quality degradation (Yamagata et al., 2018).

4.3.7 Climate Change

The category of climate change is a very decisive one as the main purpose of BECCS is to reduce pressure on this planetary boundary by removing carbon from the atmosphere. However, the amount of (negative) emissions generated through BECCS varies significantly depending on the supply chain emissions. With unsustainable biomass, emissions from a BECCS plant can not be negative at all or even higher than from a fossil CCS plant with natural gas (Cumicheo et al., 2019; Fajardy & Mac Dowell, 2017). It is crucial that emissions from land use change (direct and indirect) are considered because they constitute the highest emission source in the biomass supply chain (Fajardy & Mac Dowell, 2017). Additionally, not only CO_2 emissions matter, but also other greenhouse gases such as CH_4 and N_2O (Creutzig et al., 2015). The emitting factors along the supply chain (land use change, cultivation, transport, processing, plant-level) are listed in Table 2.

4.4 Wrap-up I: BECCS – a 'Burden Shifting' Technology

The sections 4.1-4.3 have presented the results to the first research question (*which dimensions have been assessed to evaluate the sustainability of BECCS?*) and a conceptual model that depicts the most relevant sustainability dimensions of a BECCS assessment based on the Doughnut-framework. The key message of the BECCS-Doughnut is: *An unsustainable way of BECCS implementation potentially causes a) human deprivation in seven social dimensions of wellbeing and b) environmental degradation in seven ecological categories.* Whilst BECCS is designed for reducing pressure on the planetary boundary of climate change its implementation potentially shifts the burden on other social (food security, water availability, health, social conflicts) and ecological dimensions (land conversion, biodiversity loss, nitrogen and air pollution, freshwater withdrawals), especially if implemented at the scale of gigatons (Heck et al., 2018). Optimizing the sustainability of the BECCS supply chain is thus a complex task. The following section examines the literature regarding potential trade-offs that can emerge when implementing BECCS.

4.5 Trade-offs between Sustainability Dimensions

A trade-off refers to a situation in which one goal is incompatible with another one (Dooley et al., 2018; Gibon et al., 2017; Stoy et al., 2018; Yamagata et al., 2018). The sections above have shown that BECCS is a trade-off technology as it shifts negative impacts on other sustainability dimensions, whilst addressing the problem of climate change.

For identifying a safe and just operating space for the implementation of BECCS it is therefore key to analyse trade-offs, because it is likely that sustainability optimization in one dimension leads to consequences in other dimensions. Aiming at balancing biophysical limits with social minimum capabilities, the second research question therefore asks: *Which trade-offs potentially result from BECCS implementation and how can they be navigated?*

The systematic literature review and the interviews revealed 10 trade-offs within BECCS implementation. These were grouped into three main categories: 1. Land competition trade-offs, 2. Land use efficiency trade-offs and 3. Energy system trade-offs (see Table 3). Based on the systematic review and the interviews, each of the three categories and possible ways how to navigate each trade-off will be explained in the following sections.

Table 3. BECCS implementation trade-offs and how to navigate them. Numbered sources can be found in appendix A.

	Trade-off	Coping Strategies for navigating the trade-off	Sources
Land competition trade-offs	Food vs. Bioenergy	• Use biogenic waste (end of cascade) • Forest & agricultural residues (controversial, trade-off with their function as nutrients) • Second generation energy crops grown on "marginal" land (contested concept) • Intensification (increasing fertilizer/irrigation, controversial) • Algae as biomass (technology not mature, not net negative yet) • Less livestock intense diet patterns, avoid food waste	18,19,20,22,31,41 Interviews 1,5
	Biodiversity/Conservation vs. Bioenergy	• Biomass from restoration (e.g. perennial grasses, wetland restoration/paludiculture) • Integration of bioenergy crops into landscape diversification	4,18 Interviews 1,3,4,5
	Biomaterials vs. Bioenergy	• Clear cascading hierarchy, bioenergy at the end of the cascade	41 Interviews 1,2,3,4,5
	Land-based CDR vs. Bioenergy	• Rapid defossilization reduces long-term scale of CDR • Develop marine CDR methods	20 Interview 1
Land use efficiency trade-offs	Land use minimization vs. water use minimization vs. carbon removal maximization	• Irrigation increases yield and is often needed for activating degraded land • Avoid maximization strategies and assess regional water stress carefully to prevent water depletion.	11,17,29 Interview 5
	Reduce fertilizer use vs. land use efficiency	• Avoid maximization strategies (e.g. yield maximization, zero fertilization, harvesting all residues), choose balancing approaches • Improve soil nutrients (rotation, organic manure, leave some residues as nutrients) • Perennial grasses and woody crops need less fertilizer compared to annual crops.	19,29 Interviews 1,3
	Global allocation optimization (for water, land use, yield) vs. social benefits of regional supply chains	• Acknowledge that 'optimal' pathways identified by techno-economic assessments (e.g. large scale transport fuel production and BECCS) are risking large shortfalls regarding social indicators • Rather start from supply chain: Is it transparent, reliable, feasible, just?	9,17 Interviews 3,4
Energy system trade-offs	Energetic value of BECCS vs. emissions value of BECCS (negative emissions generation vs. mitigation/defossilisation)	• Especially with scarcity assumption (there is not enough sustainable biomass) • Whole-system study needed: a) power generation with higher capture rate and therefore higher negative emissions (post-combustion) or b) decarbonise challenging sectors such as aviation, shipping with liquid biofuels (resulting in less carbon capture due to pre-combustion), but possibly higher mitigation values?	23 Interviews 2,4,6
	Cost-effectiveness vs. defossilisation speed maximization	• Policies should ensure that BECCS is not a "buying time" option for fossil industries, but fulfils targeted energy provision while compensating only strictly defined residual emissions	24 Interviews 1,2
	Efficient energy provision vs. negative emissions maximization	• Efficiency loss could be balanced by increased energy efficiency on the demand side and demand reduction generally	42,43 Interview 1

4.5.1 Land Use Competition Trade-offs

Generally, bioenergy production competes for land with other important land use functions such as food production, biodiversity, and partially also carbon removal (Creutzig et al., 2021). All of these land use functions are projected to increase whilst partially being incompatible with each other (Creutzig et al., 2021). The food versus bioenergy trade-off can be navigated through different means. The main principle is that no food should be used for energy production (Doelman et al., 2018). Several alternatives exist, even though they do not come without controversy. Using non-food lignocellulosic energy crops is an important alternative to food crops, however they still need land and can therefore directly or indirectly displace food production. Many models suggest using only 'marginal land' for energy crops to avoid this effect, but this is a contested classification, because 'unused' marginal land could still be of importance for biodiversity or local livelihoods. Another alternative is using forest or agricultural residues (Negri & Guillén-Gosálbez, 2022; Wu et al., 2023). However, an over-utilisation of residues has negative consequences for soil fertility, erosion, evapotranspiration, and soil carbon (Calvin et al., 2021; Fajardy et al., 2018) and results in the need for increased fertilization. Agricultural intensification could also increase land use efficiency but would likewise shift the burden to other planetary boundaries (fertilizer use and freshwater withdrawal) (Heck et al., 2018). Algae could deliver biomass without any need for land however, the technology readiness level is still low and negative emissions seem unachievable (Melara et al., 2020). The only alternatives without objection are the use of biogenic waste and reducing pressure on land via dietary change, as plant-based diets require much less land than livestock (Calvin et al., 2021).

The negative consequences of bioenergy plantations for biodiversity have already been presented (see 4.3.2). A way of navigating the trade-off between land required for bioenergy and land required for conservation could be the combination of habitat and landscape restoration with a certain degree of biomass provision as ecosystem service for bioenergy. Paludiculture from restored peatlands is an example for such a strategy (Tanneberger et al., 2021). Perennial crops have higher biodiversity and soil carbon values compared to highly degraded or arable land, especially when contributing to landscape diversification, for example in combination with hedgerows (Donnison et al., 2021) (Interviews 1 & 3).

Another trade-off has been highlighted in several interviews, but only within one article: A growing bioeconomy needs biomass for material use instead of burning it for energy production. As a result, there is competition for biomass when it is yielded. A clear cascading use of the biomass could help navigating this trade-off: Any material use (building material, chemicals, etc.) should have a higher priority than energy production which is positioned at the end of the cascade for any type of biogenic waste (Material Economics, 2021; Moriarty & Honnery, 2016; NRW.Energy4Climate, 2023). BECCS also competes for land with other land-based CDR technologies such as afforestation (Doelman et al., 2018). The general need for CDR can be reduced with ambitious decarbonization which would reduce the reliance on CDR for remaining emissions. The land demand by CDR could also be reduced if more marine CDR is developed (Interview 1).

4.5.2 Land Use Efficiency Trade-offs

As competition for land is a key trade-off for BECCS implementation, many scholars suggest measures for increasing land use efficiency on the basis of global allocation models. However, there are trade-offs within these allocation strategies: Whilst land use minimization would require maximum productivity (yield per land unit), this increased productivity would mostly be at the expense of other planetary boundaries (if done through irrigation or fertilizer intensification). Other global efficient allocation models suggest growing the biomass in regions where it is most efficient in terms of soil fertility, marginal land availability, or water availability (Fajardy & Mac Dowell, 2020). By contrast, Thrän et al. (2020) argue that these global models often end up suggesting a supply chain that puts identified social dimensions at risk (e.g., large scale imports from the Global South, centralized large power plants in the industrialized regions) (Fajardy & Mac Dowell, 2020). This type of land use optimization would then constitute a trade-off with a regional, less complex, and therefore more manageable supply chain (Thrän et al., 2020). As many of the 'optimal' regions for biomass growth are actually found outside Europe and in the Global South, it seems questionable to see a cultivation region as 'optimal' only on the basis of land use efficiency criteria. Taking a precautionary approach, an optimal supply chain is rather one that is transparent and reliable in terms of minimizing social shortfall and ecological risks (Interviews 3 & 4). This is maybe not always the most land use efficient one, but the most effective one in the sense of guaranteeing sustainability.

4.5.3 Energy System Trade-offs

The literature review also revealed some trade-offs within the energy system if BECCS is to be implemented. First, there is a trade-off between the energetic value (the ability to provide defossilized energy) and the emissions value (the ability to provide negative emissions) of BECCS. Neil Grant et al. (2021) highlight that if negative emissions should be maximized (the emissions value), BECCS would be employed by installing large centralized power plants for producing electricity because this bioenergy production with post-combustion CCS yields the highest negative emissions. However, other renewable energies such as wind or solar already provide cheap defossilized electricity at scale and low cost, thus the energetic value of electricity produced by BECCS is low. On the other hand, producing biofuels for sectors that are challenging to decarbonise (e.g., shipping, aviation) could have a high energetic value as there are only limited and expensive fossil-free alternatives. Nonetheless, this would reduce negative emissions due to pre-combustion CCS and up to 50% of the carbon content remaining in the fuel with the resulting emissions upon combustion (N. Grant et al., 2021). Second, cost-effectiveness is traded against fast decarbonization. BECCS is an attractive technology in many models because it allows a cost-effective delay on the decarbonization pathway (Butnar et al., 2020). This is criticized by some scholars, because delaying the fossil phase-out is a risk if BECCS does not reach its projected upscaling rate (Palmer & Carton, 2021). Avoiding this risk would result in a higher decarbonization speed and therefore higher costs. The third trade-off, efficient energy provision vs. negative emissions might be inevitable, because applying CCS to bioenergy production always implies an energy penalty for the energy demand of the CCS process (Tanzer et al., 2020). Furthermore, biomass has a lower energy density than fossil fuels which leads to further efficiency loss (Cumicheo et al., 2019).

4.6 Wrap-up II: BECCS Implementation Is Riddled with Trade-offs

Whilst BECCS can actually play a role in solving climate change, its implementation is riddled with trade-offs regarding other important sustainability dimensions. Almost all 'wedges' of the Doughnut are potentially negatively affected by implementing BECCS at scale – except for 'income & work' and 'energy' (see chapter 4.2). Further trade-offs emerge with competing land use options and the integration of BECCS into the energy system. Implementing BECCS sustainably therefore means balancing many trade-offs in a way that none of the affected sustainability dimensions is facing unjustified collateral damage.

5. Discussion

In this chapter, I interpret key findings of the review with the normative background of strong sustainability and the Doughnut-framework (see section 2). This interpretation is supported by suggestions from the interviews. The objective is giving guidance on how to weigh different sustainability dimensions and which questions to ask first when trying to implement BECCS within a safe and just operating space. However, I want to emphasize that I do neither make a claim about the best suited life cycle assessment or greenhouse gas accounting method nor will I deliver a generalized statement about which type of BECCS is the most sustainable one. There are too many dimensions which need to be weighed one against another in each specific context.

5.1 Three Key Interpretations of the Results

In this section I discuss three key interpretations of the results as guiding assumptions for the sustainability assessment decision tree as a 'tool' for practitioners (as presented in section 5.2). The three key interpretations of my results are: 1) sustainability of the biomass is key; 2) the safe and just operating space for BECCS is narrow; and 3) the implementation of BECCS should be limited and targeted.

5.1.1 Sustainability of the Biomass Is Key

The large majority of the sustainability (sub-)dimensions actually relate to the bioenergy (BE) side of BECCS. The sustainability of the CCS process carries some risks in the dimensions of *Climate Change, Safe Geological Storage,* and to some extent (but much less than bioenergy) on *Freshwater Withdrawal*. All the other dimensions are heavily influenced by the degree of sustainability in the biomass supply chain. This relates especially to many social dimensions and the land, water, fertilizer, and greenhouse gas footprint of the biomass cultivation (Creutzig et al., 2021; Heck et al., 2018). Thus, for any BECCS project, ensuring long-term sustainability of the feedstock should be the key concern (Interview 6). Jeswani et al. (2022) highlight the problem that many Life Cycle Assessments do not include land use change (LUC) in their calculations. This is highly problematic, because LUC is one of the key variables which make unsustainable biomass unable to reach negative emissions and potentially perform even worse than fossil fuels (Cumicheo et al., 2019; Fajardy & Mac Dowell, 2017; Jeswani et al., 2022). This undermines the core goal of BECCS – not to speak of further 'burden shifting' side effects on other ecological dimensions.

5.1.2 The Safe and Just Operating Space for BECCS is Narrow

Due to the large list of sustainability risks and trade-offs, some scholars suggest not implementing BECCS at all (McElwee et al., 2020; Shue, 2017). Nevertheless, most articles did not go that far, but rather discussed limits of scale of BECCS implementation. Creutzig et al. (2021) suggests not exceeding a precautionary threshold value of 0.5 million km^2 globally, which is basically the current global land used for bioenergy. Another review suggests a sustainable global BECCS implementation potential of 0.5-5 gigatons of negative CO_2 emissions (Fuss et al., 2018). This potential is questioned by Heck et al. (2018) who suggest a sustainable potential of only 0.1 gigatons negative CO_2 emissions through dedicated bioenergy plantations. Higher negative emissions would be possible, but "only if the precautionary principle of the planetary boundaries framework was discarded" (Heck et al., 2018, p. 153). As a comparison, the range of negative emissions needed for net zero by 2050 in scenarios that are compatible with the Paris Agreement (limiting global temperature rise to below 1.5°C) lies between 5.5-16 $GtCO_2$ (S. M. Smith et al., 2023). Generally, these numbers are tentative and confronted with large uncertainties, so that other researchers claim that it is even impossible to quantify any amount of sustainable biomass potential (Calvin et al., 2021). The main conclusion I can derive is that implementing BECCS is a matter of scale and that a safe and just operating space for BECCS will be quite limited by several social and ecological dimensions (Asibor et al., 2021; Krause et al., 2018; P. Smith et al., 2019). It is therefore important to not overly rely on BECCS for negative emissions at scale, but rather develop many different technologies of carbon removal (Minx et al., 2018).

5.1.3 The BECCS Implementation Principle: Limited and Targeted

Up until now, the analysis has established that there is indeed a sustainable way of implementing BECCS, but only to a limited extent, because otherwise negative side effects become too large. Each of the ecological dimensions constitutes a limiting factor for a sustainable scale of BECCS. Sustainable biomass will be very much needed, but also very scarce. BECCS implementation should therefore be targeted (with a prioritization for applications where it is most beneficial) and limited (so that collateral harmful effects on other important sustainability dimensions are avoided). The word 'limited' highlights that a general rule of 'the more the better' is not valid for BECCS whereas the word 'targeted' refers to the argument that not all BECCS applications are equally effective due to trade-offs (see section 4.4.3). This BECCS implementation principle – limited and targeted – could help keep the technology within a safe and just operating space where it actually contributes to solving the problem of climate change via negative emissions without excessive collateral damage on social and ecological sustainability dimensions.

5.2 The Decision Tree as a Practical Tool for BECCS Assessments

Admittedly, the task of translating the principle of limited and targeted implementation into practice requires weighing between different trade-offs and sustainability (sub-)dimensions. This certainly calls for democratic deliberation to make justified and legitimate implementation decisions (Boettcher et al., 2023; Minx et al., 2018). The decision tree for a sustainability assessment of BECCS strategies and projects at hand (Figure 5) should therefore not be understood as the ultimate truth, but as a suggestion backed up by state-of-the-art evidence in this formative phase of policy development in the German and wider EU context (Boettcher et al., 2023). It has been developed on the basis of the systematic literature review, semi-structured interviews, and tested in a workshop (see methods chapter 2).

BECCS sustainability assessment decision tree

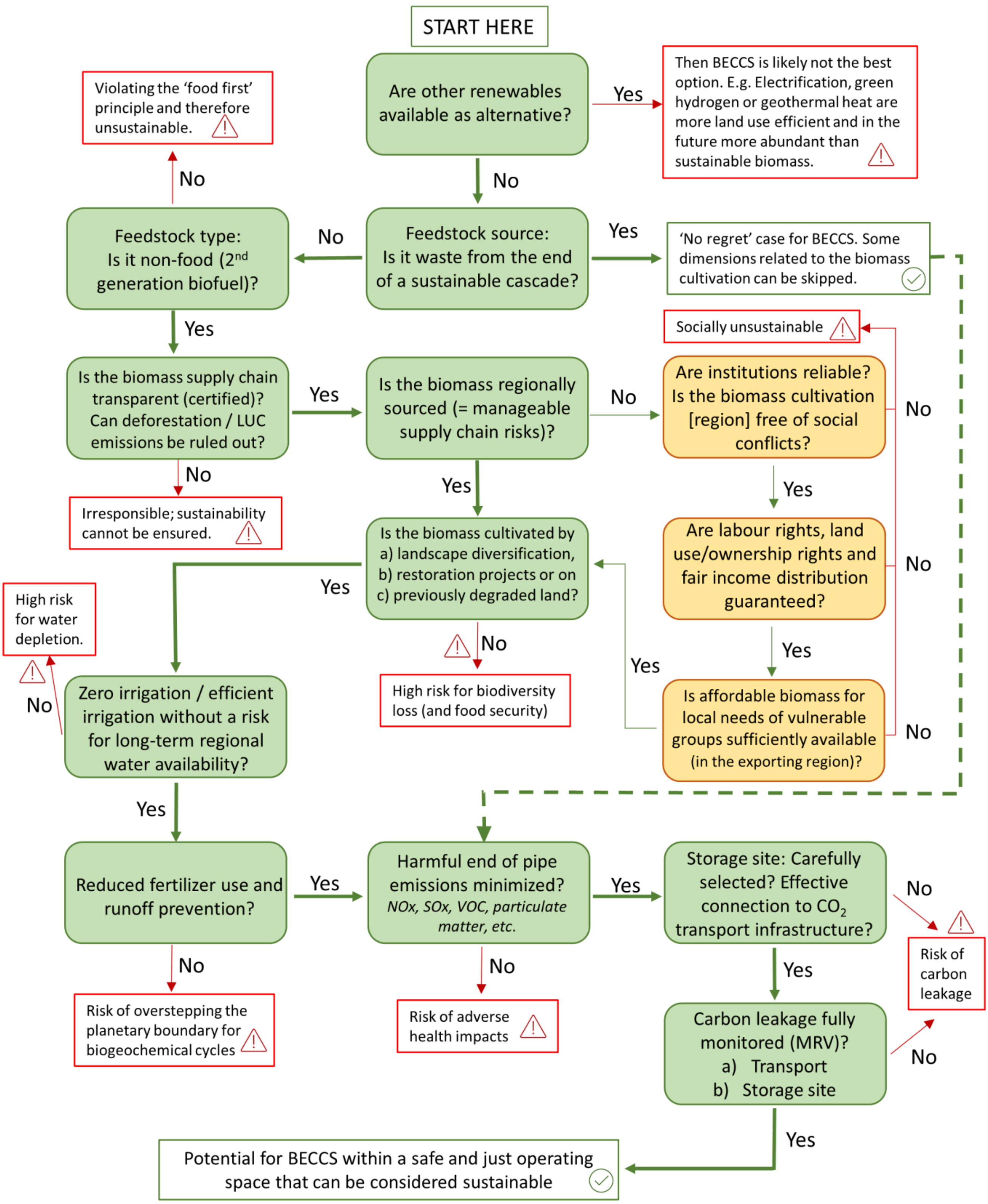

Figure 5. BECCS Sustainability Assessment Decision Tree. The pathways defined by green arrows highlights sustainable supply chains. The first is a shorter one, based only on sustainable waste as feedstock. The second one is rather complex for the case that energy crops are involved. In yellow: Social assessment categories which have to be evaluated if the feedstock is not regionally sourced. The red text boxes highlight important risks.

This decision tree (Figure 5) starts with the energy system and industry sector perspective. Acknowledging that sustainable biomass will be very scarce, the first question asks if other – more land use efficient – renewable energy sources could be used for the same purpose. This can help limiting and targeting biomass use (Wu et al., 2023). This question refers to the trade-off between emissions and energetic value of BECCS (see 4.5.3). Several interviewees (1,2,3,4) argued that BECCS might actually have its highest value in addressing industrial applications that are hard to decarbonize (N. Grant et al., 2021). As an example, given in interviews number 2 and 3, cement and lime production have high residual process emissions that need to be captured by CCS anyways and require high temperature heat which is hard to electrify (Cavalett et al., 2022). Thus, cement and lime are industrial niches with a sustainable potential for BECCS without generating excessive biomass demand (Cavalett et al., 2022). If electrification or green hydrogen are feasible alternatives to BECCS, these should be prioritized instead (Interviews 1 & 2). Another example: Cars can run as battery electric vehicles without any need of bio- or synfuels on the basis of BECCS. But BECCS could play a role for aviation because hydrogen or batteries are not projected to be applicable in aviation (Material Economics, 2021). Making a final decision on this question requires more granular and context-specific assessments. But it is an important question to be asked right at the beginning because diving into the complex biomass supply chain only makes sense if the BECCS application in question is actually addressing an important decarbonization gap (Interviews 1,2,3,4).

Acknowledging limited availability of sustainable biomass equally requires establishing a hierarchy for its use. Biomass has high value in substituting fossil and high emission materials (e.g., building with wood instead of cement, biogenic plastic, etc.) (Moriarty & Honnery, 2017). The second question of the decision tree therefore asks if a sustainable cascading use of the biomass has been applied, addressing the 'biomaterials vs. bioenergy' trade-off (see 4.5.1) (NRW.Energy4Climate, 2023).

These first two questions reassure the application of the principle 'limited and targeted' while simultaneously defining a low-risk sustainable use case for BECCS ('no regret case'): Waste-based BECCS at the end of a sustainable biomass use cascade in a key priority area for (BE)CCS (Interviews 2, 3, 4, 5). If other types of biomass should be used, the associated risks and trade-offs are more complex.

The 'food first' principle had been highlighted by many authors (see 4.2.3 and 4.4.1), therefore looking at the non-waste feedstock type as the next question seems reasonable. The subsequent question addresses the transparency and reliability of the biomass supply chain with a simple rationale: The review has shown such manifold adverse effects that can reach planetary scale so that a guarantee for sustainability is needed (e.g. a reliable certification or authority) (Interviews 4 & 5). If this reliability is not given, the associated risks are too high and therefore the BECCS application case can be classified as irresponsible and potentially unsustainable.

The rationale for subsequently addressing the question about regional biomass is straightforward again. With regional suppliers, the supply chain will be relatively short with very few intermediaries and therefore quite manageable for minimizing social and ecological risks (Interviews 3 & 4). With global trade, the number of intermediaries increases and important sustainability information easily gets unverifiable (Interview 4). This is why I added the yellow boxes as additional social checkboxes for the case of imports. Some scholars suggested that sourcing biomass for BECCS in the Global South might be too risky and should therefore not be envisaged (Hansson et al., 2020) whilst others have highlighted a certain potential if the biomass cultivation is sustainably integrated into existing agricultural systems with empowerment for farmers (Creutzig et al., 2015). Thus, the yellow checkboxes must be added to the "optimal" green supply chain pathway, if the biomass is imported from countries with higher associated social shortfall potential.

These and the following checkboxes connect back to the dimensions of the Doughnut and can be assessed more thoroughly with the related subdimensions (see results chapter 4). Thus, this assessment decision tree helps getting a quick overview of all relevant dimensions of the BECCS-Doughnut and therefore addresses the identified translation gap from science to practice. It should not replace a comprehensive sustainability assessment that covers the subdimensions systematically. But it facilitates a vital democratic debate about how to implement BECCS via structuring the discussion into topics that can be addressed one by one in a constructive way.

6. Contributions to Sustainability Science and Limitations

Since this thesis is written in the field of sustainability science, in this chapter I want to discuss and reflect its contributions to and its position within this broad field of research.

6.1 Position of this Thesis within Sustainability Science

According to the matrix for structuring sustainability science, suggested by Jerneck et al. (2011), I adopted a problem-solving research approach of sustainability science with a focus on pathways, strategies, and implementation. Interestingly, the four core sustainability challenges of the matrix (climate change, biodiversity loss, land use change & water scarcity) are all within the scope of this thesis. Bioenergy has been identified as a typical example of a *wicked problem* (Jerneck et al., 2011). Now adding CCS to bioenergy involves even more uncertainties. Furthermore, if a decision to implement BECCS is taken today, the effects will be seen with a time lag of many years as it will take years to ramp up the necessary infrastructure (Fuss et al., 2018). But if decisions are not taken very soon, the window of opportunity for reaching climate goals on time closes (IPCC, 2023). Thus, the BECCS conundrum is a case of post-normal science involving urgent decisions with high stakes on the basis of uncertain facts and values in dispute (Funtowicz & Ravetz, 1993).

As this thesis deals with a wicked problem based on dynamically evolving literature, the uncertainties have to be kept in mind. When I suggest how to structure the debate it should therefore be seen as the start of a process, not as unequivocal results (Spangenberg, 2011). Furthermore, the underlying rationale of this thesis includes normative judgements and assumptions. These are described and made explicit in the following section.

6.2 Normative Implications of this Thesis

As sustainability is a normative concept and the process of problem definition is a normative process in itself, Spangenberg (2011) argues that within sustainability science, normativity should be made explicit. This thesis follows a 'strong' sustainability concept (see 2.1), conceptualized through the Doughnut, which has some normative implications. For example, strong sustainability means being agnostic about economic growth and is rather characterized by an understanding of a steady-state economy (Daly, 2005). For the case of BECCS, exemplary for this type of thinking, this means also asking the question of sufficiency: Do we really need it? (Raworth, 2022) Are there ways to generally reduce energy consumption and emissions not only through efficiency but also through consuming and producing less? As the potential for BECCS is limited, reducing energy demand should be a key priority complementary to the type of sustainability assessment developed in this thesis (Interview 1).

The Doughnut framework furthermore has an important focus on social justice because the emphasis on ecological limits and premises of strong sustainability should not be understood wrongly as a focus on ecological dimensions only. It is rather the opposite: If unlimited economic growth cannot lift the boat for all in the long run, income distribution and social justice matters even more (Raworth, 2022). It cannot be emphasized enough that human wellbeing within planetary boundaries can only thrive if social minimum standards of wellbeing are achievable for everyone (Raworth, 2022). Generally, throughout the literature review there was much higher attention to ecological issues related to BECCS than to social ones. Following the Doughnut framework, I intentionally gave social dimensions the same importance as limiting factors within the framework as the ecological ones even though they were mentioned less frequently.

Finally, the principle of 'limited and targeted implementation' (see section 5) normatively implies following a precautionary rationale. The precautionary principle is a weakly defined concept, but here

I understand it as considering the case of failure, especially where detrimental impacts can be irreversible (Steel, 2014). In the case of negative emissions this means that the scale of BECCS deployment should be on a limited scale to avoid major collateral transgressions of planetary boundaries. However, not reaching the Paris Agreement goals might also lead to irreversible damage of the Earth System and negative emissions will be needed for mitigating climate change in the long run (IPCC, 2023). Therefore, no technology with a sustainability potential should be rejected on a generalized level, even if the potential is limited (Asibor et al., 2021). The narrow safe and just operating space for sustainable BECCS (see section 5.1) gives orientation for how this potential can achieved – but only as part of a diversified basket of CDR technologies, because BECCS might actually not deliver what has been promised (Creutzig et al., 2021; Minx et al., 2018).

6.3 Research Design: Boundary Work, Relevance and Translation

Going beyond academia and doing transdisciplinary research is an important part of sustainability science (Spangenberg, 2011). There are some transdisciplinary elements in my research design: From the beginning of and throughout the research process, I spoke to NGO-members about their challenges, problems, and knowledge gaps and how my thesis could produce useful results to them. The research process culminated in a workshop with practitioners from NGOs, industry, and think tanks so that I could include feedback on the results. This process of "boundary work" (Cash et al., 2003) or "extended peer community" (Spangenberg, 2011) ensures usefulness and relevance as key criteria for practice-oriented problem-solving research. However, the adopted approach is only partially transdisciplinary, still following a knowledge-first approach (Miller, 2013) without creating systematic participatory processes or real-world-lab contexts.

I furthermore adopted the principles of credibility, salience, and legitimacy into my research design (Cash et al., 2003). Credibility is addressed by following a systematic review approach that is reproducible. Salience is addressed through involving NGO-members into the formulation of research questions and by synthesizing the results into a decision tree that translates important findings into applicable language and makes them more relevant for decision making in practice. Legitimacy is addressed by making normative implications explicit and by presenting a decision tree that is left open for different weighting and prioritizing through a broader debate.

6.4 Limitations and further Research

There are a few limitations and recommendations for further research that I want to highlight. Ideally, a systematic review is conducted by a team, not a single author as in this case, to reduce selection biases (Haddaway et al., 2020). I conducted interviews and a workshop as complementary methods to include other perspectives and avoid blind spots. The stakeholder dialogue started with the NGO

Germanwatch and then expanded into their network of collaborating actors. However, the total number of interviews (n=6) is limited and therefore there are limits to generalizing the results. With other stakeholders involved, research questions and results presentation might have been different. Thus, more work could be done to improve results in terms of usefulness and applicability through a continuing dialogue with a broader range of stakeholders.

Second, I decided to keep a problem-solving approach with a focus on relevance and applicability for stakeholders in practice. Other authors have adopted a critical research approach to the BECCS conundrum which would be very interesting to combine with my findings in future research (Buck, 2022; Gambhir et al., 2019; Ho, 2023; Low & Schäfer, 2020; Malm & Carton, 2021; Morrow et al., 2020; Palmer & Carton, 2021; Rubiano Rivadeneira & Carton, 2022; Sovacool et al., 2022; Stoddard et al., 2021).

Third, the literature and the interviews focus on the German and the wider EU-context. Any comprehensive sustainability assessment should be context-sensitive, so results from other regions might be different.

Fourth, I have excluded certain dimensions from the original Doughnut framework. Such a decision always carries a risk of obscuring some impacts, especially because most social and ecological dimensions are interrelated. Exclusion of a sustainability dimension should therefore not be understood as 'there is no relevance at all', but rather in the way that the reviewed literature has not brought up these categories as directly impacted through the implementation of BECCS. On the other hand, I have added one new ecological category to the other ones that were taken from the planetary boundary framework: *Safe geological storage*. This could raise some controversy as it is not a planetary boundary in its original sense. Additionally, the reviewed literature had a limited focus on this dimension. One reason for this gap could be that the retrieved literature about BECCS focuses to a larger extent on the bioenergy side of the topic than on the CCS side.

Fifth and finally, for further research it would also be very interesting to apply this type of application of the Doughnut framework to other technologies for the sustainability transition such as DACCS, hydrogen or other CDR technologies.

7. Conclusions

The first research question asked: w*hich dimensions have been assessed to evaluate the sustainability of BECCS?* Seven social and seven ecological dimensions with 59 subdimensions were presented in section 4 and conceptualized by the 'BECCS-Doughnut'. This conceptual model was inspired and guided by the Doughnut-framework (Raworth, 2022), which added social dimensions to the planetary boundaries as a guiding framework of strong sustainability. A comprehensive sustainability assessment should therefore go beyond a narrow focus on lifecycle emissions and include the social and ecological dimensions of the BECCS-Doughnut. Generally, there is a high risk from BECCS implementation to cause collateral transgressions of planetary boundaries such as biodiversity, freshwater withdrawal, land conversion, and nitrogen pollution if unsustainable biomass feedstock is used at large scales. Using unsustainable biomass that involves land use change, deforestation or large N_2O emissions can even undermine the key purpose of producing negative emissions and thus negatively impact climate change. Several social dimensions where BECCS implementation could result in negative impacts are food security, health, water access, justice and social equity as well as stability and peace.

The second research question asked about *trade-offs potentially resulting from BECCS implementation and how they can be navigated.* A list of ten trade-offs with coping strategies for navigating them was presented in section 4.5. Many of them involve limiting factors for the scale of sustainable BECCS. Thus, the safe and just operating space for implementing BECCS is narrow and therefore the guiding principle for BECCS implementation should be 'limited and targeted' deployment. Limited refers to the scarcity of sustainable biomass and the question of scale, whereas targeted means that if sustainable BECCS is limited, it should be used where it is most beneficial for reaching climate targets and where trade-offs are minimised. Finally, a sustainability assessment decision tree has been developed for translating the principle of 'limited and targeted', the long lists of trade-offs and social and ecological subdimensions into a concise guiding framework for decision making and position building in practice, targeting representatives from NGOs, industry, and politics that are faced with high time pressure in the current formative phase of CDR policies in Germany and the wider EU context.

To sum up, the identified knowledge gap of a) how to navigate the tension between BECCS as a possible solution for achieving negative emissions and BECCS as a sustainability risk and b) which dimensions to assess for evaluating the sustainability of BECCS is therefore addressed with three key contributions of this thesis: a) a comprehensive set of social and ecological sustainability assessment dimensions, b) a list of implementation trade-offs and coping strategies and c) a decision tree for sustainability assessments and for structuring the urgently needed democratic debate on if and how to implement BECCS.

8. List of References

Allen, M. R., Friedlingstein, P., Girardin, C. A. J., Jenkins, S., Malhi, Y., Mitchell-Larson, E., Peters, G. P., & Rajamani, L. (2022). Net Zero: Science, Origins, and Implications. *Annual Review of Environment and Resources*, *47*(1), annurev-environ-112320-105050. https://doi.org/10.1146/annurev-environ-112320-105050

Asibor, J. O., Clough, P. T., Nabavi, S. A., & Manovic, V. (2021). Assessment of optimal conditions for the performance of greenhouse gas removal methods. *Journal of Environmental Management*, *294*, 113039. https://doi.org/10.1016/j.jenvman.2021.113039

Asibor, J. O., Clough, P. T., Nabavi, S. A., & Manovic, V. (2022). A country-level assessment of the deployment potential of greenhouse gas removal technologies. *Journal of Environmental Management*, *323*. Scopus. https://doi.org/10.1016/j.jenvman.2022.116211

Boettcher, M., Schenuit, F., & Geden, O. (2023). The formative phase of German carbon dioxide removal policy: Positioning between precaution, pragmatism and innovation. *Energy Research & Social Science*, *98*, 103018. https://doi.org/10.1016/j.erss.2023.103018

Buck, H. J. (2022). Mining the air: Political ecologies of the circular carbon economy. *Environment and Planning E: Nature and Space*, *5*(3), 1086–1105. https://doi.org/10.1177/25148486211061452

Burns, W. C. G. (2016). Human Rights Dimensions of Bioenergy With Carbon Capture and Storage: A Framework for Climate Justice in the Realm of Climate Geoengineering. *Climate Justice*, 22.

Butnar, I., Broad, O., Baltazar Solano Rodriguez, & Paul E. Dodds. (2020). The role of bioenergy for global deep decarbonization: CO2 removal or low-carbon energy? *GCB Bioenergy*, *12*(3), 198–212. https://doi.org/10.1111/gcbb.12666

Calvin, K., Cowie, A., Berndes, G., 1966, Arneth, A., Cherubini, F., Portugal-Pereira, J., Grassi, G., House, J. I., Johnson, F. X., Popp, A., Rounsevell, M., Slade, R., & Smith, P. (2021). Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy*, *13*(9), 1346–1371. https://doi.org/10.1111/gcbb.12863

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jäger, J., & Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences*, *100*(14), 8086–8091. https://doi.org/10.1073/pnas.1231332100

Cavalett, O., Watanabe, M. D. B., Fleiger, K., Hoenig, V., & Cherubini, F. (2022). LCA and negative emission potential of retrofitted cement plants under oxyfuel conditions at high biogenic fuel shares. *Scientific Reports*, *12*(1), 8924. https://doi.org/10.1038/s41598-022-13064-w

Chiquier, S., Patrizio, P., Bui, M., Sunny, N., & Dowell, N. M. (2022). A comparative analysis of the efficiency, timing, and permanence of CO2 removal pathways. Energy & Environmental Science, 15(10), 4389–4403. https://doi.org/10.1039/D2EE01021F

Clery, D. S., Vaughan, N. E., Forster, J., Lorenzoni, I., Gough, C. A., & Chilvers, J. (2021). Bringing greenhouse gas removal down to earth: Stakeholder supply chain appraisals reveal complex challenges. *Global Environmental Change*, *71*, 102369. https://doi.org/10.1016/j.gloenvcha.2021.102369

Creutzig, F., Erb, K.-H., Haberl, H., Hof, C., Hunsberger, C., & Roe, S. (2021). Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments. *GCB Bioenergy*, *13*(4), 510–515. https://doi.org/10.1111/gcbb.12798

Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Robledo-Abad, C., Rose, S., Smith, P., … Masera, O. (2015). Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*, *7*(5), 916–944. https://doi.org/10.1111/gcbb.12205

Cumicheo, C., Mac Dowell, N., & Shah, N. (2019). Natural gas and BECCS: A comparative analysis of alternative configurations for negative emissions power generation. *International Journal of Greenhouse Gas Control*, *90*, 102798. https://doi.org/10.1016/j.ijggc.2019.102798

Daly, H. (2005). Economics in a full world. *Scientific American*, *293*(3), 100–107.

Doelman, J. C., Stehfest, E., Tabeau, A., van Meijl, H., Lassaletta, L., Gernaat, D. E. H. J., Hermans, K., Harmsen, M., Daioglou, V., Biemans, H., van der Sluis, S., & van Vuuren, D. P. (2018). Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. *Global Environmental Change*, *48*, 119–135. https://doi.org/10.1016/j.gloenvcha.2017.11.014

Donnison, C., Holland, R. A., Harris, Z. M., Eigenbrod, F., & Taylor, G. (2021). Land-use change from food to energy: Meta-analysis unravels effects of bioenergy on biodiversity and cultural ecosystem services. *Environmental Research Letters*, *16*(11), 113005. https://doi.org/10.1088/1748-9326/ac22be

Dooley, K., Christoff, P., & Nicholas, K. A. (2018). Co-producing climate policy and negative emissions: Trade-offs for sustainable land-use. *Global Sustainability*, *1*, e3. https://doi.org/10.1017/sus.2018.6

Döring, N., & Bortz, J. (2016). *Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften* [Research methods and evaluation in the social and human sciences*]*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-41089-5

European Commission. (2022, November 30). *Commission proposes certification of carbon removals*. European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7156

Fajardy, M., Chiquier, S., & Dowell, N. M. (2018). Investigating the BECCS resource nexus: Delivering sustainable negative emissions. *Energy & Environmental Science*, *11*(12), 3408–3430. https://doi.org/10.1039/C8EE01676C

Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy & Environmental Science*, *10*(6), 1389–1426. https://doi.org/10.1039/C7EE00465F

Fajardy, M., & Mac Dowell, N. (2020). Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal. *One Earth*, *3*(2), 214–225. https://doi.org/10.1016/j.oneear.2020.07.014

Funtowicz, S. O., & Ravetz, J. R. (1993). Science for the post-normal age. *Futures*, *25*(7), 739–755. https://doi.org/10.1016/0016-3287(93)90022-L

Furre, A.-K., Eiken, O., Alnes, H., Vevatne, J. N., & Kiær, A. F. (2017). 20 Years of Monitoring CO2-injection at Sleipner. *Energy Procedia*, *114*, 3916–3926. https://doi.org/10.1016/j.egypro.2017.03.1523

Fuss, S., Jones, C. D., Kraxner, F., Peters, G. P., Smith, P., Tavoni, M., Vuuren, D. P. van, Canadell, J. G., Jackson, R. B., Milne, J., Moreira, J. R., Nakicenovic, N., Sharifi, A., & Yamagata, Y. (2016). Research priorities for negative emissions. *Environmental Research Letters*, *11*(11), 115007. https://doi.org/10.1088/1748-9326/11/11/115007

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

Galletta, A., & Cross, W. E. (2013). *Mastering the Semi-Structured Interview and Beyond: From Research Design to Analysis and Publication*. NYU Press. https://www.jstor.org/stable/j.ctt9qgh5x

Gambhir, A., Butnar, I., Li, P.-H., Smith, P., & Strachan, N. (2019). A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, through the Lens of BECCS. *Energies*, *12*(9), 1747. https://doi.org/10.3390/en12091747

Gibon, T., Arvesen, A., & Hertwich, E. G. (2017). Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. *Renewable and Sustainable Energy Reviews*, *76*, 1283–1290. https://doi.org/10.1016/j.rser.2017.03.078

Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal*, *26*(2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Grant, N., Hawkes, A., Napp, T., & Gambhir, A. (2021). Cost reductions in renewables can substantially erode the value of carbon capture and storage in mitigation pathways. *One Earth*, *4*(11), 1588–1601. https://doi.org/10.1016/j.oneear.2021.10.024

Haddaway, N., Bethel, A., Dicks, L. V., Koricheva, J., Macura, B., Petrokofsky, G., Pullin, A. S., Savilaakso, S., & Stewart, G. B. (2020). Eight problems with literature reviews and how to fix them. *Nature Ecology & Evolution*, *4*(12), 1582–1589. https://doi.org/10.1038/s41559-020-01295-x

Haddaway, N., Macura, B., Whaley, P., & Pullin, A. (2018a). *ROSES for Systematic Review Protocols. Version 1.0*. https://doi.org/10.6084/M9.FIGSHARE.5897269

Haddaway, N., Macura, B., Whaley, P., & Pullin, A. S. (2018b). ROSES RepOrting standards for Systematic Evidence Syntheses: Pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. *Environmental Evidence*, *7*(1), 7. https://doi.org/10.1186/s13750-018-0121-7

Hanssen, S. v., Steinmann, Z. j. n., Daioglou, V., Cˇengic´, M., Van vuuren, D. p., & Huijbregts, M. a. j. (2022). Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity. *GCB Bioenergy*, *14*(3), 307–321. https://doi.org/10.1111/gcbb.12911

Hansson, A., Fridahl, M., Haikola, S., Yanda, P., Pauline, N., & Mabhuye, E. (2020). Preconditions for bioenergy with carbon capture and storage (BECCS) in sub-Saharan Africa: The case of Tanzania. *Environment, Development and Sustainability*, *22*(7), 6851–6875. https://doi.org/10.1007/s10668-019-00517-y

Heck, V., Gerten, D., Lucht, W., & Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, *8*(2), 151-155. https://doi.org/10.1038/s41558-017-0064-y

Ho, D. T. (2023). Carbon dioxide removal is not a current climate solution—We need to change the narrative. *Nature*, *616*(7955), 9. https://doi.org/10.1038/d41586-023-00953-x

Honegger, M., Michaelowa, A., & Roy, J. (2021). Potential implications of carbon dioxide removal for the sustainable development goals. *Climate Policy*, *21*(5), 678–698. https://doi.org/10.1080/14693062.2020.1843388

IPCC. (2023). Summary for Policymakers. In: *Climate Change 2023: Synthesis Report.* A Report of the Intergovernmental Panel on Climate Change. 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 (eds.)]. IPCC, Geneva, Switzerland (in press).

Jerneck, A., Olsson, L., Ness, B., Anderberg, S., Baier, M., Clark, E., Hickler, T., Hornborg, A., Kronsell, A., Lövbrand, E., & Persson, J. (2011). Structuring sustainability science. *Sustainability Science*, *6*(1), 69–82. https://doi.org/10.1007/s11625-010-0117-x

Jeswani, H. K., Saharudin, D. M., & Azapagic, A. (2022). Environmental sustainability of negative emissions technologies: A review. *Sustainable Production and Consumption*, *33*, 608–635. https://doi.org/10.1016/j.spc.2022.06.028

Kallio, H., Pietilä, A.-M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: Developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, *72*(12), 2954–2965. https://doi.org/10.1111/jan.13031

Krause, A., Knoke, T., & Rammig, A. (2020). A regional assessment of land-based carbon mitigation potentials: Bioenergy, BECCS, reforestation, and forest management. *GCB Bioenergy*, *12*(5), 346–360. https://doi.org/10.1111/gcbb.12675

Krause, A., Pugh, T. A. M., Bayer, A. D., Li, W., Leung, F., Bondeau, A., Doelman, J. C., Humpenöder, F., Anthoni, P., Bodirsky, B. L., Ciais, P., Müller, C., Murray-Tortarolo, G., Olin, S., Popp, A., Sitch, S., Stehfest, E., & Arneth, A. (2018). Large uncertainty in carbon uptake potential of land-based climate-change mitigation efforts. *Global Change Biology*, *24*(7), 3025–3038. https://doi.org/10.1111/gcb.14144

Krevor, S., de Coninck, H., Gasda, S. E., Ghaleigh, N. S., de Gooyert, V., Hajibeygi, H., Juanes, R., Neufeld, J., Roberts, J. J., & Swennenhuis, F. (2023). Subsurface carbon dioxide and hydrogen storage for a sustainable energy future. *Nature Reviews Earth & Environment*, *4*(2), 102–118. https://doi.org/10.1038/s43017-022-00376-8

Lask, J., Slavica Rukavina, Ivana Zorić, Jason Kam, Andreas Kiesel, Iris Lewandowski, & Moritz Wagner. (2021). Lignocellulosic ethanol production combined with CCS—A study of GHG reductions and potential environmental trade-offs. *GCB Bioenergy*, *13*(2), 336–347. https://doi.org/10.1111/gcbb.12781

Low, S., & Schäfer, S. (2020). Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling. *Energy Research & Social Science*, *60*, 101326. https://doi.org/10.1016/j.erss.2019.101326

Malm, A., & Carton, W. (2021). Seize the Means of Carbon Removal: The Political Economy of Direct Air Capture. *Historical Materialism*, *29*(1), 3–48. https://doi.org/10.1163/1569206X-29012021

Material Economics. (2021). *EU Biomass Use In A Net-Zero Economy—A Course Correction for EU Biomass*. Material Economics. https://materialeconomics.com/latest-updates/eu-biomass-use

McElwee, P., Calvin, K., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Le Hoang, A., Lwasa, S., Nkem, J., Nkonya, E., Saigusa, N., Soussana, J.-F., Taboada, M. A., Manning, F., Nampanzira, D., & Smith, P. (2020). The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN Sustainable Development Goals. *Global Change Biology*, *26*(9), 4691–4721. https://doi.org/10.1111/gcb.15219

Melara, A. J., Singh, U., & Colosi, L. M. (2020). Is aquatic bioenergy with carbon capture and storage a sustainable negative emission technology? Insights from a spatially explicit environmental life-cycle assessment. *Energy Conversion and Management*, *224*, 113300. https://doi.org/10.1016/j.enconman.2020.113300

Miller, T. R. (2013). Constructing sustainability science: Emerging perspectives and research trajectories. *Sustainability Science*, *8*(2), 279–293. https://doi.org/10.1007/s11625-012-0180-6

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., Garcia, W. de O., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., & Dominguez, M. del M. Z. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 063001. https://doi.org/10.1088/1748-9326/aabf9b

Moriarty, P., & Honnery, D. (2016). Review: Assessing the climate mitigation potential of biomass. *AIMS Energy*, *5*(1), 20–38. https://doi.org/10.3934/energy.2017.1.20

Moriarty, P., & Honnery, D. (2017). Review: Assessing the climate mitigation potential of biomass. *AIMS Energy*, *5*(1), 20–38. https://doi.org/10.3934/energy.2017.1.20

Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., Geden, O., Ghosh, A., Low, S., Njamnshi, A., Noël, J., Táíwò, O. O., Talati, S., & Wilcox, J. (2020). Principles for Thinking about Carbon Dioxide Removal in Just Climate Policy. *One Earth*, *3*(2), 150–153. https://doi.org/10.1016/j.oneear.2020.07.015

Negri, V., Galán-Martín, Á., Pozo, C., Fajardy, M., Reiner, D. M., Mac Dowell, N., & Guillén-Gosálbez, G. (2021). Life cycle optimization of BECCS supply chains in the European Union. *Applied Energy*, *298*, 117252. https://doi.org/10.1016/j.apenergy.2021.117252

Negri, V., & Guillén-Gosálbez, G. (2022). Implications of Optimal BECCS Supply Chains on Absolute Sustainability. In Y. Yamashita & M. Kano (Eds.), *Computer Aided Chemical Engineering* (Vol. 49, pp. 619–624). Elsevier. https://doi.org/10.1016/B978-0-323-85159-6.50103-2

NRW.Energy4Climate. (2023). *Nachhaltiger Einsatz von Biomasse—Die Rolle von Biomasse in der Energiewende und in einer klimaneutralen Industrie* [Sustainable Use of Biomass-The Role of Biomass in the Energy Transition and in a Climate-Neutral Industry]. NRW.Energy4Climate

Düsseldorf. https://www.energy4climate.nrw/fileadmin/Industrie-Produktion/Der-nachhaltige-Einsatz-von-Biomasse-cr-nrwenergy4climate.pdf

O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability*, *1*(2), 88–95. https://doi.org/10.1038/s41893-018-0021-4

Palmer, J., & Carton, W. (2021). Carbon Removal as Carbon Revival? Bioenergy, Negative Emissions, and the Politics of Alternative Energy Futures. *Frontiers in Climate*, *3*. https://www.frontiersin.org/articles/10.3389/fclim.2021.678031

Pelenc, J., & Ballet, J. (2015). Strong sustainability, critical natural capital and the capability approach. *Ecological Economics*, *112*, 36–44. https://doi.org/10.1016/j.ecolecon.2015.02.006

Popp, A., Lotze-Campen, H., Leimbach, M., Knopf, B., Beringer, T., Bauer, N., & Bodirsky, B. (2011). On sustainability of bioenergy production: Integrating co-emissions from agricultural intensification. *Biomass and Bioenergy*, *35*(12), 4770–4780. https://doi.org/10.1016/j.biombioe.2010.06.014

Pour, N., Webley, P. A., & Cook, P. J. (2017). A Sustainability Framework for Bioenergy with Carbon Capture and Storage (BECCS) Technologies. *Energy Procedia*, *114*, 6044–6056. https://doi.org/10.1016/j.egypro.2017.03.1741

Raworth, K. (2017). A Doughnut for the Anthropocene: Humanity's compass in the 21st century. *The Lancet Planetary Health*, *1*(2), e48–e49. https://doi.org/10.1016/S2542-5196(17)30028-1

Raworth, K. (2020, April 8). *Introducing the Amsterdam City Doughnut | Kate Raworth*. https://www.kateraworth.com/2020/04/08/amsterdam-city-doughnut/

Raworth, K. (2022). *Doughnut economics: Seven ways to think like a 21st-century economist*. Penguin Books.

Rosa, L., Reimer, J. A., Went, M. S., & D'Odorico, P. (2020). Hydrological limits to carbon capture and storage. *Nature Sustainability*, *3*(8), 658–666. https://doi.org/10.1038/s41893-020-0532-7

Rosa, L., Sanchez, D. L., Realmonte, G., Baldocchi, D., & D'Odorico, P. (2021). The water footprint of carbon capture and storage technologies. Renewable and Sustainable Energy Reviews, 138, 110511. https://doi.org/10.1016/j.rser.2020.110511

Rubiano Rivadeneira, N., & Carton, W. (2022). (In)justice in modelled climate futures: A review of integrated assessment modelling critiques through a justice lens. *Energy Research & Social Science*, *92*, 102781. https://doi.org/10.1016/j.erss.2022.102781

Scheidel, A., & Sorman, A. H. (2012). Energy transitions and the global land rush: Ultimate drivers and persistent consequences. *Global Environmental Change*, *22*(3), 588–595. https://doi.org/10.1016/j.gloenvcha.2011.12.005

Shue, H. (2017). Climate dreaming: Negative emissions, risk transfer, and irreversibility. *Journal of Human Rights and the Environment*, *8*(2), 203–216. https://doi.org/10.4337/jhre.2017.02.02

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., Griscom, B., Hagemann, N., Kammann, C., Kraxner, F., Minx, J. C., Popp, A., Renforth, P., Vicente Vicente, J. L., & Keesstra, S. (2019). Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals. *Annual Review of Environment and Resources*, *44*(1), 255–286. https://doi.org/10.1146/annurev-environ-101718-033129

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., … Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, *6*(1), 42–50. https://doi.org/10.1038/nclimate2870

Smith, S. M., Geden, O., Nemet, G. F., Gidden, M. J., Lamb, W. F., Powis, C., Bellamy, R., Callaghan, M. W., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G. P., Pratama, Y., … Minx, J. C. (2023). *The State of Carbon Dioxide Removal—1st Edition*. The State of Carbon Dioxide Removal. https://doi.org/10.17605/OSF.IO/W3B4Z

Sovacool, B. K., Baum, C. M., & Low, S. (2022). Climate protection or privilege? A whole systems justice milieu of twenty negative emissions and solar geoengineering technologies. *Political Geography*, *97*, 102702. https://doi.org/10.1016/j.polgeo.2022.102702

Spangenberg, J. H. (2011). Sustainability science: A review, an analysis and some empirical lessons. *Environmental Conservation*, *38*(3), 275–287. https://doi.org/10.1017/S0376892911000270

Steel, D. (Ed.). (2014). The precaution controversy. In *Philosophy and the Precautionary Principle: Science, Evidence, and Environmental Policy* (pp. 1–16). Cambridge University Press. https://doi.org/10.1017/CBO9781139939652.002

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

Stenzel, F., Greve, P., Lucht, W., Tramberend, S., Wada, Y., & Gerten, D. (2021). Irrigation of biomass plantations may globally increase water stress more than climate change. *Nature Communications*, *12*(1), 1512. https://doi.org/10.1038/s41467-021-21640-3

Stoddard, I., Anderson, K., Capstick, S., Carton, W., Depledge, J., Facer, K., Gough, C., Hache, F., Hoolohan, C., Hultman, M., Hällström, N., Kartha, S., Klinsky, S., Kuchler, M., Lövbrand, E., Nasiritousi, N., Newell, P., Peters, G. P., Sokona, Y., … Williams, M. (2021). Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve? *Annual Review of Environment and Resources*, *46*(1), 653–689. https://doi.org/10.1146/annurev-environ-012220-011104

Stoy, P. C., Ahmed, S., Jarchow, M., Rashford, B., Swanson, D., Albeke, S., Bromley, G., Brookshire, E. N. J., Dixon, M. D., Haggerty, J., Miller, P., Peyton, B., Royem, A., Spangler, L., Straub, C., & Poulter, B. (2018). Opportunities and Trade-offs among BECCS and the Food, Water, Energy, Biodiversity, and Social Systems Nexus at Regional Scales. *BioScience*, *68*(2), 100–111. https://doi.org/10.1093/biosci/bix145

Table Media. (2023). *Modernisierungspaket für Klimaschutz und Planungsbeschleunigung* [Modernization package for climate action and planning acceleration]. Table Media Berlin. https://table.media/berlin/wp-content/uploads/sites/21/2023/03/Ergebnis-Koalitionsausschuss-28.-Maerz-2023.pdf

Tanneberger, F., Appulo, L., Ewert, S., Lakner, S., Ó Brolcháin, N., Peters, J., & Wichtmann, W. (2021). The Power of Nature-Based Solutions: How Peatlands Can Help Us to Achieve Key EU Sustainability Objectives. *Advanced Sustainable Systems*, *5*(1), 2000146. https://doi.org/10.1002/adsu.202000146

Tanzer, S. E., Blok, K., & Ramírez, A. (2020). Can bioenergy with carbon capture and storage result in carbon negative steel? *International Journal of Greenhouse Gas Control*, *100*, 103104. https://doi.org/10.1016/j.ijggc.2020.103104

Thrän, D., Bauschmann, M., Dahmen, N., Erlach, B., Heinbach, K., Hirschl, B., Hildebrand, J., Rau, I., Majer, S., Oehmichen, K., Schweizer-Ries, P., & Hennig, C. (2020). Bioenergy beyond the German "Energiewende"–Assessment framework for integrated bioenergy strategies. *Biomass and Bioenergy*, *142*, 105769. https://doi.org/10.1016/j.biombioe.2020.105769

Turner, R. A., & Wills, J. (2022). Downscaling doughnut economics for sustainability governance. *Current Opinion in Environmental Sustainability*, *56*, 101180. https://doi.org/10.1016/j.cosust.2022.101180

van Vuuren, D. P., Hof, A. F., van Sluisveld, M. A. E., & Riahi, K. (2017). Open discussion of negative emissions is urgently needed. *Nature Energy*, *2*(12), 902–904. https://doi.org/10.1038/s41560-017-0055-2

Vaughan, N. E., & Gough, C. (2016). Expert assessment concludes negative emissions scenarios may not deliver. *Environmental Research Letters*, *11*(9), 095003. https://doi.org/10.1088/1748-9326/11/9/095003

Wang-Erlandsson, L., Tobian, A., van der Ent, R. J., Fetzer, I., te Wierik, S., Porkka, M., Staal, A., Jaramillo, F., Dahlmann, H., Singh, C., Greve, P., Gerten, D., Keys, P. W., Gleeson, T., Cornell, S. E., Steffen, W., Bai, X., & Rockström, J. (2022). A planetary boundary for green water. *Nature Reviews Earth & Environment*, *3*(6), 380–392. https://doi.org/10.1038/s43017-022-00287-8

Wu, F., Muller, A., & Pfenninger, S. (2023). Strategic uses for ancillary bioenergy in a carbon-neutral and fossil-free 2050 European energy system. *Environmental Research Letters*, *18*(1), 014019. https://doi.org/10.1088/1748-9326/aca9e1

Yamagata, Y., Hanasaki, N., Ito, A., Kinoshita, T., Murakami, D., & Zhou, Q. (2018). Estimating water–food–ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6). *Sustainability Science*, *13*(2), 301–313. https://doi.org/10.1007/s11625-017-0522-5

Appendix A: Reference List for Tables 1-3

1 Clery, D. S., Vaughan, N. E., Forster, J., Lorenzoni, I., Gough, C. A., & Chilvers, J. (2021). Bringing greenhouse gas removal down to earth: Stakeholder supply chain appraisals reveal complex challenges. Global Environmental Change, 71, 102369. https://doi.org/10.1016/j.gloenvcha.2021.102369

2 Pour, N., Webley, P. A., & Cook, P. J. (2017). A Sustainability Framework for Bioenergy with Carbon Capture and Storage (BECCS) Technologies. Energy Procedia, 114, 6044–6056. https://doi.org/10.1016/j.egypro.2017.03.1741

3 Creutzig, F., Ravindranath, N. h., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Robledo-Abad, C., Rose, S., Smith, P., … Masera, O. (2015). Bioenergy and climate change mitigation: An assessment. GCB Bioenergy, 7(5), 916–944. https://doi.org/10.1111/gcbb.12205

4 Creutzig, F., Erb, K.-H., Haberl, H., Hof, C., Hunsberger, C., & Roe, S. (2021). Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments. GCB Bioenergy, 13(4), 510–515. https://doi.org/10.1111/gcbb.12798

5 Hansson, A., Fridahl, M., Haikola, S., Yanda, P., Pauline, N., & Mabhuye, E. (2020). Preconditions for bioenergy with carbon capture and storage (BECCS) in sub-Saharan Africa: The case of Tanzania. Environment, Development and Sustainability, 22(7), 6851–6875. https://doi.org/10.1007/s10668-019-00517-y

6 Krause, A., Thomas Knoke, & Anja Rammig. (2020). A regional assessment of land-based carbon mitigation potentials: Bioenergy, BECCS, reforestation, and forest management. GCB Bioenergy, 12(5), 346–360. https://doi.org/10.1111/gcbb.12675

7 Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., Griscom, B., Hagemann, N., Kammann, C., Kraxner, F., Minx, J. C., Popp, A., Renforth, P., Vicente Vicente, J. L., & Keesstra, S. (2019). Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals. Annual Review of Environment and Resources, 44(1), 255–286. https://doi.org/10.1146/annurev-environ-101718-033129

8 Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters, 13(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

9 Thrän, D., Bauschmann, M., Dahmen, N., Erlach, B., Heinbach, K., Hirschl, B., Hildebrand, J., Rau, I., Majer, S., Oehmichen, K., Schweizer-Ries, P., & Hennig, C. (2020). Bioenergy beyond the German "Energiewende"–Assessment framework for integrated bioenergy strategies. Biomass and Bioenergy, 142, 105769. https://doi.org/10.1016/j.biombioe.2020.105769

10 Honegger, M., Michaelowa, A., & Roy, J. (2021). Potential implications of carbon dioxide removal for the sustainable development goals. Climate Policy, 21(5), 678–698. https://doi.org/10.1080/14693062.2020.1843388

11 Yamagata, Y., Hanasaki, N., Ito, A., Kinoshita, T., Murakami, D., & Zhou, Q. (2018). Estimating water–food–ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6). Sustainability Science, 13(2), 301–313. https://doi.org/10.1007/s11625-017-0522-5

12 Stoy, P. C., Ahmed, S., Jarchow, M., Rashford, B., Swanson, D., Albeke, S., Bromley, G., Brookshire, E. N. J., Dixon, M. D., Haggerty, J., Miller, P., Peyton, B., Royem, A., Spangler, L., Straub, C., & Poulter, B. (2018). Opportunities and Trade-offs among BECCS and the Food, Water, Energy, Biodiversity, and Social Systems Nexus at Regional Scales. BioScience, 68(2), 100–111.

13 Donnison, C., Holland, R. A., Harris, Z. M., Eigenbrod, F., & Taylor, G. (2021). Land-use change from food to energy: Meta-analysis unravels effects of bioenergy on biodiversity and cultural ecosystem services. Environmental Research Letters, 16(11), 113005. https://doi.org/10.1088/1748-9326/ac22be

14 McElwee, P., Calvin, K., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Le Hoang, A., Lwasa, S., Nkem, J., Nkonya, E., Saigusa, N., Soussana, J.-F., Taboada, M. A., Manning, F., Nampanzira, D., & Smith, P. (2020). The impact of interventions in the global land and agri-food sectors on Nature's

Contributions to People and the UN Sustainable Development Goals. Global Change Biology, 26(9), 4691–4721. https://doi.org/10.1111/gcb.15219
15 Asibor, J. O., Clough, P. T., Nabavi, S. A., & Manovic, V. (2021). Assessment of optimal conditions for the performance of greenhouse gas removal methods. Journal of Environmental Management, 294, 113039. https://doi.org/10.1016/j.jenvman.2021.113039
16 Negri, V., & Guillén-Gosálbez, G. (2022). Implications of Optimal BECCS Supply Chains on Absolute Sustainability. In Computer Aided Chemical Engineering (Vol. 49, pp. 619–624). Elsevier. https://doi.org/10.1016/B978-0-323-85159-6.50103-2
17 Fajardy, M., Chiquier, S., & Mac Dowell, N. (2018). Investigating the BECCS resource nexus: Delivering sustainable negative emissions. Energy & Environmental Science, 11(12), 3408–3430. https://doi.org/10.1039/C8EE01676C
18 Hanssen, S. v., Steinmann, Z. j. n., Daioglou, V., Cˇengic´, M., Van vuuren, D. p., & Huijbregts, M. a. j. (2022). Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity. GCB Bioenergy, 14(3), 307–321. https://doi.org/10.1111/gcbb.12911
19 Calvin, K., Cowie, A., Berndes, G., 1966, Arneth, A., Cherubini, F., Portugal-Pereira, J., Grassi, G., House, J. I., Johnson, F. X., Popp, A., Rounsevell, M., Slade, R., & Smith, P. (2021). Bioenergy for climate change mitigation: Scale and sustainability. GCB Bioenergy, 13(9), 1346–1371. https://doi.org/10.1111/gcbb.12863
20 Doelman, J. C., Stehfest, E., Tabeau, A., van Meijl, H., Lassaletta, L., Gernaat, D. E. H. J., Hermans, K., Harmsen, M., Daioglou, V., Biemans, H., van der Sluis, S., & van Vuuren, D. P. (2018). Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. Global Environmental Change, 48, 119–135. https://doi.org/10.1016/j.gloenvcha.2017.11.014
21 Fajardy, M., & Mac Dowell, N. (2020). Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal. One Earth, 3(2), 214–225. https://doi.org/10.1016/j.oneear.2020.07.014
22 Wu, F., Muller, A., & Pfenninger, S. (2023). Strategic uses for ancillary bioenergy in a carbon-neutral and fossil-free 2050 European energy system. Environmental Research Letters, 18(1), 014019. https://doi.org/10.1088/1748-9326/aca9e1
23 Grant, N., Hawkes, A., Napp, T., & Gambhir, A. (2021). Cost reductions in renewables can substantially erode the value of carbon capture and storage in mitigation pathways. One Earth, 4(11), 1588–1601. https://doi.org/10.1016/j.oneear.2021.10.024
24 Butnar, I., Broad, O., Baltazar Solano Rodriguez, & Paul E. Dodds. (2020). The role of bioenergy for global deep decarbonization: CO2 removal or low-carbon energy? GCB Bioenergy, 12(3), 198–212. https://doi.org/10.1111/gcbb.12666
25 Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente Vicente, J. L., Wilcox, J., & del Mar Zamora Dominguez, M. (2018). Negative emissions—Part 1: Research landscape and synthesis. Environmental Research Letters, 13(6), 063001. https://doi.org/10.1088/1748-9326/aabf9b
26 Jeswani, H. K., Saharudin, D. M., & Azapagic, A. (2022). Environmental sustainability of negative emissions technologies: A review. Sustainable Production and Consumption, 33, 608–635. https://doi.org/10.1016/j.spc.2022.06.028
27 Lask, J., Slavica Rukavina, Ivana Zorić, Jason Kam, Andreas Kiesel, Iris Lewandowski, & Moritz Wagner. (2021). Lignocellulosic ethanol production combined with CCS—A study of GHG reductions and potential environmental trade-offs. GCB Bioenergy, 13(2), 336–347. https://doi.org/10.1111/gcbb.12781
28 Stenzel, F., Greve, P., Lucht, W., Tramberend, S., Wada, Y., & Gerten, D. (2021). Irrigation of biomass plantations may globally increase water stress more than climate change. Nature Communications, 12(1), 1512. https://doi.org/10.1038/s41467-021-21640-3
29 Heck, V., Gerten, D., Lucht, W., & Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. Nature Climate Change, 8(2),151-155. https://doi.org/10.1038/s41558-017-0064-y
30 Dooley, K., Christoff, P., & Nicholas, K. A. (2018). Co-producing climate policy and negative emissions: Trade-offs for sustainable land-use. Global Sustainability, 1. https://doi.org/10.1017/sus.2018.6
31 Melara, A. J., Singh, U., & Colosi, L. M. (2020). Is aquatic bioenergy with carbon capture and storage a sustainable negative emission technology? Insights from a spatially explicit environmental life-cycle

assessment. Energy Conversion and Management, 224, 113300. https://doi.org/10.1016/j.enconman.2020.113300
32 Singh, J., & Dhar, D. W. (2019). Overview of Carbon Capture Technology: Microalgal Biorefinery Concept and State-of-the-Art. Frontiers in Marine Science, 6. https://www.frontiersin.org/articles/10.3389/fmars.2019.00029
33 Krevor, S., de Coninck, H., Gasda, S. E., Ghaleigh, N. S., de Gooyert, V., Hajibeygi, H., Juanes, R., Neufeld, J., Roberts, J. J., & Swennenhuis, F. (2023). Subsurface carbon dioxide and hydrogen storage for a sustainable energy future. Nature Reviews Earth & Environment, 4(2), 102-118. https://doi.org/10.1038/s43017-022-00376-8
34 Furre, A.-K., Eiken, O., Alnes, H., Vevatne, J. N., & Kiær, A. F. (2017). 20 Years of Monitoring CO2-injection at Sleipner. Energy Procedia, 114, 3916–3926. https://doi.org/10.1016/j.egypro.2017.03.1523
35 Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., Fennell, P. S., Fuss, S., Galindo, A., Hackett, L. A., Hallett, J. P., Herzog, H. J., Jackson, G., Kemper, J., Krevor, S., Maitland, G. C., Matuszewski, M., Metcalfe, I. S., Petit, C., … Dowell, N. M. (2018). Carbon capture and storage (CCS): The way forward. Energy & Environmental Science, 11(5), 1062–1176. https://doi.org/10.1039/C7EE02342A
36 Dolan, K. A., Stoy, P. C., & Poulter, B. (2020). Land management and climate change determine second-generation bioenergy potential of the US Northern Great Plains. GCB Bioenergy, 12(7), 491–509. https://doi.org/10.1111/gcbb.12686
37 Rosa, L., Sanchez, D. L., Realmonte, G., Baldocchi, D., & D'Odorico, P. (2021). The water footprint of carbon capture and storage technologies. Renewable and Sustainable Energy Reviews, 138, 110511. https://doi.org/10.1016/j.rser.2020.110511
38 Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? Energy & Environmental Science, 10(6), 1389–1426. https://doi.org/10.1039/C7EE00465F
39 Almena, A., Thornley, P., Chong, K., & Röder, M. (2022). Carbon dioxide removal potential from decentralised bioenergy with carbon capture and storage (BECCS) and the relevance of operational choices. Biomass and Bioenergy, 159, 106406. https://doi.org/10.1016/j.biombioe.2022.106406
40 Popp, A., Lotze-Campen, H., Leimbach, M., Knopf, B., Beringer, T., Bauer, N., & Bodirsky, B. (2011). On sustainability of bioenergy production: Integrating co-emissions from agricultural intensification. Biomass and Bioenergy, 35(12), 4770–4780. https://doi.org/10.1016/j.biombioe.2010.06.014
41 Moriarty, P., & Honnery, D. (2017). Review: Assessing the climate mitigation potential of biomass. AIMS Energy, 5(1), 20–38. https://doi.org/10.3934/energy.2017.1.20
42 Tanzer, S. E., Blok, K., & Ramírez, A. (2020). Can bioenergy with carbon capture and storage result in carbon negative steel? International Journal of Greenhouse Gas Control, 100, 103104. https://doi.org/10.1016/j.ijggc.2020.103104
43 Cumicheo, C., Mac Dowell, N., & Shah, N. (2019). Natural gas and BECCS: A comparative analysis of alternative configurations for negative emissions power generation. International Journal of Greenhouse Gas Control, 90, 102798. https://doi.org/10.1016/j.ijggc.2019.102798

Appendix B: Systematic Review Protocol

Title (at that time): Can we rely on BECCS? A systematic review on sustainability criteria and trade-offs around Bioenergy with Carbon Capture and Storage (BECCS) [in Germany]

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Abstract (at that time)

The IPCC (AR6) denominates negative emissions as requirement for stabilizing temperatures below 2°C global warming and the related SSP.1 scenarios heavily rely on them for the second half of the 21st century (see Figure SPM.4). These scenarios explicitly involve technologies for directly removing CO_2 from the atmosphere and therefore point to Bio-Energy Carbon Capture and Storage (BECCS) to a varying extent. However, there is a growing body of criticism that considers relying on BECCS a risky strategy because of several social and ecological sustainability problems and trade-offs (such as impacts on planetary boundaries like biodiversity, freshwater, biogeochemical cycled and land use, but also social issues like health or food security).

This systematic review aims at analysing and summarizing the whole picture of sustainability dimensions that are used to assess impacts, risks and potentials of BECCS as well as the described trade-offs between different sustainability dimensions.

The search strategy includes a comprehensive screening of peer reviewed articles on Scopus with a rather generic search string. The review's results will be brought together in a conceptual framework, guided by the framework of a safe and just space for humanity. The collected criteria and the related trade-offs will be synthesised as a narrative synthesis. The review will provide the basis for developing a sustainability assessment toolkit for NGOs, industry and government officials aiming at providing a comprehensive set of sustainability dimensions for assessing potential risks of implementing BECCS regionally.

Background (Theory of change)

The results should contribute to closing the gap between global and general assessments on the one hand and local decision-making on the other hand by developing a framework for a safe and just operating space for implementing BECCS. This operating space is constrained by ecological/biophysical limits of the earth system as well as by social thresholds that guarantee basic capabilities for everyone. The globally reviewed criteria and trade-offs will be used to develop this conceptual model of a safe and just operating space for BECCS, applied to the context of Germany.

This conceptual model will guide the analysis by acknowledging the planetary boundaries and social minimum standards of wellbeing. With the question of sustainable bioenergy (and respectively CCS), many of the sustainability criteria are depending on local geographic circumstances. The question of risks and potentials of implementing BECCS can therefore not be generalized. Assessing risks and potentials in practice needs guidance based on scientific evidence. Whilst there is a growing body of sustainability assessments of BECCS, there is a lack of systematizing and summarizing the results of those assessments in a way that produces orientation knowledge. This systematic review should help NGOs, governments and industry to make informed decisions on BECCS implementation that reduce social and environmental risks and that keeps BECCS application within a scale that can be reconciled with the planetary boundaries. Its results will therefore be presented in a synthesized way as a sustainability assessment kit.

Stakeholder Engagement

The need for systematically reviewing BECCS literature regarding sustainability criteria has been formulated first by a project where several NGOs (Germanwatch, E3G, Bellona) collaborate aiming at ranking prioritizing different CCS applications in EU industries from a sustainability point of view. The result has not been published yet. Within this process it became difficult to assess BECCS, because it opens up many more sustainability dimensions than CCS alone. This is where the need for further research was formulated and also why the objective is to develop a framework with orientation knowledge as a result. Further exchange in formulating the research question has been done with peer students and with several researchers from LUCSUS, including my thesis supervisor.

Stakeholder Involvement is planned throughout the research process. I will conduct expert interviews along the different research stages to complement the literature and possible related bias. And preliminary results will be shared with stakeholders, especially within the mentioned NGOs, the cluster "industrial transformation" at Germanwatch with its network alliance. Additionally, a workshop with the preliminary results will generate feedback on the usefulness and comprehensibility of the suggested dimensions and criteria for assessing the sustainability of BECCS.

Objectives

RQ1: Which dimensions have been assessed to evaluate the sustainability of BECCS?

> The objective is to make sure that a sustainability assessment includes all relevant dimensions.

RQ2: Which trade-offs potentially result from BECCS implementation and how can they be navigated?

> The objective is to make sure that a sustainability assessment is able to recognize and weigh potential trade-offs which should also facilitate the democratic debate about the contested question if and how to implement BECCS and which sustainability dimensions should be prioritized.

Search strategy

The initial set of articles will be retrieved from the Scopus database. The search string (see below) accounts for important synonyms to reduce a possible selection bias and will be applied to title, abstract and keywords for articles. Additionally, I will also search for grey literature via google and recommendations from the expert interviews and forward/backward citation screening to identify seminal papers.

As this review is part of my Master thesis, it is supposed to be individual work so that there is clearly a risk for bias. This is why I will conduct expert interviews for complementary perspectives. Additionally, a workshop with the preliminary results will be held with the goal of bringing in different perspectives and critiques.

Search string

TITLE-ABS-KEY ((((bioenergy OR biomass) AND "negative emissions") OR (beccs OR (bioenergy AND (ccs OR "carbon capture and storage")))) AND (trade-off* OR (sustainab* AND(criteria OR eval* OR assess*))))

Languages

English (mainly), German

Bibliographic databases: Scopus (Database request on the 03.02.2023)

Web-based search engines: Google

Organisational websites: NGOs, German ministries, EU organizations, Think tanks for the energy sector.

Comprehensiveness

The search string uses very general terms including synonyms, so that there is a high probability that the initial scope of papers being screened is quite comprehensive. The resulting paper list was trialed by benchmarking (known papers of relevance were found within the list). Additionally, forward and backward tracking of citations will be conducted where sources mention other papers for giving important data for answering the research questions. The review process will be complemented by expert interviews and they will be asked if they can recommend important publications. This might be especially relevant for assembling grey literature and reducing the publication bias.

Screening strategy

In a first step, titles and abstracts will be screened. Decisions to include/exclude articles will be made according to the criteria mentioned below. The screening will be done on the basis of a complete excel list, retrieved directly from Scopus. This spreadsheet will document the reason for inclusion/exclusion and categorize the included papers accordingly. Consequently, the replicability of the results and transparency about the decisions is guaranteed.

Consistency checking

As the review will be conducted as MA-thesis, there are no resources for screening with more than one person. This weakens the objectivity of the analysis. As a consequence, expert interviews and stakeholder involvement are included as complementing methods to provide guidance, double-check the results and detect blind spots.

Inclusion criteria

- Sustainability criteria assessed:
    - Social criteria
    - Ecological criteria
- Trade-offs related to BECCS or between different sustainability criteria

Reasons for exclusion

- Assessments without ecological/social focus (= sustainability focus)
- Techn.: Purely technical paper (i.e. engineering)
- Context outside Europe (esp. if climate zone is very different)
- Language: Not English or German
- NR = Not related, very different focus on other topics
- Quality (critical appraisal for grey literature)
- No access

I will provide a list of articles excluded at full text with reasons for exclusion.

Critical appraisal strategy

Generally, all peer-reviewed papers will be considered as already being critically examined by experts of the field. Thus, for those articles retrieved from Scopus, scientific rigour can be expected. When retrieving the article from the journal, I will check if there has been any reply or correction to account for already given criticism. Otherwise my critical appraisal will focus on grey literature (not peer reviewed). Appraisal criteria will mostly relate to transparency and replicability in a first step and if they are replicable, critically examine the accuracy of the methods.

As the review will be conducted as MA-thesis, there are no resources for consistency checking of the critical appraisal with more than one person. This weakens the objectivity of the analysis. In case of doubts when doing the appraisal, the thesis supervisor will be contacted.

Narrative synthesis strategy

First of all, vote counting will be avoided. The evidence base as a whole will be critically examined and the results will be reported, especially where heterogeneous results are found or where less than three sources are mentioning a certain criteria/dimension. Citations will be transparent about the source of information. Where helpful, especially with more complex results (e.g. regional differences) or a range of different data, tables will provide the results.

The narrative synthesis will be structured following the recommendations of Popay et al. (2006).

A conceptual model and a criteria list, clustered according to the conceptual model, will be provided.

Publication bias

Grey literature will be included to reduce publication bias. The research process includes the following strategies: Searching via Google with similar keywords and searching for online publications of important actors and organizations that are mentioned in literature and stakeholder/expert interviews.

Knowledge gap identification strategy

Expert interviews and Stakeholder engagement, as described above.

Procedural independence

The author has no publications that have to be examined in the review.

Competing interests

The author has no competing interests.

Appendix C: Semi-Structured Interview Guide

Introduction (5 Minutes)

- Thank you very much for taking the time for this interview
    - Introduce myself quickly
    - Research aim: Assessing sustainability of BECCS and make the state of the knowledge accessible for civil society

Important formal issues first:

All information is confidential and will only be used for the purpose of this research project. I will record and transcribe this interview. Do you agree with the recording? Then I would start the recording now.

Thank you for your permission to record. Can you please confirm again on this recording your permission? Thank you. Before we start with the questions, I would like to point out that the interview is entirely voluntary, and you can discontinue it at any moment.

Do you consent, that I can use your answers for my project?

Do you want to stay anonymous?

Lastly, if you want me to explain a question further, please do let me know.

Do you have any questions before we start?

[questions/comments marked in grey are optional – to be asked if there is time left]

Part I: Sustainability criteria (RQ1) (15 Minutes)

➔ General context: All questions to be thought within the European context

a) **Personal relationship to the topic:** In which ways do you have to deal with Bioenergy with Carbon Capture and Storage (CCS) currently in your professional life?
b) **Personal opinion:** What do you personally think:
    a. What is your attitude towards BECCS?
c) **Project perspective:** Imagine there is a BECCS plant to be built. What would you look at first to inform yourself about if this is a sustainable plan that deserves support?
d) **General perspective:** Are there more criteria you consider relevant when assessing the sustainability of BECCS?
    a. Take time here, ask back and forth, ask to explain further.
    b. [Ranking: Which are most important?]
e) [Scale: How feasible is implementing BECCS at a large scale (within Europe)?
    a. If limits of scale are mentioned: How would you assess a sustainable scale of BECCS implementation within biophysical / social boundaries?
f) Risks: Which risks do you see when implementing BECCS [at a large scale]?]

Part II: Trade-offs (RQ2) (15 Minutes)

a) **<u>Trade-offs:</u>** Which trade-offs might exist between the different sustainability criteria/dimensions?
   [explanation: this means that maximizing one dimension results in worsening impacts in another dimension, if examples needed: carbon removal at the expense of biodiversity, land use change, water use, but also either maximising carbon removal OR energy production, crops for food or energy, …]
   - Are there more trade-offs you know about? Which ones?

b) **<u>Weighting/Ranking:</u>**
   - What are sustainable ways in dealing with these trade-offs?
   - When thinking about the trade-offs you mentioned already: Would you give certain sustainability dimensions a higher importance than others?
     - If yes: Which ones? How do you justify this higher priority?
     - If no: Do you think it is not necessary to prioritize? Is it possible to balance out the trade-offs? How?
     - [Ask more weighing questions regarding specific trade-offs from the literature:
       1. Biodiversity vs. Crops for carbon removal / Energy production
       2. Regional biomass source vs. Water use / land use change minimisation
       3. Food vs. Energy/carbon removal
       4. Energy production vs. Maximum negative emissions
       5. Add according review]

Part III: Decision making (15 Minutes)

a) [Regulation perspective: Imagine a national strategy (for example GER) aiming at regulating and/or supporting BECCS. How should this regulation look like in order to implement BECCS in a sustainable way?]
b) My goal is to develop a tool for NGOs, industry, policy makers that helps overlooking quickly all relevant sustainability dimensions and encourages the discussion about priorities for BECCS implementation. Do you have ideas how this could look like?
   a. What would this tool need to be useful for your work?

Part IV: Final comments

a) Is there anything else you want to mention?
b) Do you have any additional recommendation where I should have a look at (literature, organisations, etc.) o who I should talk to?
c) Any questions for me?

Thank you very much! I’m happy to share my results with you at the end of the process.