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Deployment of biochar systems in rural areas as a negative emissions technology –
A qualitative analysis of socio-technical drivers and barriers in Germany

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List of abbreviations

BECCS ... *Bioenergy carbon capture and storage*
CDR ... *Carbon dioxide removal*
DAC ... *Direct air capture*
DBFZ ... *Deutsches Biomasse Forschungszentrum*
EBC ... European Biochar Certificate
EBI ... *European Biochar Industry Consortium*
FVPK ... *Fachverband Pflanzenkohle*
GHG ... *Greenhouse gas*
IAMs ... *Integrated Assessment Models*
IÖW ... *Institute for Ecological Economy Research*
IPCC ... *Intergovernmental Panel on Climate Change*
MLP ... *Multi-Level Perspective*
NETs ... *Negative emissions technologies*
PAH ... *Polycyclic aromatic hydrocarbon*
PyCCS ... *Pyrogenic carbon capture and storage*
STS ... *Socio-technial system*

Abstract

Despite the urgent need to reduce greenhouse gas (GHG) emissions, the implementation of negative emissions technologies (NETs) lags behind. Biochar, which is a carbonaceous product of the thermochemical conversion of biomass, can be applied to agricultural soils. By this it provides a solution for carbon dioxide removal (CDR). This thesis aimed to shed light on socio-technical drivers and barriers for regional biochar value chains in Germany.

For this purpose, a qualitative research approach was conducted to firstly identify potential biochar value chain and actor configurations. Secondly, drivers and barriers that affect biochar implementation were investigated by a qualitative content analysis. According to a triangulation approach, data from a focus group was supplemented by the conduct of 13 semi-structured expert interviews. By doing this, it was aimed at gaining a holistic picture of biochar systems and their implementation also considering non-technical factors that affect technology deployment.

The analysis revealed that biochar value chain configurations range from small scale systems, in which only one actor carries out the value chain steps, to larger scale systems, in which various actor groups perform the different steps. Moreover, the findings identified different actor groups as agents for biochar value chains, with different potentials and needs. This thesis revealed that despite the level of technological maturity, institutional barriers, such as a lack of enabling policies, insufficient financial incentives and the bureaucratic effort for approval, compliance, funding and certification impede biochar technology adoption. Moreover, the findings shed light to the currently insufficient communication and stakeholder cooperation. Biochar as a NET still lacks awareness, which is accompanied by misperceptions, problematic legitimacy and insufficient perceived relevance. The identified drivers and barriers were then discussed and interpreted to develop recommendations for action for policymakers that aim at facilitating biochar deployment.

This thesis addressed the research gap on the implementation process of negative emission technologies with a specific focus on biochar. Moreover, it contributes to biochar research by investigating non-technical factors. A specific focus has been placed to the actors that constitute the social system. Regarding the latter, this thesis adds to biochar research by incorporating the stakeholders’ perspective and thus addressing the gap between research and practice.

1 Introduction

Climate change requires a radical reduction of greenhouse gas emissions, which can only be achieved through joint global efforts. This is represented by the Paris Agreement, which provides a framework to collectively restrict global warming to within 2°C above pre-industrial levels (or even to 1,5°C) (Rogelj et al., 2016; Sanderson et al., 2016; UNFCCC, 2015). Besides the increased effort to combat climate change, national climate protection contributions are insufficient to meet these long-term temperature goals (Rogelj et al., 2016; United Nations Environment Programme, 2022).
In line with the need to cut emissions to achieve the climate targets, the role of NETs is gaining increased awareness (Forster et al., 2020; Minx et al., 2018; Thoni et al., 2020; Werner et al., 2018). NETs are solutions to capture CO_2 emissions from the atmosphere and range from bioenergy carbon capture and storage (BECCS) or direct air capture (DAC) to nature-based options, such as afforestation and reforestation. All of them vary regarding to their tech-readiness, permanence, costs, carbon sequestration potential and side effects (Minx et al., 2018). The 6^{th} assessment report of the Intergovernmental Panel on Climate Change (IPCC) highlighted the need for NETs to address the decreasing carbon budget (IPCC, 2022a). This is further reflected in the incorporation of NETs in the IPCC's mitigation pathways and the associated Integrated Assessment Models (IAMs) (Minx et al., 2018; Štrubelj, 2022; Van Beek et al., 2020).

Regarding the need for radical emission reductions, not only the potential of technologies and low carbon innovations is increasingly being discussed, but also the role of broader transitions. Such transitions specifically consider the processes of change to shift the current economy to a low-carbon system and particularly emphasize the dependence on changes throughout all involved components, such as actors, business models, institutions and infrastructure (F. W. Geels et al., 2016, 2017; Markard et al., 2016; Ou et al., 2021). Hereby, several studies indicate the relevance of social, cultural and institutional aspects that shape the implementation of new technologies to combat climate change and accompany systemic change (Fallde & Eklund, 2015; Morgunova, 2021; Ramirez, 2021).

1.1 Problem statement and research questions

Besides the growing number of publications on NETs, the literature so far mainly focuses on aggregated global potentials, neglecting regional differences (Buck, 2016; Fajardy et al., 2019). Moreover, most studies focus on the techno-economic potential and therefore disregard the social dynamics which not only co-evolve with the development of NETs but simultaneously guide their deployment (Buck, 2016; Forster et al., 2020; Markusson et al., 2012; Minx et al., 2018; Nemet et al., 2018). Minx et al. (2018) report a gap between the assumed level of deployment in the IAMs and the current development and potential for adoption. Hence, with the urgency of tackling climate change, the implementation of NETs must be further investigated. As pointed out by Buck (2016), "By integrating empirical research on public and producer perceptions, barriers to adoption, conditions driving new technologies, and social impacts, projections about negative emissions technologies can become more realistic and more useful to climate change policymaking" (p.155).

Biochar constitutes one of the NETs and belongs to pyrogenic carbon capture and storage (PyCCS) (Papageorgiou et al., 2022; H.-P. Schmidt et al., 2019; Woolf et al., 2021). Hereby, the pyrolysis of biomass produces biochar, a carbonaceous solid product, which can then be applied to agricultural soils and hence contributes to carbon sequestration (EBC, 2022; H.-P. Schmidt et al., 2019). Only recently has biochar gained more attention as a viable option for CDR (Woolf et al., 2021). In 2018, the IPCC Special Report acknowledged biochar as a viable NET for the first time (IPCC, 2022b). In comparison to other NETs, biochar "can be a strategic option to be developed in the near-term before other technologies emerge" and holds several advantages, such as technological maturity and co-benefits for soil and environment (Tisserant et al., 2022; Werner et al., 2018).
Nevertheless, research about adoption and implementation of biochar technology remains scarce (Minx et al., 2018). Besides the increased number of publications on biochar, most studies solely focus on techno-economic or biophysical aspects of biochar as NET (Ayaz et al., 2021; Buss et al., 2022; Hersh et al., 2019; Nematian et al., 2021; Tisserant et al., 2022; You et al., 2022). Moreover, do only a few studies consider the regional deployment of biochar systems (Bruckman & Bruckman, 2016; Otte & Vik, 2017; Zabaniotou et al., 2015) as well as the socio-cultural factors that affect their implementation (Gwenzi et al., 2015; A. Latawiec et al., 2017; Otte & Vik, 2017; Thengane et al., 2021). Furthermore, the perspective of different stakeholder groups is largely neglected, besides a few studies which incorporate the farmer's perspectives (A. Latawiec et al., 2017; Niemmanee et al., 2019).

However, literature indicates the relevance of actors and associated socio-cultural and institutional factors affecting biochar implementation. For example, Otte and Vik (2017) show that lacking knowledge on biochar technology as well as the level of diversification of the agricultural system affect biochar implementation. Moreover, the lack of an enabling legislative framework as well as insufficient openness for new practices pose barriers to biochar adoption in Sub-Saharan Africa (Gwenzi et al., 2015). This indicates that biochar implementation is not shaped by technical issues alone, but also by the actors and associated social components.

Considering the increased importance of NETs, and yet the little scientific attention to its implementation especially of affecting social rather than technocentric aspects, this thesis aims at investigating the implementation of biochar as a NET. It strives at contributing to the existing research by holistically analysing actors, institutions and socio-cultural aspects that affect the deployment of biochar technology. Moreover, this study adds to existing literature by incorporating the stakeholder's perspective and hence drawing on findings from practice. To meet these objectives, the following research questions have been developed:

RQ1: What are potential regional biochar value chains and what is the associated network of actors?

RQ2: What are the socio-technical drivers and barriers for regional biochar value chains in Germany?

1.2 Research approach and design

In order to investigate the stated research objectives, qualitative research is conducted. The research approach strives at contributing to the scarce studies on NET implementation, with a specific focus on the integration of stakeholders' perceptions to uncover socio-technical aspects that guide biochar development. The first research question aims at generating knowledge on biochar systems and the involved actors and by this poses a foundation for the investigation of biochar implementation from the actor's perspective. Based on these insights, this thesis applies a socio-technical system (STS) perspective to biochar systems to shed light on the technical and especially non-technical factors that shape technology development. According to a triangulation approach the following three data sources will be used to answer the research questions: literature, focus group and semi-structured expert interviews. The expert interviews constitute the main part of this research approach. The incorporation of the stakeholders' perspectives through the conduction of expert interviews contributes to biochar research by uncovering insights from practice. Based on this, socio-technical drivers and barriers will be empirically identified to then develop recommendations for the relevant actor groups to foster biochar implementation.

This thesis is written within the *Landgewinn*[1]-research project, conducted by the Institute for Ecological Economy Research (IÖW). The project aims at analysing decarbonization strategies in the agricultural sector. One of the strategies investigated is biochar. The project focuses on biochar production and its application to agricultural soils with the two-fold goals of carbon sequestration and soil benefits (*IÖW: Landgewinn – Energiesystemanalyse von Dekarbonisierungsstrategien Der Landwirtschaft*, n.d.).

This thesis is structured as follows. The next chapter outlines the theoretical foundations of this research. Within this chapter, an insight into the drivers and barriers identified in current literature is provided as a foundation for this study (see Chapter 2). Chapter 3 presents the methodological approach and provides an in-depth explanation of the empirical approach. The data collection, with specific focus on the semi-structured expert interviews, as well as the qualitative content analysis are described. This is followed by the presentation of the findings on the value chain and actor configurations (see Section 4.1), and on the identified drivers and barriers (see Section 4.2). The findings are then discussed and interpreted in Chapter 5. Within the discussion, the results are related to each other and interpreted in terms of the literature. Based on this, recommendations for action are developed. Finally, Chapter 6 provides a synthesis of the conducted research and presents an outlook for future research.

2 Theoretical Background

This chapter provides a starting point for the empirical part of this thesis by reviewing the literature. First, a general insight into the topic of biochar is given and a common terminology is defined, representing the focus of the thesis. Then, the state of knowledge on biochar value chains is presented. In a next step, socio-technical drivers and barriers identified within the literature search are presented.

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[1] Further information on the project can be obtained via the project website https://fyi-landgewinn.de.

2.1 Biochar

Biochar is a solid material obtained by thermochemically or hydrothermally converting renewable feedstock (Azzi et al., 2021b; Haubold-Rosar et al., 2016; Woolf et al., 2010). Restrictions of the term biochar are often made to include only certain raw materials, manufacturing processes or end uses. Mostly, the definition of biochar is limited to the conversion of raw material via pyrolysis. Pyrolysis is the thermochemical conversion of raw material in a zero or low-oxygen environment (Ayaz et al., 2021; Boateng et al., 2015; Kalus et al., 2019; Lehmann & Joseph, 2015; Oni et al., 2019). This definition excludes coals from hydrothermal conversion (Kalus et al., 2019; Otte & Vik, 2017; H.-P. Schmidt et al., 2021). The term pyrolysis sometimes refers to the specific process of pyrolysis, and sometimes covers a wider range of processes that include pyrolysis as a sub-step, such as gasification and torrefaction (Kalus et al., 2019; H.-P. Schmidt et al., 2021). This thesis follows the definition of the European Biochar Certificate (EBC) according to which the conversion takes place through “biomass pyrolysis, a process whereby organic substances are broken down at temperatures ranging from 350°C to 1000 °C in a low-oxygen process” (EBC, 2022, p. 10). The EBC understands gasification “as part of the pyrolysis technology spectrum” and allows this conversion technology “if optimized for biochar production” (EBC, 2022, p. 10).
In earlier stages, the focus was solely on soil application (Lehmann et al., 2006; Teichmann, 2014). More recently, applications of biochar in other sectors, such as the construction industry, have been considered (Bartoli et al., 2020; H. Schmidt et al., 2021; H.-P. Schmidt et al., 2019). This is also represented by the EBC guidelines (EBC, 2022). However, this thesis follows the more traditional perspective, with the intended end-use in the soil as the focus is on the agricultural sector (Haubold-Rosar et al., 2016; Laghari et al., 2016).

Biochar as an NET

Through the thermochemical decomposition of biomass the inherent, photosynthetically fixed carbon is transformed into solid (biochar), liquid (bio-oil), and gaseous (syngas) outputs (Qambrani et al., 2017; H.-P. Schmidt et al., 2019). When biochar, a recalcitrant form of carbon, is applied to soils the biological and chemical degradation of the transformed biomass is severely hampered. In other words, by applying biochar to soils the carbon is withdrawn from the short-term carbon cycle and stored considerably longer compared to the decay of the untreated biomass (Lehmann et al., 2021; Mašek, 2016; Woolf et al., 2021; Xie et al., 2022). The carbon content varies from 30% to 95% depending on the feedstock and conversion process as well the conversion parameter such as temperature, heating rate and residence time (Cha et al., 2016; EBC, 2022; H.-P. Schmidt et al., 2021). Woolf et al. (2021) report an even higher variation in produced carbon content of biochar based on feedstock and technology choice ranging from 7 to 79%. Based on the global mean temperature of 14,9° Celsius, the stable fraction of the carbon is calculated to be between 63% and 82% of the carbon content (Woolf et al., 2021). Hence, carbon is stored in the soil in the long-term and contributes to terrestrial carbon stocks (Lehmann et al., 2021; Papageorgiou et al., 2022; Qambrani et al., 2017; Xie et al., 2022). Biochar’s capability of sequestering carbon depends not only on the stable carbon content but on the biochar yield (Xie et al., 2022). Despite the potential

negative effect on GHG emissions, overall there is consensus that biochar has a substantial potential to reduce GHG emissions and hence contributes to climate change mitigation (Enaime & Lübken, 2021; Werner et al., 2018).
Therefore, biochar as an NET comprises not only biochar production or the operation of pyrolysis plants but the whole practice of producing biochar and its end-application to agricultural soils. Both processes together constitute the NET. This reflects Buck's (2016) suggestion to not just consider the deployment of technology for CDR but rather to regard the associated practices, such as carbon management. This perspective highlights the idea that the way of deployment and implementation matters and that these technologies cannot be separated from their social implications.

Currently no state-regulated trade of biochar CO_2 certificates exists. However, Haubold-Rosar et al. (2016) theoretically describe different options to incorporate biochar into the official carbon certificate trading. The EBC provides a guideline for the quantification and certification of the biochar carbon sinks (EBC, 2020). The possibility to trade this value currently only exists in the voluntary markets (Haubold-Rosar et al., 2016).

Biochar domains and co-benefits

Besides the aforementioned carbon sequestration potential, biochar can positively affect soil properties, such as the water holding capacity, soil pH and porosity (Joseph, 2012; Song et al., 2022). Further, by affecting soil properties, biochar can potentially increase crop productivity (Jeffery et al., 2017; Schmidt, et al., 2021). Soil improvements as a co-benefit of biochar application have received much attention in biochar research (Enaime & Lübken, 2021; Kalus et al., 2019, 2019; Qambrani et al., 2017). Different meta-studies suggest that biochar in general, positively affects crop productivity (Jeffery et al., 2017; Schmidt et al., 2021). A meta-study by Schmidt et. al (2021) shows an overall positive effect on biomass yields but also outlines that this depends on the specific biochar or biochar-additive and the regional soil properties. The potential for soil benefits is highest in the tropics and subtropics, often related to degraded or infertile soils with high acidity (Joseph et al., 2021; Schmidt et al., 2021; Song et al., 2022). Whereas in temperate regions, soils tend to be closer to their maximum potential and the potential for enhancement with biochar is more uncertain (Atkinson et al., 2010; Blanco-Canqui, 2021; Jeffery et al., 2017; Schmidt et al., 2021). However, research indicates that biochar application to temperate soils leads to soil benefits and productivity increases, depending on biochar properties and soil conditions (Blanco-Canqui, 2021; Karer et al., 2013; Lévesque et al., 2022). In addition, Lévesque et al. (2022) point out the need to investigate biochar's potential for temperate regions considering increased climate challenges.
Moreover, biochar can also be applied to manure management and animal feed. By this, biochar benefits resource efficiency and animal health (Akdeniz, 2019; Man et al., 2021). By recycling and upgrading biomass to a valuable bio-product, biochar supports the circular bioeconomy (Abbas et al., 2021; Bugge et al., 2019; Liu et al., 2021; Oni et al., 2019; Papageorgiou et al., 2022). Regional material cycles can be closed by the production and application of biochar and thus resource efficiency can be increased (Ayaz et al., 2021; Haubold-Rosar et al., 2016; Papageorgiou et al., 2022). By adding value to waste materials, biochar contributes to waste management (Lehmann & Joseph,

2015; Liu et al., 2021). Further, biochar can be used for energy production as biochar can substitute fossil fuels (Kant Bhatia et al., 2021; Lehmann & Joseph, 2015).
To conclude, biochar contributes to domains other than climate change mitigation. Therefore, biochar systems entail different “entry points” (Lehmann & Joseph, 2015, p. 7). By touching on these various domains, biochar comprises trade-offs and entails synergies (Jeffery et al., 2015b; Kalus et al., 2019; Lehmann & Joseph, 2015; P. Smith et al., 2019a; Song et al., 2022). The focus of this thesis is primarily, in line with the objectives of the *Landgewinn*-project, on the application for carbon storage and soil improvement (FIY Landgewinn, 2022; *IÖW: Landgewinn – Energiesystemanalyse von Dekarbonisierungsstrategien Der Landwirtschaft*, n.d.).

2.2 Value chain

In the following, the biochar value chain will be described to gain a deeper understanding of the involved steps. The value chain can broadly be divided into biomass provision, conversion and application (see Figure 1) (Haubold-Rosar et al., 2016; Sohi et al., 2015; Zanli et al., 2022). The biomass provision entails the acquisition of biochar feedstocks and its pre-treatment. This phase is then followed by the biomass conversion using a particular technology. Finally, there is the utilization phase, which comprises the application of the biochar and consists of several utilization cycles with material and energy recovery (Anderson et al., 2017; Azzi et al., 2021b; Haubold-Rosar et al., 2016; Sohi et al., 2015; Thengane et al., 2021; Zilberman et al., 2022). Additionally, there are processes such as packaging, storage and transportation in between these steps (Anderson et al., 2017; Zanli et al., 2022). A more detailed description of the steps is provided in the following.

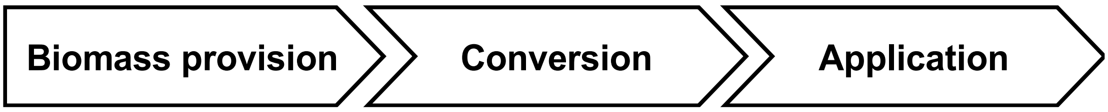

Figure 1: Biomass value chain (own figure based on (Anderson et al., 2017; Azzi et al., 2021b; Thengane et al., 2021; Zanli et al., 2022; Zilberman et al., 2022))

Biomass provision

The biomass provision stage includes the biomass collection, storage and transport to the production site (Anderson et al., 2017; Haubold-Rosar et al., 2016; Thengane et al., 2021). A wide variety of potential feedstock can be used for the production of biochar (Gabhane et al., 2020; Oni et al., 2019; Teichmann, 2014; Yaashikaa et al., 2020). The EBC provides a positive list of permissible biomasses. For example, agricultural and forestry biomass, organic residues from food processing, residues from landscape management and other organic wastes are listed (EBC, 2022). Agricultural biomasses comprise residual and waste materials and primarily produced biomass for biochar production (Azzi et al., 2021b). This thesis does not consider the latter as the use of residues is beneficial for different reasons (Anderson et al., 2017; Downie et al., 2012; Garcia et al., 2022; Maroušek et al., 2019). First, biomass from primary production entails usage competition (Azzi et al., 2021b; Meyer et al., 2017; P. Smith et al., 2019a). Nevertheless, the limited availability of residual biomass can lead to competing uses, which could intensify due to the planned expansion of energy production from residues

(Azzi et al., 2021b; Haubold-Rosar et al., 2016; Shackley et al., 2011). However, focusing on residual and waste materials for biomass provision contributes to sustainability through the valorisation of waste streams (P. Smith et al., 2019a). Next, the economic viability is an argument to focus on residues from agriculture and forestry without further usage options (H.-P. Schmidt et al., 2021; Shackley et al., 2011; Zilberman et al., 2022).
The acquisition of biomass is followed by pre-treatment processes such as drying, crushing or sieving (Anderson et al., 2017; Chun et al., 2021; Sohi et al., 2015; Thengane et al., 2021; Zilberman et al., 2022). The need for these processes depends on the feedstock quality and on technological specifications regarding, for example, the moisture content. With these processes, the suitability of feedstocks for pyrolysis is improved (Anderson et al., 2017).
The choice of biomass and associated feedstock suitability significantly shapes biochar properties and quality (Kamali et al., 2022). For example, with the focus on the end-application into soils, „the biomass must not contain any paint residues, solvents or other potentially toxic impurities" to ensure a safe application to soils (EBC, 2022, p. 14). Hence, the suitability of different biomasses depends on the intended end-use in soils as a carbon sink and soil conditioner (Haubold-Rosar et al., 2016; Kamali et al., 2022).
In addition to the choice and collection of biomass as well as the pre-treatment, this phase also entails, if necessary, the storage and transportation of biomass (Anderson et al., 2017). Feedstock logistics can, for example, comprise the collection and transport from forests, farms or processing plants to biochar production sites (Anderson et al., 2017). Storage allows for detaching biochar production from biomass provisioning (Anderson et al., 2017).

Biochar production

The biomass conversion step comprises production of biochar and co-products, namely bio-oil and syngas and required post-treatment processes (Anderson et al., 2017; Lefebvre et al., 2021; Sohi et al., 2015; Thengane et al., 2021).
As described in Section 2.1, biochar, defined for the scope of the thesis, is produced by thermochemical conversion, more specifically by pyrolysis or gasification. Besides the relevance of the choice and suitability of the feedstock, biochar characteristics are also determined by the technology and the conversion parameters (Kalus et al., 2019). The application and implementation of a biochar system depends on the technological feasibility, both of the individual system components, namely biomass, conversion and application, and of the interaction of these components in the whole system. Therefore there is a need to design, adjust and control the conversion process according to the other system components (Crombie et al., 2015; Sundberg et al., 2020; You et al., 2022).
The production of biochar can range from small scale systems to large scale industrial production through a variety of technologies (Anderson et al., 2017; Boateng et al., 2015; European Biochar Industry Consortium [EBI], 2022; Joseph & Taylor, 2014; P. Smith et al., 2019a; Zilberman et al., 2022). Technological opportunities range from traditional kilns and modern small scale pyrolysis plants (Anderson et al., 2017; Boateng et al., 2015; Zilberman et al., 2022) to different commercially available technologies for medium to large scale production (Zanli et al., 2022). The various technologies differ regarding the technological development stage from earlier development stages to pilot plants and industrial ones (Haubold-Rosar et al., 2016). Furthermore, the different technologies can

be differentiated in terms of scale and vary according to feedstock requirements and co-product production (Anderson et al., 2017).
In general, the step of biochar production is characterized by the configuration of the pyrolysis equipment (Azzi et al., 2021b; Sohi et al., 2015) and the conversion phase can differ regarding the type of reactor, the mode of operation as well as heating method (Boateng et al., 2015). For example, there are small scale kilns and retorts, only the latter allowing for the recovery of energy (Boateng et al., 2015). Another example for a technology design is given by Llorach-Massana et al. (2017), who report on a pyrolysis technology that comprises a grinding module. Hence, in this case, pre-treatments are integrated into the conversion. In another case, grinding is a separated process (Campion et al., 2021).

The conversion process, more specifically the process parameters such as temperature, heating rate and residence time, determine the proportion of the type of end-products and thus biochar yield, as well as their characteristics (Ayaz et al., 2021; Cha et al., 2016; Yaashikaa et al., 2020). Regardless of the ratio of end products produced, the resulting by-products' use influences the biochar system's sustainability and economic viability (EBC, 2022; Haubold-Rosar et al., 2016; Shackley et al., 2011; P. Smith et al., 2019b; Werner et al., 2018). Mostly, the bio-oil and syngas are burned for thermal and electric energy production, however material utilization is another option (Haubold-Rosar et al., 2016; H.-P. Schmidt et al., 2019; Sohi et al., 2015). Different options for energy utilization exist. For example, the heat from gas combustion can be used to dry the biomass within the biochar system (Lefebvre et al., 2021) as well as for conversion processes and post-treatment (Campion et al., 2021). In modern small scale system the gas can be used to run the pyrolysis process (Sparrevik et al., 2014). Further, electricity generation or feeding into the district heating grid are possibilities (Azzi et al., 2019). However, in traditional small scale systems options for recovery of the generated energy are limited (Zilberman et al., 2022).
Woolf et al. (2021) suggest that the carbon capture and storage of the CO_2 from the combustion of the syngas, as well as storage of bio-oil in geological reservoirs significantly increases the potential of biochar systems as a NET as this reduces the re-emission of CO_2. However, these options are not regarded due to the scope of the thesis.

Post-treatments might be required to improve the biochar for a specific application. These post-treatments comprise grinding, pelletization and blending (Anderson et al., 2017; EBC, 2022; Lefebvre et al., 2021; Thengane et al., 2021). The high adsorption capacity and cation exchange capacity of biochar can reduce the nutrient availability of plants. In order to optimize the potential benefits and hinder negative effects on soils biochar has to be activated with nutrient-rich organic materials instead of applying pure and untreated chars (H.-P. Schmidt, 2011). For example, composting with organics, can improve biochar performance (Anderson et al., 2017). According to the EBC guidelines the pure biochar is mostly refined into biochar-based products such as composts, fertilizers or feeding (EBC, 2022). By mixing, composting and fermentation processes biochar properties are enhanced regarding surface area, microporosity and nutrient enrichment (Bundesminesterium für Land- und Forstwirtschaft [BMLFUW], 2017; Haubold-Rosar et al., 2016; H.-P. Schmidt, 2011). With this economic and soil benefits can be achieved, also in temperate regions. Moreover, not only biochar benefits but also a positive effect on the composting process is given (H. Schmidt et al., 2021). Hence, in the European market co-composting is a common measure to produce biochar-based products (H. Schmidt et al., 2021).

Biochar application

Biochar application entails the transport to the site of application (Lefebvre et al., 2021) or more general distribution logistics (Anderson et al., 2017). Packaging, storage and transport depend on the biochar properties and on end-consumer needs (Anderson et al., 2017). This thesis focuses on the end use in agricultural soils as the focus is on the potential for carbon sequestration and soil improvements. Agricultural uses comprise the use as a soil amendment, as an animal feed ingredient, compost additive, biochar based fertilizer and the application for manure treatment (EBC, 2022; Enaime & Lübken, 2021; Kalus et al., 2019; H.-P. Schmidt et al., 2019, 2021). Biochar can be applied manually or by application equipment (Anderson et al., 2017) such as via fertilizer spreading machinery (Lefebvre et al., 2021). It can be distinguished between a direct and indirect application. The latter is based on the before described pre-treatment, where the biochar is mixed with other soil additives such as manure, compost or other fertilizers (EBC, 2020; Haubold-Rosar et al., 2016; H.-P. Schmidt, 2011; Song et al., 2022). Co-application can increase nutrient use efficiency, economic viability (Joseph et al., 2021; H. Schmidt et al., 2021) and crop productivity as well as other ecosystem services (Blanco-Canqui, 2021) and has received increased attention lately (Agegnehu et al., 2017; Haubold-Rosar et al., 2016; Sanchez-Reinoso et al., 2020). Another approach, in line with cascading usage, is the application of biochar as an additive in animal feed and the subsequent loading of the biochar, followed by application as a soil amendment (BMLFUW, 2017). Through cascading usage the described usage competition can be addressed (Haubold-Rosar et al., 2016). In a study by Azzi et al. (2019), the main part of biochar is added to the manure and a small portion is first added to the animal feed, consequentially being part of the manure. Both approaches are followed by the end application as a soil amendment. The described biochar value chain, including the introduced sub-steps, is depicted in detail in Figure 2.

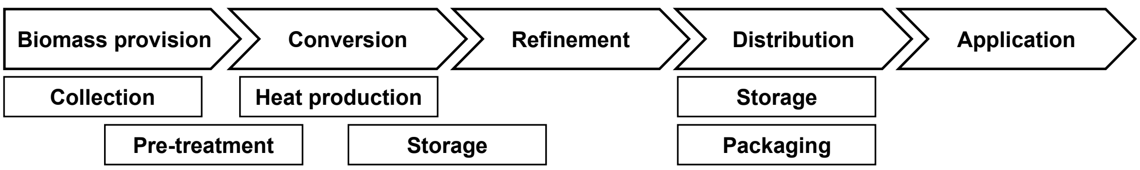

Figure 2: Detailed biomass value chain with sub-steps based on (Anderson et al., 2017; Azzi et al., 2021b)

Value chain configuration and associated actor groups

Depending on the scale and configuration of the system, the described sub-processes can vary. For example, biomass can be converted to feedstocks within the step of biomass collection (Anderson et al., 2017) or at the production site (Anderson et al., 2017; Llorach-Massana et al., 2017; Roberts et al., 2010) or both (Anderson et al., 2017). Further, biochar blending can be implemented at the production or at the application site

(Anderson et al., 2017; Azzi et al., 2019). Hence, the configuration and location of the sub-steps differ.
The length of the value chain varies, for example, traditional biochar systems use available local biomass and ignore the usage of the energetic by-products (Zilberman et al., 2022). Options range from small scale (Azzi et al., 2021b; Sørmo et al., 2020) to larger scale, more centralized biochar systems (Azzi et al., 2019; Otte & Vik, 2017; Papageorgiou et al., 2022). In the case of small scale on farm production the farmer fulfils the function of biomass provision, conversion and application (Sparrevik et al., 2014). In contrast, Anderson et al. (2017) describe other options, where two companies engage in biochar business, the first by providing biomass, using the heat and applying the biochar and the second as the biochar and heat producer. Moreover, more complex biochar systems with a diverse set of involved actors fulfilling the described function in the value chain are mentioned (Anderson et al., 2017). Hence, various system configurations and associated relevant actor groups constitute regional biochar concepts. The potential value chains can be characterized by various levels of vertical integration (Anderson et al., 2017; Sesko et al., 2015).

Regarding the actor roles, there is the biomass provider, the biochar producer, the distributor and the buyer (Thengane et al., 2021). Azzi et al. (2021b) point out that several actor groups, such as farmers, agricultural cooperatives and waste companies engage in biochar production. Moreover, biochar companies operate pyrolysis plants and produce biochar (Azzi et al., 2021b; Leach et al., 2012; Thengane et al., 2021). However, Anderson et al. (2017) mention a lack of commercial enterprises engaging with biochar. In addition, the equipment manufacturer fulfils a relevant function for biochar value chains (Leach et al., 2012; Thengane et al., 2021).
Besides the relevant actors for fulfilling the functions in biochar value chains, several other stakeholder groups that affect biochar development are mentioned in the literature. Scientists, non-governmental organizations and consultancies are mentioned, especially with regard to the option of incorporating biochar into carbon markets (Leach et al., 2012). Moreover, certifiers, investors and policymakers play a role in biochar development (Kong et al., 2014; Leach et al., 2012; Niemmanee et al., 2019; Thengane et al., 2021; Zanli et al., 2022).

2.3 Socio technical systems and transitions

Technology and innovation studies have increasingly acknowledged the interdependence of technological development and the co-evolvement of the society (Hughes, 1986; Trist, 1981). Regarding this, different theories and frameworks were developed that analyze the co-evolutionary development of new technologies and the actors involved (Bugge et al., 2019; F. W. Geels, 2004; Hughes, 1986; Trist, 1981).
The STS theory emphasizes that the technological sub-system co-evolves with heterogenous social elements, such as political and cultural factors (F. W. Geels, 2004; F. W. Geels et al., 2017; A. Smith & Stirling, 2008). For the analysis from a STS perspective, the interdependence and re-alignment of the social and technological sub-system have to be anticipated (Clegg, 2000; F. W. Geels et al., 2008; A. Smith & Stirling, 2008). The technological sub-system comprises not only the technology itself but also resources, materials and the related infrastructure and processes needed to turn these

inputs into outputs in order to fulfil societal functions (Clegg, 2000; F. W. Geels, 2004; Militello et al., 2014). The focus on the fulfilment of societal functions again indicates the interplay with society and the importance of the use and functionality of a technology and not only of its development (F. W. Geels, 2004). According to Smith and Stirling (2008), for the fulfilment of environmental goals structural changes are needed in addition to new technology. So, to enable environmental benefits by deploying a new technology, changes in the (social) sub-system are needed, such as a new value chain organization. The social sub-system consists of a network of actors and is shaped by their characteristics, relationships, and guiding rules and institutions (F. W. Geels, 2004; Rip & Kemp, 1998). For example, technology implementation partially depends on the fit to existing practices of the actors and requires changes in work processes (F. W. Geels, 2004; A. Smith & Stirling, 2008). Simultaneously, new technologies open up possibilities for new work practices and ways of organization (A. Smith & Stirling, 2008).

To sum up, this perspective takes into account that the STS comprises various elements such as knowledge, policies, culture, technical artifacts and infrastructure which co-evolve and undergo different alignment processes and, by this, determine the success of the STS (F. W. Geels et al., 2017; Markusson et al., 2012). In other words, this approach embeds technology in the context "that enable it to work" (A. Smith & Stirling, 2008, p. 6). This is supported by Geels (2004), who stated that the functioning of a STS depends on the activities of the network of actors.

According to Lehmann and Joseph (2015), biochar should be considered from a system perspective to address possible trade-offs and to enable the sustainability of biochar production and use. As explained in Section 2.2, different configurations of the biochar system with regard to feedstock, technology and end-product are possible, "therefore the motivation or entry point for a biochar system can be very different" depending on the overarching goal (Lehmann & Joseph, 2015, p. 6). The relevance of goals and motivation do already indicate that technology does not develop and diffuse on its own but is guided by human behavior (F. W. Geels, 2004; Rip & Kemp, 1998).

Otte and Vik (2017) have already highlighted the need to look at biochar implementation through the lens of a STS in order to pay attention to socio-cultural and political factors affecting the successful implementation of biochar systems on different scales in Norway. This approach followed Davis et al. (2014) call to apply the STS approach to a broader range of problems than the original application fields: design of jobs, IT-systems and crowd disasters. Following this, this thesis investigates the drivers and barriers of rural biochar concepts in Germany through the perspective of an STS. Based on the approach by Otte and Vik (2017), adopted from Davis et al. (2014), the six dimensions of the STS framework, namely: 'people', 'goals', 'culture', 'infrastructure', 'technology' and 'processes and procedures' are used to analyze rural biochar value systems from an STS perspective.

Socio-technical transitions and the Multi-Level Perspective

From the 2000s, the studies on technological change, innovation systems and STS has been further complemented by studies on socio-technical transitions (Bugge et al., 2019). Socio-technical transitions describe the processes needed to shift the existing system from one system configuration to another, hence it takes into account systemic

change (Bugge et al., 2019; F. W. Geels et al., 2008). This perspective highlights that in order to address environmental challenges by the deployment of new technologies, change in other system components, such as the guiding institutions, is needed (F. W. Geels et al., 2008).
Different theories and frameworks are used to investigate these processes of change. The Multi-Level Perspective (MLP) framework analyses transitions by differentiating between three analytic levels: the landscape, socio-technical regime and niche level. The landscape captures exogenous “deep structural trends”, such as “economic growth, wars and environmental challenges” (F. W. Geels, 2002, p. 1260; F. W. Geels et al., 2017). The socio-technical regime is constituted by the rules, institutions and practices supporting the existing system and only providing potential for incremental changes along path-dependent trajectories. Hence, “socio-technical regimes account for the stability of existing socio-technical systems“ (F. W. Geels & Kemp, 2007, p. 443). In the niche level, radical innovations are developed. These niches provide a protected space for learning processes and the development of networks to foster radical innovations (F. W. Geels, 2002). Transitions are driven by interactions and alignments between these three levels. Landscape pressures can destabilize the existing regime and in the interaction with tensions in the regime create “windows of opportunities” for the diffusion of niche innovations (F. W. Geels, 2002, p. 6). The MLP framework complements the theory on STS, by broadening the scope and analyzing the processes of change associated with long-term transforming systems (F. W. Geels & Schot, 2007; Weber & Rohracher, 2012).

2.4 Literature review: socio-technical drivers and barriers

In this chapter the socio-technical drivers and barriers identified in the literature are elaborated on. Drivers are factors that enable biochar production and usage, whereas barriers hinder biochar development. Factors that are described as positively affecting biochar development but not yet in place are described as potential drivers. The literature review aims to compile the available information in a structured way in order to clarify the state of knowledge and research. For structuring, one needs a theory or a certain perspective (Webster & Watson, 2002). In this thesis, the before described STS perspective is used and the findings are structured according to the six dimensions of the STS: ‘people’, ‘goals’, ‘culture’, ‘infrastructure’, ‘technology’ and ‘processes and procedures’.

2.4.1 Goals

As already indicated in Section 2.1 biochar touches on several domains, therefore various goals can be pursued by biochar engagement, which are presented in the following. The identified goals are summarized in Table 1[2].
According to Lehmann and Joseph (2015), biochar can be linked to the following four main targets: “soil improvement, mitigation of climate change or nutrient pollution, waste management and energy generation” (Lehmann & Joseph, 2015, p. 7). Likewise, Jeffery et al. (2015) report on the various goals which are pursued with biochar systems, such as negative emissions, soil benefits, waste management, pollutant immobilization and

[2] For the extended version with reference see Appendix A (Table I).

bioenergy production. This is in line with various studies highlighting its contribution to sustainable land management, climate change mitigation and sustainable resource management (A. E. Latawiec et al., 2017; Rittl et al., 2015; You et al., 2022). Further, biochar benefits for fertility and crop productivity, food production and energy provision are mentioned in the literature (Kamali et al., 2022; A. E. Latawiec et al., 2017; Rittl et al., 2015; You et al., 2022).
A study by Rogers et al. (2022) shows that the main motivations along farmers for biochar deployment are improved soil structure and increased productivity as well as economic benefits. This is followed by climate change mitigation as a driver for biochar engagement. Latawiec et al. (2017) identified diverse motives of farmers for biochar deployment such as plant and animal benefits, soil benefits and crop productivity as well as the general positive attitude towards human and nature. For farmers in Brazil the climate change mitigation potential was not the guiding motivation, rather the potential for increased crop productivity convinced the farmers to apply biochar (Rittl et al., 2015). Other pursued aims along farmers are productivity increase, cost reductions and reduced exposure to smoke (Mahmoud et al., 2021). Ayaz et al. (2021) point out that biochar's benefits are in line with the goals of a sustainable development in the agricultural sector.

Table 1: Goals identified within the literature review

Goals
• Climate change mitigation
• Soil benefits
• Crop productivity and food security
• Waste management
• Energy security

2.4.2 People

Regarding the actors involved, the following drivers and barriers were identified within the literature research (see Table 2[3]). Stakeholder cooperation enables biochar development (Kong et al., 2014; Leach et al., 2012; E. Singh et al., 2022). Simultaneously, insufficient cooperation among research institutes is said to pose a hindering aspect (Gwenzi et al., 2015). This in line with Sundberg et al. (2020), who state that transdisciplinary research collaboration has the potential to foster biochar development. Moreover, the need for knowledge dissemination and education is mentioned (Karim et al., 2022; A. Latawiec et al., 2017; P. M. Rogers et al., 2022; E. Singh et al., 2022). General, there is a need to promote biochar and improve communication to raise awareness along relevant actor groups (Niemmanee et al., 2019; E. Singh et al., 2022; Song et al., 2022).

Table 2: People-related drivers and barriers based on literature research

[3] For the extended version of the table with more detailed information and references see Appendix A (Table II).

Drivers	Barriers
• Alliances and cooperation along stakeholder groups • Biochar conferences • P[4]: collaboration between science and practice • P: information exchange • P: transdisciplinary research collaboration	• Need for joint action by all stakeholder • Insufficient communication and information exchange • Need for knowledge transfer, education and demonstration • Need for promotion and awareness raising of biochar

2.4.3 Culture

The literature acknowledges that cultural aspects affect biochar engagement. A summary of identified drivers and barriers is presented in Table 3[5]. Public perception and (social) acceptance, as well as people's attitudes, affect biochar deployment (Gwenzi et al., 2015; Kamali et al., 2022; Kong et al., 2014). According to Downie et al. (2012) public trust in biochar technology can be supported by science-based regulations. This is in line with Garcia et al. (2022), who state that voluntary certification is one measure to increase acceptance. simultaneously public confidence fosters needed investment.

The lack of awareness is seen as a hindering aspect according to several studies (Garcia et al., 2022; Karim et al., 2022; A. E. Latawiec et al., 2017; Niemmanee et al., 2019; Thengane et al., 2021; Zanli et al., 2022; Zilberman et al., 2022). However, Leach et al. (2012) mention the farmers' awareness of biochar technology as a driver. More specifically, the farmers' attitudes are a decisive aspect and entail, among other aspects, the openness to new practices, the attitude toward sustainable agriculture and the risk aversion (Gwenzi et al., 2015; A. Latawiec et al., 2017; Müller et al., 2019; Zanli et al., 2022). In addition, the agricultural system affects biochar adoption, for example, with cultivation of cash crops farmers' longer-term planning increases the likeliness to invest in biochar (Hansson et al., 2021). In contrast, the uncertainty of land tenure hinders biochar engagement due to the lack of long-term investments and planning (Hansson et al., 2021).

Further, misunderstandings and negative perceptions impede biochar implementation (Thengane et al., 2021; Zanli et al., 2022). In addition, lacking political will leads to lacking political support for biochar (P. M. Rogers et al., 2022). This is underlined by Rittl et al. (2015), who state that the potential benefits of biochar are not represented in "climate change and agriculture regimes" (p.46).

[4] P marks potential drivers. These are factors that are expected to have a positive impact on biochar development but are not yet present, as explained in the Section 2.4.

[5] For the extended version of the table with more detailed information and references see Appendix A (Table III).

Table 3: Cultural drivers and barriers based on literature review

Drivers	Barriers
• Growing interest in biochar technology	• Lack of awareness of biochar technologies • Lacking customer perceptions
Farmers' • awareness of biochar technology • positive attitude towards biochar production and usage • openness for new technologies • trust in biochar technology • familiarity with technology • positive attitude towards sustainable agriculture	Farmers' • risk aversion • lack of awareness of biochar technology • lack of openness for new practices • lacking willingness to cooperate
• Orientation of the agricultural system	• Orientation of the agricultural system
• P[6]: positive perception of society • Acceptance of technology	• Lack of political will
	• Misunderstanding as well as wrong and negative perceptions, reluctance due to (environmental) concerns • Need to raise acceptance • Need for public trust in biochar technology

2.4.4 Technology

Regarding the technology, the following drivers and barriers were discovered in the literature (see Table 4[7]). The technological development and availability of technologies contribute to biochar development (Garcia et al., 2022; Kong et al., 2014; Mašek, 2016). Moreover, the literature acknowledges that technology costs are relevant (Nematian et al., 2021; Thengane et al., 2021; Vochozka et al., 2016). According to Thenghane et al. (2021), the high costs hinder biochar production. However, technological development is associated with decreased costs of production (Nematian et al., 2021; Song et al., 2022; Vochozka et al., 2016) and small scale systems are beneficiary due to low costs

[6] P marks potential drivers. These are factors that are expected to have a positive impact on biochar development but are not yet present, as explained in the Section 2.4.

[7] For the extended version of the table with more detailed information and references see Appendix A (Table IV).

(Gwenzi et al., 2015). Not only the costs, but the simplicity of small scale technologies is mentioned as beneficial (Gwenzi et al., 2015; A. E. Latawiec et al., 2019). However, this is accompanied by lacking energy usage options for small scale technologies (Downie et al., 2012; Gwenzi et al., 2015).
Further, the requirement of pre-treatment processes, in other words, the suitability of feedstocks for conversion, affects biochar production (Chang et al., 2015; Downie et al., 2012; Kong et al., 2014; Roberts et al., 2010; You et al., 2022; Zanli et al., 2022). Moreover, technical knowledge is required and can either pose a driver in the case of existence or a barrier if, for example, farmers lack technical skills for biochar production and application (Gwenzi et al., 2015; Niemmanee et al., 2019; P. M. Rogers et al., 2022; Zanli et al., 2022). For example, there is the need to design and control the conversion process appropriately and to adjust conversion to biomass and pursued outcome (Crombie et al., 2015; Sundberg et al., 2020; You et al., 2022b). The lack of knowledge on biochar technology (Kong et al., 2014; Maroušek et al., 2019; Vochozka et al., 2016), especially from farmers, is seen as a hindering aspect (A. Latawiec et al., 2017; Niemmanee et al., 2019). Other aspects that were identified are additional labor demand (Bellè et al., 2022) and emissions (Thengane et al., 2021). Biochar application also poses a barrier, as it requires resources and technical knowledge (Hansson et al., 2021).

Besides the ongoing research and existing scientific findings (Kamali et al., 2022; Kong et al., 2014; A. Latawiec et al., 2017), there is a need to address research gaps and for example to conduct field level research (Kamali et al., 2022; Thengane et al., 2021; You et al., 2022). Scientific findings are needed to direct certification, develop criteria and guide decision making regarding production and usage (Gwenzi et al., 2015; Verheijen et al., 2012). Besides the existence of various biochar publications, publications must be standardized to enable comparison and synthesis of findings (Jeffery et al., 2015).

Table 4: Technology-related drivers and barriers based on the literature review

Drivers	Barriers
• Existing technologies and ongoing technological development • P[8]: technological flexibility regarding inputs	• Low system efficiencies • Technological feedstock constraints, requiring equipment and costly and addition pre-treatment processes
• Reduced production costs due to technological development	• Time and costs of biochar production • Labor demand
• Technological knowledge	• Lack of technical knowledge
• Cheap and simple small-scale technologies	• Small scale technologies lack energy usage option
• Co-benefits of technology compared to other NETs	• Emissions
• Established research level and progress and ongoing biochar research • P: Long-term field research	• Required resources and technical knowledge for application
	• Lack of long-term field-research • Lack of data and research gaps • Lack of knowledge on biochar technology • Uncertainty and unpredictability of site-specific biochar impacts

2.4.5 Infrastructure

The different infrastructure-related drivers and barriers identified within the literature search are summarized in Table 5[9]. The availability of feedstocks and usage of residues is seen as a driver for biochar implementation (Ayaz et al., 2021; Garcia et al., 2022; Mahmoud et al., 2021; P. M. Rogers et al., 2022; Sundberg et al., 2020; Thengane et al., 2021). However, the choice of feedstock as well as logistics, affect the economic and ecological performance of the system and can either pose a driver or a barrier (Chang et al., 2015; Maroušek et al., 2019; P. M. Rogers et al., 2022; Thengane et al., 2021; Vochozka et al., 2016; You et al., 2022; Zanli et al., 2022; Zilberman et al., 2022). Regarding the latter, biomass collection, transportation and storage affect the performance of the biochar system (Thengane et al., 2021; Zilberman et al., 2022). The

[8] P marks potential drivers. These are factors that are expected to have a positive impact on biochar development but are not yet present, as explained in the Section 2.4.

[9] For the extended version of the table with more detailed information and references see Appendix A (Table V).

scale of implementation is a relevant factor, as short transport distances enable the performance of the biochar system. Some authors, therefore, suggest decentralized production close to the biomass provision (and biochar application) (Maroušek et al., 2019; Roberts et al., 2010; Thengane et al., 2021; Zanli et al., 2022) as given with on-farm production (You et al., 2022). Others highlight mobile systems as beneficial due to reduced feedstock hauling distances (Nematian et al., 2021; You et al., 2022). In addition, the performance of the biochar system is influenced by the production and usage of the energetic by-products (Downie et al., 2012; Garcia et al., 2022; A. E. Latawiec et al., 2017; Maroušek et al., 2019). Further, lacking supply chains and lacking long-term contracts for biomass supply hinder biochar development (Kong et al., 2014). The variability of biochar qualities impedes distribution, but this can be addressed by certification and standardization (Kochanek et al., 2022).

Table 5: Infrastructure-related drivers and barriers

Drivers	Barriers
• (Local) availability of feedstocks • Usage and availability of residues	• Usage competition • Feedstocks costs • Seasonality of feedstocks
• Decentralized production with small scale systems close to the biomass sources • Optimized logistics • Decreased biomass hauling distance with mobile systems	• Logistics (feedstock collection, transportation, storage) and related costs • Long-distance transport of biomass
• Existing infrastructure	• Lack of supply chains • Lack of long-term contracts between biomass provider and operator of the plant • Heterogeneity of biochar qualities impedes distribution
• Co-production and usage of heat	

2.4.6 Processes and procedures

Various aspects related to processes and procedures that guide the development of biochar could be identified within the literature and are summarized in Table 6[10]. Certification, guidelines and quality criteria are relevant procedures for biochar production and usage (Conte et al., 2015; Downie et al., 2012; Garcia et al., 2022; Jeffery et al., 2017; Leach et al., 2012; Verheijen et al., 2012). Further, policies and regulations guide biochar development and can either support biochar production and usage or pose a barrier, for example, due to restrictive regulations or the heterogeneity of regulations

[10] For the extended version of the table with more detailed information and references see Appendix A (Table VI).

(Ayaz et al., 2021; Garcia et al., 2022; Gwenzi et al., 2015; A. Latawiec et al., 2017; Müller et al., 2019; Thengane et al., 2021).
Carbon crediting and the associated quantification and certification is another important procedure with the potential to act as a driver and boost biochar development but with the need for improvements (A. E. Latawiec et al., 2019; Mašek, 2016; Thengane et al., 2021). Trading of biochar carbon certificates is one potential source of income. In addition carbon price, funding and subsidies are mentioned as (potential) drivers (Chang et al., 2015; A. E. Latawiec et al., 2019; Leach et al., 2012; You et al., 2022).
In order to guide policies, decision making and the development of standards and certification systems, there is a need for comprehensive assessments of biochar systems (Azzi et al., 2021a; Jeffery et al., 2015). According to Leach et al. (2012), there is a need for science based regulation, monitoring and certification. Likewise the need for regulation, monitoring and certification drives science (Leach et al., 2012). Jeffery et al., point (2015) out the need for synthesizing existing findings to guide policies.

Table 6: Process- and procedure-related drivers and barriers

Drivers	Barriers
• Regulative change and existing regulative procedures • P: enabling policies	• Lack of enabling policy framework and regulations • Legal uncertainty and regulative heterogeneity
• Voluntary biochar quality standards and guidelines • Voluntary certification of carbon sequestration and carbon crediting • P: incorporation into carbon crediting schemes	• Need to develop and improve biochar standardization, guidelines and certification and risk assessments • Lack of standards and methodologies for carbon crediting and ecosystem services
• Funding, subsidies	• Uncertainty regarding carbon crediting regulations • Difficulties with carbon credit ownership
	• Costs of approval and controlling • Compliance with regulations and certification
	• Lack of funding

2.4.7 Interim conclusion and problem specification

The literature revealed several socio-technical drivers and barriers for biochar systems. In some contexts, specific factors are seen as a driver, whereas in other contexts these factors pose barriers. Besides the various identified findings, holistic analysis of the socio-technical drivers and barriers remains scarce. For example, many studies focus on a techno-economic assessment of biochar systems (Chiaramonti & Panoutsou, 2019; Rodrigues & Horan, 2018). Most studies, regionally focus on biochar implementation in the Global South (Niemmanee et al., 2019; Sundberg et al., 2020; You et al., 2022; Zanli et al., 2022). The implementation and performance of biochar systems depends on the local context (Jeffery et al., 2015; A. Latawiec et al., 2017). Hence, it is necessary to shift the focus to socio-technical drivers and barriers for biochar implementation in Germany. Moreover, the literature findings do not indicate specific drivers and barriers with regards to the pursued goals. On the one hand, it can be assumed that goals in the first place represent drivers and they motivate actors to engage with biochar. On the other hand, the various identified goals and the possible trade-offs pointed out by Jeffery et al. (2015) might also imply barriers inhibited in the achievement of biochar goals. This will be further investigated within this thesis. The methodological approach for this qualitative research is described in detail in the next chapter.

3 Methodology

This chapter provides an overview on the methodology used in this thesis. The overall goal is to identify socio-technical drivers and barriers for regional biochar value chains. For this purpose, a qualitative research approach was chosen to address the research gap on the socio-technical factors of biochar systems implementation. Qualitative research aims to explore the reality of experience by examining the research objects in their context and including the perspectives of those involved by generating, collecting and analyzing empirical data (Döring & Bortz, 2016). Accordingly, the qualitative research approach fulfils the requirements of the research question, which attempts to analyze biochar as an STS. This analytic approach presupposes that the technology is examined in its context, in which the network of actors plays an important role. The research design is depicted in Figure 3. The different steps of data collection, coding and data analysis are described in detailed in the following sections.

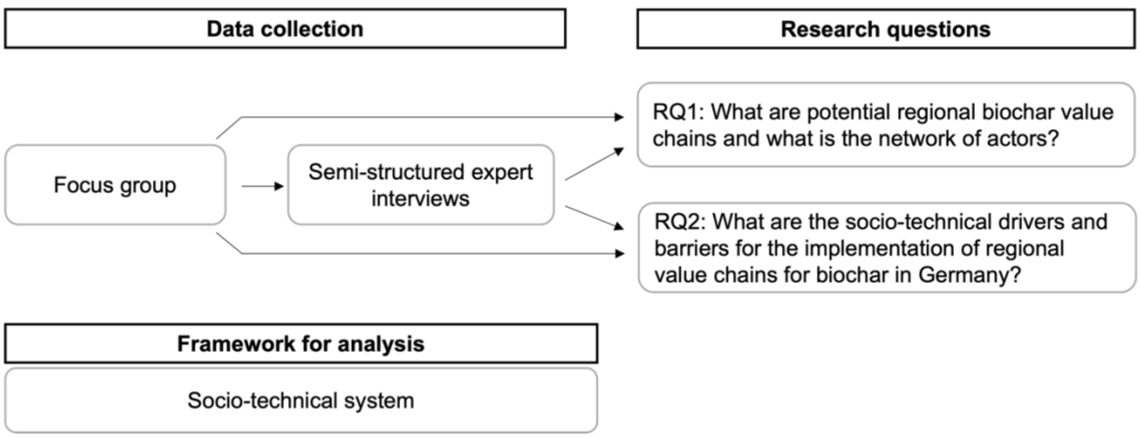

Figure 3: Visualization of research design (own figure)

3.1 Data collection

According to a triangulation approach, different data sources were combined for the investigation of the research questions. Triangulation aims at improving the knowledge gain as well as reliability (Flick, 2004). The first data source is data obtained from a focus group. The material from the focus group was analyzed to gain first insights into actors and potential socio-technical drivers and barriers of biochar production and use. Based on these findings, an interview guideline was conducted to test and supplement the findings empirically through semi-structured expert interviews. The conducted interviews constitute the core empirical data of the chosen research approach. Data sources and its collection will be described in detail below.

3.1.1 Focus group

Within the *Landgewinn*-project, introduced in Chapter 1, a focus group on biochar technology was conducted on July 7th, 2022. A focus group, an exploratory form of qualitative research, serves to ask a group of experts about their experiences and opinions on a certain topic. This is done by creation and analysis of the participants interactions. Accordingly, the facilitator has a role of special importance in this research instrument, because he or she must enable, perceive and respond to interactions (Barbour, 2007).

Regarding the scope of this thesis, the data from the focus group was used as a starting point, focusing on thematic findings. The aim was to gain first insights into biochar value chains, actors as well as drivers and barriers. The participating experts consisted of project developers, operators and users in the production and/or use of biochar in agriculture, as well as representatives of planning and approval authorities and other stakeholders with experience in biochar technology. An external service provider fully transcribed the focus group, and this transcript was used for the data analysis, which was conducted using the software MAXQDA (see supplementary material A[11]) and will be described in more detail in the Section 3.2.

3.1.2 Semi-structured expert interviews

Semi-structured interviews were chosen as an empirical research instrument to embed the findings in practice (Döring & Bortz, 2016; Hopf, 2016). This represents the aim of the thesis, which is to investigate opportunities and challenges of biochar implementation. More specifically, semi-structured expert interviews were considered appropriate as this method allows to gain insights on the knowledge and perceptions of relevant actors (Bogner et al., 2014). The expert interview as an empirical research instrument is defined by the target group or the interest in the particular knowledge that these people bring with them (Helfferich, 2014). There is no clear consensus on how to define an expert and different approaches have emerged in the course of this discussion (Bogner et al., 2014; Helfferich, 2014). The selection of an expert by the decision of the interviewer, determines to a certain extent the status of the expert. Nevertheless, specific characteristics contribute to the expert status (Bogner et al., 2014; Meuser & Nagel, 1991). They do not only hold specialist knowledge but represent organizations or institutions. Consequentially, the experiential knowledge of these people is tied to the specific functional context (Meuser & Nagel, 2009). Their exclusive knowledge and experiences obtained by their function within these organizations or institutions contributes to the research question (Bogner et al., 2014; Meuser & Nagel, 1991).

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[11] This material is provided as an external pdf and is only accessible to the reviewers for data protection reasons.

Sampling

The selection of the experts corresponds to the previously described definition based on their access to specific types of knowledge. The selection of experts identified actors with a superior role in relation to biochar and actors representing a specific stage of the value chain. Superior role in this context means that they do not represent a specific stage in the value chain but are members of relevant interest groups or belong to a significant institution or organization in the context of biochar. These actors are relevant because they have high-level knowledge concerning decision making processes or groups of people or because they have responsibility for the design, implementation, or control of a problem solution (Bogner et al., 2014; Meuser & Nagel, 1991). Hence, these actors were approached to gain insights into organizational aspects and structures of biochar production and use. Moreover, experts who represent a specific stage in the value chain and have operational knowledge were identified (e.g. a biochar producing company or a farmer who applies biochar).

An internet search as well as information from the IÖW project were used to identify relevant actors. In addition, experts were identified by recommendations from the before-interviewed experts following the snowball principle (Bryman, 2016; Reed et al., 2009).

The actors were chosen by theoretical sampling, which means that they were selected by an iterative process depending on the results from the previous interviews. This procedure was chosen to optimize the maximum theoretical knowledge gain (Döring & Bortz, 2016). In the sense of theoretical sampling, after each interview it was considered which other persons or institutions are relevant for the findings. For example, after interviewing a commercial biochar producer, an agricultural on-farm producer was interviewed. In consultation with the supervising professors, the sampling was ended after 13 interviews. In line with the scope of the thesis, the 13 experts were considered sufficient to address the goal of this study.

Table 7 provides an overview of the interviewed experts, their represented position and associated expertise. Names are disclosed for actors whose position can be considered of particular importance, such as a representative of the *European Biochar Industry Consortium (*EBI*).* Actors for whom only the role of the person is important, such as a farmer, are anonymized.

Table 7: Overviews of interviewees and their expertise

ID	Organisation	Expertise
B1	EBI	Project development and representation of interests
B2; B2.1	Biochar start-up	Biochar production, refinement and distribution
B3	Project developer for the agricultural sector as well as farmer association	Consulting, advocacy and project planning for agriculture
B4; B4.1	Disposal company	Operation of a pyrolysis plant
B5	Farmer	Agricultural expertise and engagement with the potential operation of pyrolysis plant
B6	Farmer	Biochar application
B7	Farmer	Biochar application and production
B8	Equipment manufacturer	Plant manufacture and operation of a plant
B9	Wine grower	Biochar application
B10	Contracting company	Project planning and operation
B11	Biochar trading platform	Biochar refining and trading
B12	*Deutsches Biomasse Forschungszentrum*[12] (DBFZ)	Application-oriented research and development with focus on the bioeconomy and biomass
B13	Equipment manufacturer	Plant manufacture and operation of a plant

Interview guideline

In the following, the chosen design for the interviews is elaborated on. For structuring the data collection, a semi-structured interview approach was chosen as it guarantees openness enabling unexpected insights to emerge, while providing a structure that facilitates comparability (Helfferich, 2014). The approach of a semi-structured interview can be designed with varying degrees of standardization, either to emphasize the structure or the openness more strongly (Helfferich, 2014). For this thesis, a more structured approach was chosen, using a guide with pre-formulated and open-ended questions. The structure allows for guidance in the direction of the research interest

[12] *Deutsches Biomasse Forschungszentrum* is a non-profit limited liability company for applied research into the use of declining raw materials with innovative technologies. More information about this organisation can be found on the website (https://www.dbfz.de).

reflected in the predefined thematic blocks. More specifically, the pre-formulated questions increase the relevance of the narratives concerning the research question (Helfferich, 2014). However, in line with the semi-structured interview approach, the questions were flexibly adjusted. For example, the order of the questions was modified spontaneously to omit questions that had already been answered (Döring & Bortz, 2016). The findings from the focus group as well as from the literature review were used to develop questions linked to these categories. The guideline thus represents initial hypotheses that are then confronted with social reality (Liebold & Trinczek, 2009). Nevertheless, the questions were developed with the aim of openness. This allows for the discarding of preconceptions and the uncovering of unexpected findings (Helfferich, 2014). This approach allows for theory-building by the respondents in the sense of an inductive approach (Liebold & Trinczek, 2009).

The interview guideline was developed to gain insights into the barriers and drivers related to the different elements of the biochar system. Some elements of the STS were slightly adjusted based on the findings from the literature research and the focus group (see Figure 4). By this, the theoretical framework was applied and adjusted to the scope of the research question. The adjustment of the theoretical framework which provided the guiding themes for the interview questions is described in the following section. The process of revising and adjusting the categories is described in detail in Section 3.2.
The literature review and the focus group revealed the relevance of certification systems and regulations, resulting in the adjustment of the category 'processes and procedures' to 'institutions and procedures'. According to North (1992) institutions are understood the "rules of the game in a society, more formally they are humanly devised constraints that shape human action" (p.447). Hence, for the conceptualization of biochar as an STS, institutions and procedures that prescribe and guide biochar production and usage are regarded as one of the system elements. A more detailed description of the revealed system components and its specific definition is a result of the analysis and hence provided in the results chapter (see Section 4.2).

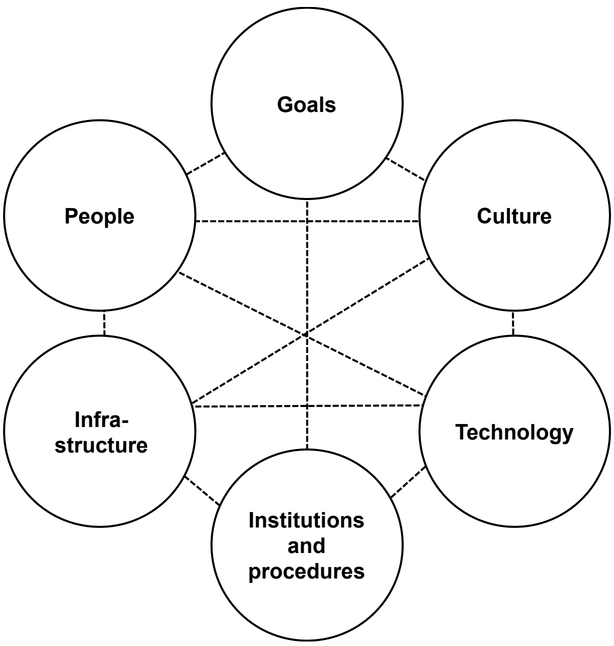

Figure 4: Socio-technical system (own figure adopted from (Davis et al., 2014))

Besides the described structure for the main part of the interviews, the interviews were organized as follows. The interviewees were informed about the purpose of the research and their right to ask for clarifications or skip questions at any time. The guideline comprises introductory questions, main questions and one final question (see Appendix C). Depending on the expert role, the focus of the questions was set differently. The guideline depicts the different possibilities, from which a certain selection was then asked and deepened depending on the focus. For example, a representative of biomass preparation was asked about this in particular, whereas farmers were asked in more depth about the application. The interview guidelines comprise a selection of sub-questions that were asked when time and the course of the interview allowed. The introductory questions aimed at gaining a general insight into the motivation for biochar engagement as well as the perception of biochar systems. The main questions were structured along the categories, to determine the decisive aspects, or drivers and barriers, for the respective category. The final question allowed the interviewees to name opportunities and challenges that were not addressed in the interview or that were particularly important according to her/his view.
The designed guide was then tested with a first actor. In this way, the practicability and the time frame were tested (Bogner et al., 2014). According to the pre-test some adjustments were made to the question to improve the understandability.

Conducting the interviews

Due to the focus on the implementation of biochar in Germany, the interviews were conducted in German. In terms of form, telephone interviews were chosen due to the lower time requirements, personnel flexibility and costs involved. In addition, participation was to be increased through greater flexibility in terms of availability (Döring & Bortz, 2016). In total, 13 interviews and two follow-up interviews were conducted between October 2022 and December 2022. A comprehensive list of the conducted interviews, the date as well as the length of the interview is provided in the Appendix B. One interview was conducted in writing due to the restricted availability of the interviewee (B13). Two interviewees (B2, B4) were consulted for a follow-up to clarify statements and gain further knowledge on specific aspects. All interviewees agreed with their interviews being transcribed and used for this research.

Transcription of the interview data

To prepare the data for analysis, the audio files from the interviews were transcribed. According to the purpose of a content analysis as well as time capacities, the interviews were transcribed according to a simplified, literal transcription according to the rules of Dresing and Pehl (2018). The following rules were pursued for the transcription. Parts of the interview that only served organizational aspects and parts of the conversation that lie outside the focus of the content, such as questions about my master program, were not transcribed because they were not relevant to the work. Besides that, the interviews were transcribed in their entirety. Language and punctuation are slightly smoothed out for better comprehensibility. The statements of the respective interview partners were

marked in the transcript with **B**[13] and an associated number. The abbreviation for the first interviewee, for example, was **B1**. The interviewer's statements and her questions were marked with **I**[14].
For the anonymized interviews, answers and content that could be traced back to the interviewee or third parties were anonymized (Bogner et al., 2014). Hence, for example the companies name was replaced by [name of a company[15]]. Repetitions of words and slips have been omitted. Pauses and interruptions were marked as follows (...). Incomprehensible parts that could not be transcribed are marked as (unv.[16]). The complete transcripts are written in German according to the interview language and provided in the supplementary material B[17]. As part of this step, I have subdivided the transcripts into sense paragraphs. Within the transcription process I created memos on the texts and familiarized myself with the content (Kuckartz, 2016). This provided the starting point for the described coding process, which is described below.

3.2 Data analysis

In the following the processes of data analysis will be described. First, the analysis to answer RQ1 will be described. This is followed by an in-depth description content-structuring qualitative content analysis and the different coding procedures.

The deductive-inductive coding process

For the data analysis a content-structuring qualitative analysis was chosen. This approach relies on categories and subcategories to structure the content of the data (Kuckartz, 2016). More specifically, a deductive-inductive categorization was carried out in order to facilitate the emergence of new knowledge and simultaneously analyzing the research object from an STS perspective, in other words, to represent the research focus (Barbour, 2007; Kuckartz, 2016). The coding process consists of two main phases, the coding of the focus group data and the coding of the interviews. The associated steps within each phase will be presented in detail in the following.
The coding was conducted via the software MAXQDA. First, the data was structured by coding it according to the six STS elements introduced in Section 2.3. These framework-based elements were used to structure the text in terms of content, i.e. to collect the findings for the six different themes. For this purpose, the whole focus group transcript was coded sequentially except for the non-substantial passages. As one sentence can comprise different topics, it is possible to assign different codes to a text passage (Barbour, 2007). As a coding rule, it was decided that sense units should be coded. A sense unit can consist of at least a single word, up to a whole section or several sections. The interview question was only coded if necessary for understanding (Kuckartz & Rädiker, 2022). Within the process of coding the deductive categories were reconsidered and definitions for the categories based on the findings were developed. Coding rules, which define what not to include, were created (see Appendix D). This step aimed at

[13] Since the interviews were conducted in German, the B stands for the German translation for interviewee.
[14] The same applies to the abbreviation I, which stands for the interviewer.
[15] Within the transcript the German translation is used [Unternehmensname].
[16] Unv. is the abbreviation for the German term 'unverständlich', which means incomprehensible.
[17] This material is provided as an external pdf.

increasing the selectivity of the categories as required by Kuckartz (2016). Within this process the deductive categories were reviewed, reconsidered and slightly. Hence, besides the usage of deductive categories, these categories were defined and adjusted based on the empirical insights. This approach allows for incorporation of the participants findings and simultaneously representing the initial research focus (Barbour, 2007). This iterative process of coding and adjustment based on the findings represents the nature of qualitative data analysis and is depicted in Figure 5 (Barbour, 2007; Kuckartz, 2016).

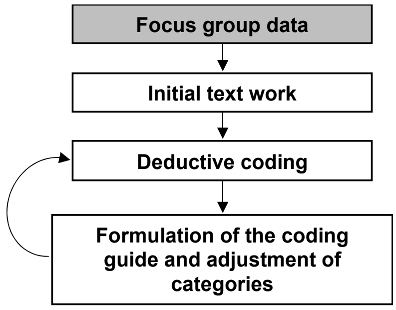

Figure 5: Deductive coding process of the focus group data(own figure adapted from (Kuckartz, 2016))

Based on the developed coding system, the semi-structured interviews were analyzed. The analysis followed a process of deductive-inductive category building, which is depicted in Figure 6 and will be described next.

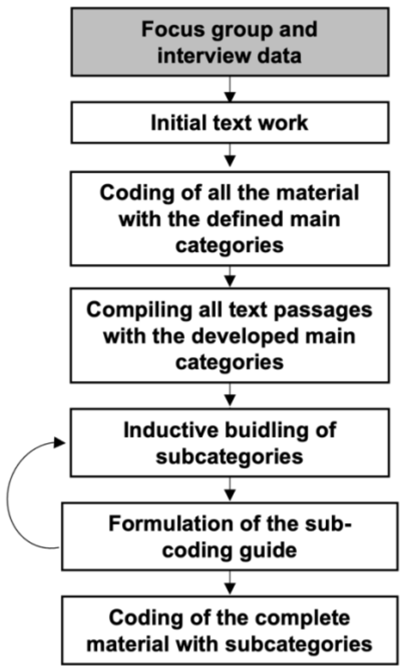

Figure 6: Deductive-inductive coding process of interview data (own figure adapted from (Kuckartz, 2016))

First, the transcripts from the interviews were coded according to the adjusted deductive categories. Building on the resulting compilation of the material with the same coding, subcategories were developed inductively. First, the sense units were transferred into short bullet points. The collection of bullet points was then sorted and summarized to develop sub-categories where appropriate. This process was initially carried out with the

first three interviews only. In the sense of an iterative process, further interviews were then treated accordingly. This process consisted of several iterations. In the next step, a coding guideline for the inductively developed sub-categories was established. In the sense of iterative coding, when new subcategories were identified, the interviews that had already been coded were checked again for passages of text in which this sub-category could be coded. The coding guideline comprises the categories, category definition as well as examples (see Appendix D). After finalizing the category system based on the main deductive categories and supplemented by the inductive subcategories, all material was analyzed using these categories.
The qualitative content analysis resulted in 13 subcategories, which will be described in Chapter 4.2. For two of the main categories no subcategories were identified. The identified and developed categories and subcategories form the basis of a data structure, which lays the groundwork for analyzing and interpreting the results.

System boundaries

The various potential configurations of biochar value chains affect the system design and boundaries as described in Chapter 2.2. As the different steps in the value chain can be linked to each other differently, uniform system boundaries were developed to allow for a structured and comparable analysis of the findings. By doing this, the findings can be considered independently of the value chain configuration. According to this distinction, technology captures the pyrolysis plant and the periphery for biomass processing and feed process. This reflects that the operation of the pyrolysis plant is regarded as the key activity. As described in the Chapter 2, biochar as a NET consists of different technological parts. First, via pyrolysis biomass is converted into biochar, syngas and bio-oil. Second, by applying the biochar to the soil carbon is sequestered and the technology fulfils the function of CDR. The flow of goods that go beyond the supply at the location and the processing are part of the infrastructural dimension as depicted in Figure 7.

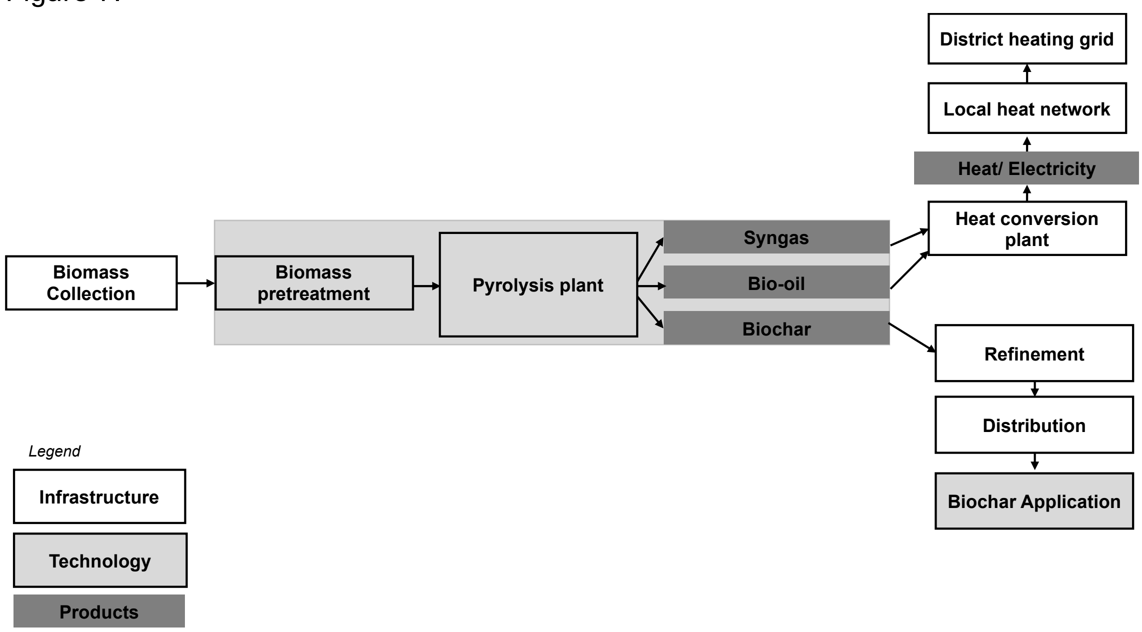

Figure 7: System boundaries (own figure)

Identify value chain configurations and actors

To answer the first research question RQ1 (*What are potential regional biochar value chains and what is the associated network of actors?)* and "to identify who holds a stake in the phenomenon under investigation" the data from the focus group was used an entry point for the identification of relevant actors along the value chain (Reed et al., 2009, p. 1937). The stakeholder analysis was iteratively extended by incorporating expert opinions from the project, the semi-structured interviews and the included snowballing process (Reed et al., 2009). The interviews were analyzed to gain an in-depth understanding of potential value chain configurations and the network of actors. The findings are elaborated on in Section 4.1.

Identify drivers and barriers

The main aim is to identify drivers and barriers that influence the production and usage of biochar. Drivers and barriers are constituted by the same factors. This means that dependent on the design and development of the factors they either form drivers or barriers. In this paper, the underlying factors are identified and classified from the context as drivers or barriers. Factors that are described as positively affecting biochar development but not yet in place are described as potential drivers.
As the aim of analysis is the investigation of socio-technical factors affecting biochar development, the investigation of economic factors, such as market dynamics and economic circumstances, is not the focus of this thesis.

4 Results

This chapter presents the findings from the research methods presented in Chapter 3. First, the identified value chains and relevant actors are elaborated on (RQ1). In Section 4.2 the identified drivers and barriers of regional biochar concepts (RQ2) based on the analysis of the focus group and interview data are provided. A summary of the identified factors, that affect biochar development and can either pose a driver or a barrier (as described in Section 3.2), is provided at the end of this chapter (see Table 16).

4.1 Identify biochar value chain and actor configurations

This section outlines the findings to answer RQ1 (*What are potential regional biochar value chains and what is the associated network of actors?*). The aim is to investigate potential biochar value chains from the actor's perspective and to uncover the relevant actors along the value chain. For this, the empirical findings on the biochar value chain, elaborated on in Chapter 2.2, are presented. The participants of the focus groups, as well as their statements, revealed relevant stakeholder groups and actor configurations. Moreover, interviewees were asked to describe a sustainable biochar concept to uncover potential value chains and associated actors. They were asked about the most relevant actors according to their views. Through this, participants' insights on potential value chains and involved actors were uncovered and will be elaborated on in the following. Figure 8 provides an extended representation of the value chain, presented in Chapter 2, based on the empirical findings. It depicts which actors can be involved in which step of the value chain. A detailed explanation of this will follow, structured along the steps of the biochar value chain.

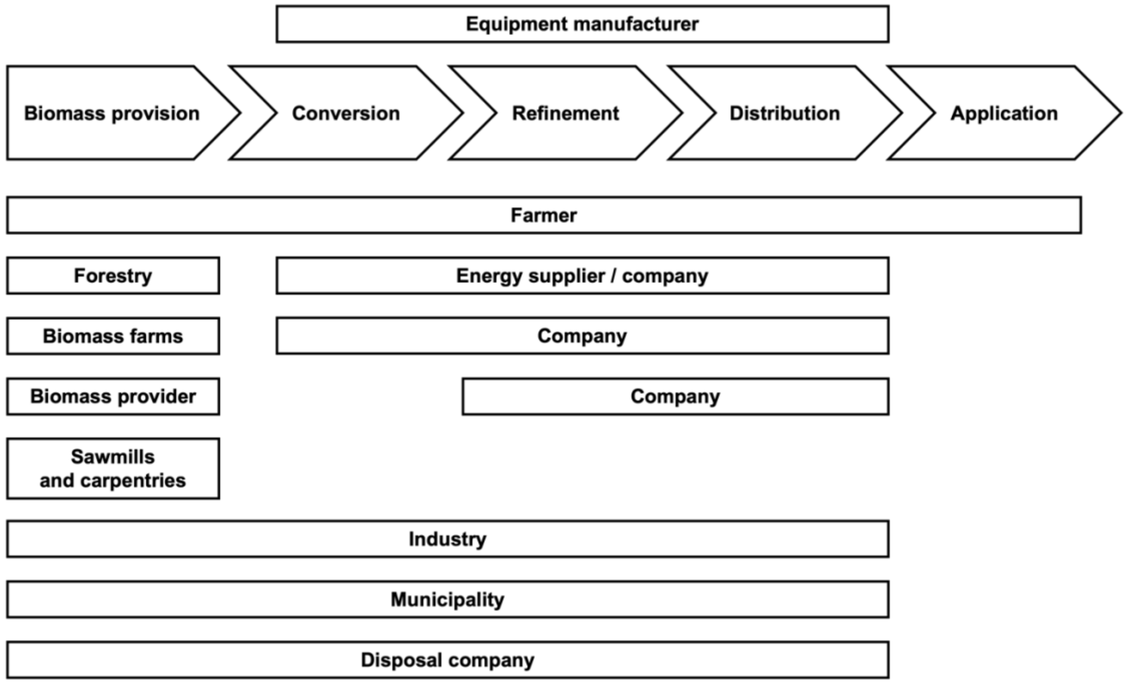

Figure 8: Identified value chain and actor configurations (own figure)

There are various potential biochar value chains and associated actor configurations. In a decentralized on-farm system, the farmer produces biochar with his agricultural residues on a small scale and applies the biochar after post-treatments on his fields (FG 15, 24, 27, 54; B3, 9; B7, 10-11). Hence, one actor takes over the role of biomass provision, pre-treatment, conversion, refinement and application. Besides the on-farm production, there are more distributed value chains with various actors working together and fulfilling different functions in the value chain. For example, one biochar-producing company described their value chain as follows: first, there is biomass purchasing, followed by the production of biochar and energy conversion to electricity and green heat, followed by the sale of the different products (B13, 4). In this case, the steps of biomass provision, conversion and application are fulfilled by different actor groups. Hence, the actors either fulfil only one step of the value chain or several to all. The identified options are described in more detail next.

Identified actors for biomass provision

For the first step, the biomass provision, various potential actors were identified and are depicted in Figure 11. Municipalities and cities with green waste or green waste providers are potential biomass providers (B1, 18; B4, 45). Besides that, the agricultural sector can act as the biomass provider (FG 54, 65, 81, 99; B1, 31; B2, 49; B3, 9). One participant mentioned the regional availability of various actors with surplus agricultural residues as a driver (B2.1, 2). This is in line with the statements of other respondents that farmers are viable biomass providers due to their access to agricultural residues (B1, 31; B2.1, 2; B10, 39). Another participant emphasized the role of the agricultural sector and stated that it is vital to involve the agricultural sector in value creation, as biomass providers and as biochar consumers (B2, 49). Further, forestry was mentioned as a potential biomass provider (FG 81, B1, 19; B2.1, 13). Another example was given by the interviewed disposal company, which collects waste from the city, green cuttings, and bio-household waste and uses these residues as well as screen overflows from its composting plants for biochar production (B4, 45). Moreover, industrial players, such as food manufacturers, can provide residues for biochar production (FG 81, B3, 21; B8, 19; B10, 7; B11, 9). The wood processing industry, for example, sawmills and carpentries, was highlighted as a potential actor for biomass provision (B1, 18; B2, 58-59). Furthermore, woodchip suppliers and biomass providers who sell, for example, landscape management material, were mentioned as existing biomass providers (B1, 25; B10, 20). This is in line with the statement of the contracting company that described the existence of potential suppliers as beneficial (B10, 35). Moreover, biomass farms are a relevant agent for biomass provision by fulfilling the function of collecting and sorting accruing resources (B12, 18).

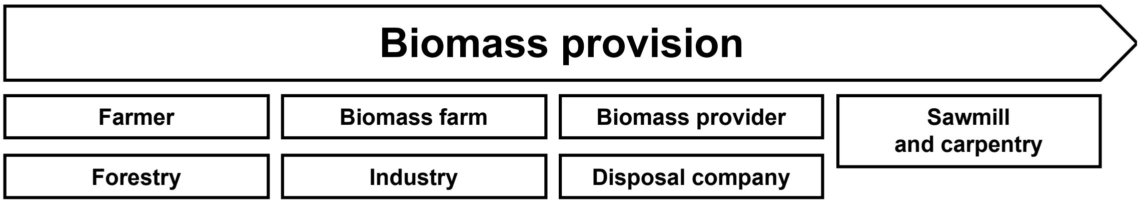

Figure 9: Identified actors for biomass provision (own figure)

Configurations for biomass provision and conversion

Different value chain and actor configurations were identified for biomass provision and conversion steps. Either the biochar producer uses its own residues, hence the biomass provider is the same actor as the biochar producer (B2, 58-59; B3, 9, 21; B6, 62-63; B8, 27) or the biochar producer purchases biomass to convert it to biochar (B1, 26; B2, 58-59; B6, 62-63; B13, 4). Moreover, one company that produces biochar supplements the company's own residues from the horse farm with external biomass (B2, 58-59), thus one actor simultaneously functions as the biomass provider and the operator but also purchases biomass (B2, 58-59; B6, 62-63). Another example where the biomass supplier is the biochar producer is the on-farm biochar production (B3, 9; B8, 27). In addition, one farmer mentioned the partnership with a processing plant to convert root biomass into chopped wood to achieve technological requirements for the conversion to biochar (FG 85). In this case, there is an intermediary actor for the biomass pre-treatment.

Another potential concept that was described is that farmers are integrated into a medium-scale biochar system, providing the biomass and jointly operating a pyrolysis plant (B2, 54-55). Besides that, one participant described a concept where the agricultural sector takes on the role of the biomass provider and applies the biochar, but another actor produces the biochar (B2, 49). Next, the uncovered actor groups for biomass conversion will be presented in detail.

Identified actors for biomass conversion

For the fulfilment of the step of biomass conversion, in other words, the operation of the pyrolysis plants, the following potential actor groups were identified (see Figure 10). Agriculture and horticulture are potential biomass providers and operators due to their access to residual materials and suitable locations (FG 214; B8, 24-25). Regarding the agricultural sector, it was acknowledged that this also comprises the vinicultural sector (B8, 24-25) and that joint operation by an agricultural cooperative is an option (FG 214). Moreover, municipalities (B1, 20; B5, 50; B11, 35) and disposal companies (B3, 15-16; B4, 45) are potential pyrolysis operators. Local energy companies and industrial players were pointed out as actors for biochar production due to their investment capacity (B1, 20; B5, 50; B10, 15-16). Especially the industry, more specifically food manufacturers, are seen as a driving agent for biomass conversion as they can function as a biomass provider, producer and energy consumer (FG 69, 102; B1, 20; B8, 16; B11, 8-9; B12, 30).

However, it was mentioned that there currently is a lack of biochar producers (B2, 41; B11, 11) to increase supply and reduce prices. More specifically, there is a lack of local producers with good and consistent quality to enable regional biochar procurement (B11, 11). This was underlined by another respondent mentioning the lack of actors turning biochar into a business model with high biochar provision (B2, 21). Nevertheless, one respondent mentioned the positive development of biochar production as a driving factor (B11, 11).

Linked to the step of pyrolysis operation, there is the equipment manufacturer, which plans, develops, and constructs pyrolysis plants (FG 27, 29). The existence of various equipment manufacturers enables biochar production (B1, 7; 11-14; B12, 40). However, regarding this, for the implementation of a plant one company stated that the provision of technical service was a critical decision aspect distance and most equipment manufacturer could not provide a quickly available service due to the distance (B4, 13). In one case, the equipment manufacturer also operates a pyrolysis plant (B8, 2).

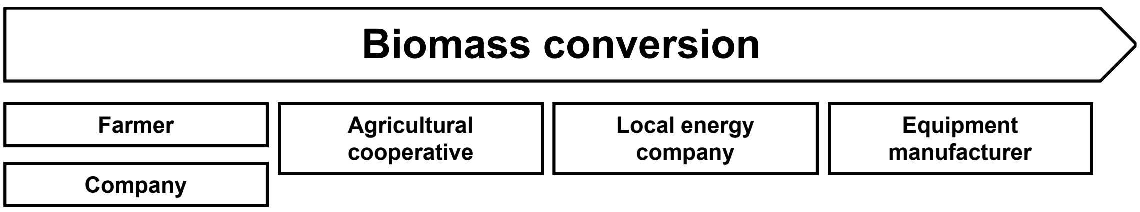

Figure 10: Identified actors for biomass conversion (own figure)

Configuration of biochar production and energy usage

Due to the co-generation of energetic by-products, there is a need for an energy consumer (B1, 10; B10, 35). In the first place, the respondents described concepts where the same actor fulfilled biochar production and energy usage (FG 56; B1, 20, B3, 21; B8, 19; B10,7; B11, 9). This is in line with the contracting company's statement that there is a need for actors with a heat demand as potential biochar producers (B10, 14, 35). Besides, there are configurations where the biochar producer cooperates with another actor or actor group for energy usage (B1, 20; B13, 19). Further, a combination of both concepts is possible. This means that the producer partially uses the generated energy and sells the excess energy to another actor (B2, 51).

Identified actors for energy usage

Several potential actor groups for energy usage were described, either only functioning as energy consumers or simultaneously as biochar producers. It is emphasized among different actors that industrial players, more specifically food manufacturers, have a constant heat demand throughout the year and hence are enabling actors for biochar production and energy consumption (FG 69, B1, 20; B3, 21; B10, 7, 10; B8, 17-19; B11, 7, 9; B12, 30, 33-34). One respondent explained that the combined operation of a pyrolysis plant and a biogas plant is a viable option due to the required heat demand for the biogas plant (B8, 24-25). However, other respondents stated that farmers lack heat demand for a viable operation of a pyrolysis plant (B10, 39). Regarding this, an agricultural cooperative is an option for energy utilization (FG 214). Another option is that the farmer that produces biochar feeds into the heat grid or cooperates with an energy consumer, such as a local energy supplier (B1, 31; B13, 19). Moreover, cooperation with direct purchasers is a possibility (B13, 19).
One respondent stated that the reliability of energy usage depends on the actor group. Hence feeding into the local heating network of the municipality is beneficiary due to their long-term existence. Simultaneously, industrial actors are seen as less stable energy consumers in the long-term due to higher uncertainty regarding their existence. However, the respondent also reports on long-term industrial actors that can provide a long-term energy consumption (B1, 12, 20). The identified actor groups for the heat consumption are depicted in Figure 11.

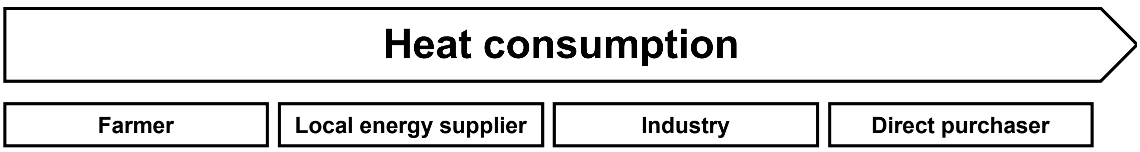

Figure 11: Identified actors for energy use (own figure)

Configuration for refinement and distribution

Different options could be identified for the steps after the biochar production, namely refinement and distribution (see Figure 12). The first option is that the biochar producer refines the biochar and either applies it or distributes it, as represented in path 1 in Figure 12 (FG 24; B2, 37; B4, 51; B7, 10-11; B8, 27). The next option is that the biochar producer sells the unrefined biochar to a company or actor who refines and trades (FG 15; B2, 37, B4, 51-52; B7, 10-11). For example, a viable concept is for a refining and trading company to take on the task of marketing, rather than the operator of a single plant taking on the task of marketing (FG 12; B1, 27). This option is depicted in path 2 in Figure 12. One respondent described that companies for the distribution of biochar according to the end-consumer requirements either refine the biochar or sell the unrefined biochar (B4, 51). In the latter case, the applicant takes over the role of refinement if needed (B4, 51) (see path 3, Figure 12).

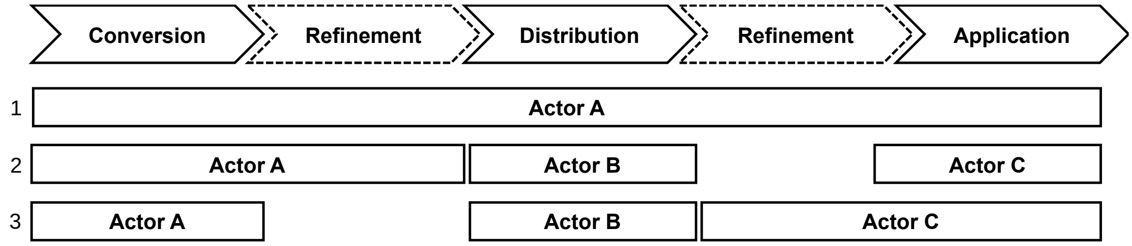

Figure 12: Actor configuration for biomass conversion, refinement and distribution (own figure)

Identified actors for refinement and distribution

The following actor groups were uncovered for the described value configurations regarding the steps after pyrolysis (see Figure 13). As mentioned, the farmer can fulfil the role of refinement (FG 24; B7, 10-11) and distribution (B7, 10-11). Besides the on-farm biochar production for his purpose, he purchases biochar and produces biochar-based composts (B7, 10-11). One respondent describes two projects currently being implemented, each of which involves a farm producing biochar, which uses the biochar for its own application and partially sells it (B8, 27). Besides, two respondents described the concept where a farmer produces biochar and cooperates with a company for biochar refinement and trade as a viable option (B1, 32-33; B2.1, 6). For example, one biochar seller, a platform, produces biochar-based products and sells these (FG 12; B1, 32-33; B11, 4). General, existing sales platforms were mentioned as a possibility for biochar distribution (B8, 29). Another example was given, where an agricultural company engaging in agricultural consulting purchases, refines and sells biochar (FG 15).
The disposal company, that produces biochar, refines the biochar combined with the production of composts, but also sells unrefined biochar (B4, 51-52). General, horticulture and agriculture can produce or purchase biochar to produce composts and soils (B8, 17). Another viable option which one participant mentioned is that the equipment manufacturer takes over the distribution (B4, 51-52; B5, 26). Agricultural wholesale was mentioned as a viable distribution channel, especially when long-term customer relationships already exist (B11, 50). Often different options are combined as for example a biochar producer partially sells large quantities of unrefined biochar to a refiner or trader as well as refined biochar-based products to smaller end consumers such as private people (B4, 51-52). Further, one biochar-producing company, which fulfils the role of equipment manufacturing and operation, described that they sell the produced biochar completely to a start-up that refines and sale biochar, respectively biochar-based products (B8, 11). Generally, some established start-ups were mentioned that provide biochar trading platforms (B2, 39-40).

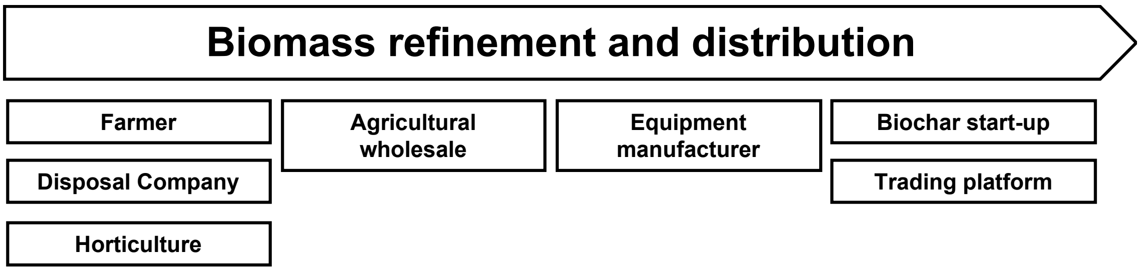

Figure 13: Identified actors for refinement and distribution (own figure)

Last, there is the end-consumer or buyer of biochar (B1, 14; B13, 2), which is relevant for increasing demand and boosting biochar (B13, 2). Different potential end-user groups were mentioned, such as private individuals (B2, 27; B7, 19), farmers (B2, 49), and state actors (B4, 56), such as palace and garden operators (B7, 19). These buyer groups vary according to the purchased quantity from small to large quantities, which also depend on the product purchased and the application quantities (B4, 51-52, 56; B7, 19). Moreover, horticulture is mentioned as a customer (B2, 27; B3, 9). However, in line with the focus of the thesis, only the agricultural sector is regarded as the end-user. Regarding this, some farmers either apply the self-produced biochar or purchase biochar for application (B2, 49).

Actor constellations and distance

Regarding the various identified value chain configurations, the interviewed emphasized the need for and the potential of decentral biochar production, with low distances between biomass provision, biochar production and heat usage, as this affects the performance of the biochar system (FG 63; 65; 164; B1, 6, 16; B2, 49-50; B3, 10, 41; B5, 8; B10, 7; B11, 48). For example, one participant explicitly mentioned that the biochar producer must be close to an actor group that functions as the energy consumer (B1, 14-17). Another example is the mentioned need to align biochar production and refinement in terms of location (B11, 48). These aspects will be elaborated in more detail in the Section 4.2 within the respective category.

Additional actors

Moreover, the respondents described additional actors of relevance and actor related needs regarding the fulfilment of specific functions. Relevant actor groups are actors for quality assurance, certification, and accreditation (B4, 41; B6, 10; B12, 42). For example, the Carbon Standards International is a service company for certification and auditing according to the EBC guidelines (FG 17). Moreover, there is a company that implements carbon certification and tracking of biochar and, by this contributes to biochar development (FG 17, 18, 135, 199, 203; B1, 44-45). This is in line with the statement that platforms and official providers for carbon crediting enable a trusted and validated carbon certification and trading process (B2, 37-39). Furthermore, a standards committee is responsible for the definition and standardization of biochar (FG 10, 29, 203).

Biochar networks, such as the *Fachverband Pflanzenkohle*[18] *(*FVPK*)*, the EBI and research institutes, were mentioned as relevant for biochar development (FG 9-10, 17, 29). They, for example establish and improve biochar certification and by this contribute to sustainable biochar production and usage (FG 29). Regarding this, the EBI represents and supports the biochar industry (FG 17). In-depth insights on networking and cooperation is presented in Section 4.2.2.

[18] The *Fachverband Pflanzenkohle* is a professional association, founded in 2017, with the purpose of supporting a sustainable biochar development. Further information can be obtained via their website https://fachverbandpflanzenkohle.org.

Moreover, governmental and authority bodies were mentioned as relevant stakeholder groups for biochar development (B2, 63; B4.1, 21; B4, 30; B7, 59; B11, 35). One respondent pointed out the need for actors to quantify ecosystem services and turn this into a business, in other words, to market the ecosystem services provided by biochar (B2, 61). Moreover, consulting bodies can play a role in biochar development (FG 17). One respondent mentioned the relevance and need for investors to boost biochar development (B7, 23). Scientific actors and research institutes contribute to biochar development (FG 1, 9, 29) by improving research and scientific evidence on biochar technology and its impacts (FG 224). At the same time, practitioners and the cooperation of both actor groups are essential (FG 29, 169). Consumers of agricultural products and, more generally, society are also seen as important stakeholder groups (B3, 5, 60; B7, 92). Figure 14 depicts the identified stakeholder groups for biochar development.

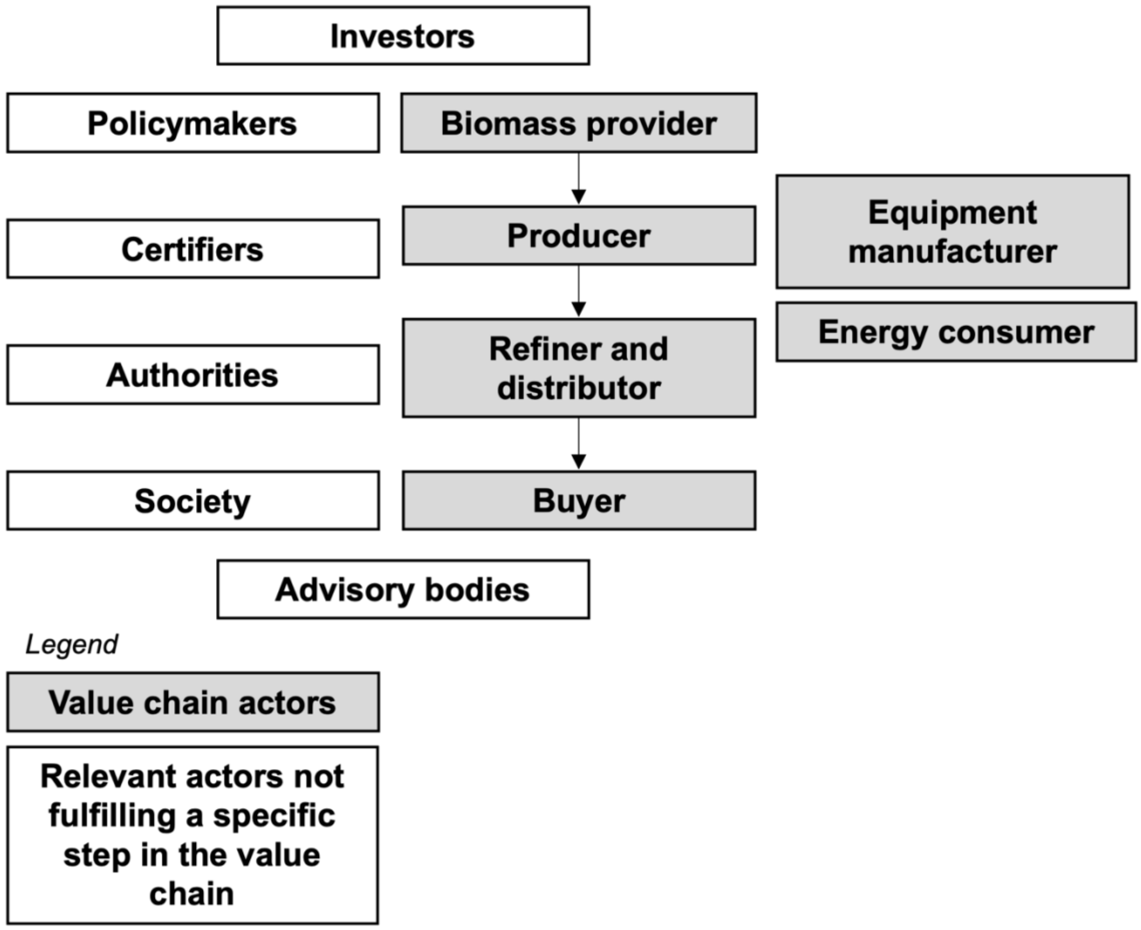

Figure 14: Biochar stakeholder (own figure)

4.2 Identify potential drivers and barriers

This chapter provides the empirical findings relevant for RQ2 as outlined in the Section 1.1. The findings from the focus group provided an empirical entry into the analysis and are represented with a specific focus on drivers and barriers related to the STS dimensions. These results are supplemented by in-depth findings obtained from the interviews. The developed STS categories developed according to the methodological approach (see Chapter 3) provide the structure for this chapter. Table 8 presents the inductively derived coding structure on which the analysis is based. The coding guidelines are provided in Appendix D. Examples from the coded interview statements are used to illustrate the results.

Table 8: Deductive main categories and inductively developed sub-categories

Main categories	Inductively developed subcategories
People	People and their function
	Cooperation and interaction
	Communication and knowledge dissemination
Goals	-
Culture	-
Technology	Biomass pre-treatment and suitability
	Pyrolysis
	Application
	Knowledge
Infrastructure	Biomass provision and logistics
	Heat utilisation
	Biochar distribution or procurement
Institutions and procedures	Regulation and certification
	Carbon crediting
	Funding

4.2.1 Goals

This category depicts the driving motivation and purpose to engage with biochar. This includes the highest valued advantages of the actors involved in biochar implementation.

Findings from the focus group

Different goals and motivational factors could be identified within the focus group. There are actor groups, especially representative from science, supporting biochar as a NET for climate protection (FG 1, 9, 27, 17, 29) and emphasizing the need for sustainable biochar production and use (FG 17, 29). In contrast, soil benefits and nutrient management are critical in the agricultural sector and therefore the driving force to apply biochar instead of its climate mitigation potential (FG 3, 27, 183-184, 203). The application of biochar is motivated by the aims of efficient nutrient management, the potential cascading usage and humus formation (FG 3, 5, 14). For example, the main motivation for one farmer to apply biochar is improved soil fertility (FG 203). Further, improved animal health und slurry management are driving advantages (FG 5, 9). For one participant, the motivation to produce biochar on farm was partially economically driven as procurement of biochar is too expensive (FG 54). The farmer added that the economic advantage of biochar application is an indirect effect of the reduction of fungicides and fertilizers (FG 207). Further, humus formation, productivity increase or other options for economic gains are of relevance (FG 198). This is in line with the statement that the motivation for farmers to apply biochar must exceed the goal of carbon sequestration due to lacking economic rewards for CDR (FG 198).

Findings from the interviews

The interviewees were asked to describe about their motivation for biochar engagement in order to investigate the pursued goals along various actors. Further, they were asked which role carbon sequestration plays. For this main category, no sub-categories were developed.

Various motivational factors for engaging with biochar could be identified among the actors, such as climate change mitigation, environmental co-benefits, economic incentives, and others. Many respondents emphasized its climate mitigation potential (B1, 2; B3, 2, 30; B8, 6; B9, 22; B11, 2; B12, 15; B13, 2, 13). This is accompanied by the acknowledgment of the need for negative emission technologies (B1, 2; B8, 6), as this recently enables biochar to become more prominent (B8, 6). This is consistent with a farmer who indicated that carbon sequestration will become more important for him in the future (B5, 5-6). Further, it was mentioned that the decarbonization potential, especially in comparison to alternative technologies such as composting, was the major driver to engage with biochar (B4, 7; B12, 15).

> "Before, we only recently started to look more closely at this whole climate protection issue in Europe and Germany. The production of biochar is one of the net zero technologies and is suitable for permanently removing carbon from the carbon cycle."[19] (B8, 6)

For actors pursuing the goal of carbon sequestration, carbon crediting might be of high relevance, this is elaborated on in Section 4.2.6. For the agricultural sector, carbon sequestration is not a guiding incentive due to the lack of financial reward for this service (B7, 6; B13, 9). Not only the carbon sequestration potential is seen as a benefit, but the associated co-benefits in terms of the positive environmental impact (B3, 2, 30; B13, 13). Soil improvements and productivity increases are of major importance (B3, 19, 30; B7, 63; B9,10; B13, 13). One farmer mentioned that the improvement of soil fertility without increased fertilization is in line with the overall goals of the agricultural sector (B9, 10). Co-benefits of biochar, such as nutrient recycling and water holding capacity were mentioned (B3, 2; B12, 40; B5, 50). However, these incentives are linked to regional differences depending on the regional soil conditions (B3, 19, 26; B12, 40). Hence, in regions with degraded soils, farmers are more likely to adopt biochar to improve soil properties (B3, 19, 26). Biochar is also seen as one instrument to address negative climate impacts such as water stress (B4, 9; B8, 24; B13, 13). One farmer considered biochar also as a measure to contribute to producing healthy food (B7, 63). Moreover, biochar contributes to humus formation (B9, 22). Besides the various goals related to soil health, the costs of biochar hamper the application (B4, 49; B5, 36; B6, 66; B11, 42; B13, 12-13).

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[19] Translated with deepl.com, for original quote see Appendix (B8,6)

In addition, the goals of efficient resource management (B3, 12; B4, 5-7, 9) and circular economy (B3, 12; B12, 2-3, 15) promote the commitment to biochar, this is strengthened by the existence of unused residues (B2, 2-3; B4, 5-7). Furthermore, the option for cascading usage and related benefits are seen as a driver (B3, 26; B8, 6). For example, biochar can contribute to slurry optimization and reduce odor emissions when first applied to the feeding (B3, 26; B9, 19, 22). One participant elaborated on regional problems that might be addressed by biochar production and usage, as this enables the regional exchange of organic materials and nutrient recycling (B3, 12).
The combination of different advantages such as carbon sequestration and soil improvements is seen as a major chance (B3, 19, 30; B13, 13). One participant highlighted that the sole carbon sequestration is insufficient (B3, 19), hence pointing out the importance of the potential co-benefits (B3, 19, 50).

> “All the more reason to think about how I can stop climate change by sequestering CO_2 and doing it in a sensible way that optimizes the ecosystem performance of the soil.“[20] (B3, 50)

Moreover, other pursued goals were mentioned. For example, according to one respondent, the production of heat and electricity drives biochar production (B2, 50). Regarding energy production, biochar can contribute to independence, in other words, to self-sufficient energy provision (B8, 18). Furthermore, regional value creation, business diversification and general economic reasons were brought up (B2, 2-3; B4, 5-7; B10, 5; B11, 2; B12, 15; B13, 2).
One farmer stated that carbon sequestration is not a sufficient motivation from an economic perspective, rather he considers biochar application as a long-term investment in the future environment and in future generations (B7, 6).

> "So now, when I look at my agricultural profession from an economic point of view, I find it difficult to calculate the use of biochar positively. But if I now also take it into account as a family man, I want to pass on soils that should actually be better, as I took them over at the time, then the carbon sink is of course a different story."[21] (B7, 6)

This is in line with various statements that mentioned an idealistic motivation to engage with biochar (B6, 69; B10, 5; B11, 21; B13, 2). One participant also described that the on-farm production supports the production of high-quality biochar due to the incentive provided by the application to the own fields (B7, 50). For farmers (environmental) benefits do not outweigh the costs (B11, 21; B12, 66). Besides the various environmental benefits, such as improved animal welfare and reduced veterinary costs, economic incentives are missing (B7, 6; B12, 66; B11, 21). Further, according to one interviewee, economic incentives determine biochar production by larger companies or municipal actors and hamper biochar quality (B7, 50). Table 9[22] provides a summary of the identified and described goals.

[20] Translated with deepl.com, for original quote see Appendix (B3, 50)
[21] Translated with deepl.com, for original quote see Appendix (B7, 6)
[22] For the extended table with the references from the transcripts see Appendix E (Table XII and Table XIII).

Table 9: Empirically identified goals

Goals
• Climate change mitigation (FG[23], I[24])
• Soil benefits (FG, I)
• Environmental co-benefits (FG, I)
• Resource management (I)
• Energy provision (I)
• Economic goals (FG, I)
• Idealistic motivation (FG, I)

4.2.2 People

In the following, the actor-related aspects that influence biochar adoption are described. This category depicts statements on the social interactions between people (potentially) involved in biochar development.

Findings from the focus group

The focus group revealed the relevance of communication to spread information on biochar technology and increase awareness, in general, and more specifically in the agricultural sector (FG 48, 221). Symposiums, events, and group dates allow for the dissemination of information and improve communication among potentially interested people (FG 221-222). Moreover, networking with relevant actor groups enables joint goal setting and negotiation and supports biochar development (FG 29, 223). Associations such as the FVPK are enabling actors for communication, knowledge dissemination and exchange along different actor groups (FG 9-10, 17, 29, 109-110, 121, 221, 224).
The linking of research and practice actors is important (FG 121, 169, 224, 226). The focus group revealed that actors from different associations and organizations cooperate and jointly engage in the topic of biochar (FG 9-10, 17, 121). For example, the EBI, Carbon Standards International, and the FVPK collaborate for a widespread sustainable biochar deployment (FG 9-10, 17, 29, 121).
The contribution of discussion on biochar technology, its chances, and hurdles was brought up several times (FG 109-110, 117, 109-110). For example, ongoing discussions on carbon sinks, specifically biochar as a carbon sink, affect biochar development and enable change and progress (FG 109-110, 117). Another example is the discussion on permitted input materials, specifically sewage sludge (FG 109-110). Several times the relevance of various associations facilitating knowledge dissemination and exchange was mentioned (FG 9-10, 17, 109-110, 121).

[23] FG marks the findings from the analysis of the focus group (=FG) data.
[24] I marks the findings from the analysis of the interview (=I) data.

However, the complexity of the biochar topic makes communication difficult and at the same time, requires precisely for this reason communication to increase understanding (FG 48). It was pointed out that there is a need to disseminate the current level of knowledge (FG 117). In general, there is a lack of science-based education on carbon sinks, specifically on biochar as a carbon sink (FG 48, 121). Moreover, communication faces barriers as specific actor groups lack openness and understanding (FG 210-211).

Findings from the interviews

In the following, people-related drivers and barriers that could be identified in the interviews are described. Two subcategories could be established based on the findings: 'cooperation and organization' and 'communication and knowledge dissemination'.

Cooperation and organization

'Cooperation and organization' depicts all statements on existing cooperation, options for cooperation and associated challenges as well as on the organization of actors for biochar production and usage, for example, the joint biochar production by a cooperative. The ongoing development of cooperation along the value chain enables biochar production. For example, waste management companies capable of biomass coordination and provision collaborate with farms that operate the plant and apply biochar (B8, 46). Another example is the cooperation of a farmer who produces biochar and energy, the latter being sold to a heating cooperative (B8, 46). In general, the cooperation of a biochar producing actor next to an industrial company as a heat consumer is a viable option (B8, 46). Established cooperation with biomass suppliers were mentioned as an enabling aspect (B13, 18-19). The organization and coordination at the municipal level is seen as the starting point for cooperation between relevant actors for the organization of biomass flows and investment (B7, 38-39; B11, 35). For example, municipalities can act as biomass collectors and coordinators and enable cooperation with farmers as the end-users (B11, 35).

> "But it is also a state task somewhere, you can't (...) so it certainly makes sense for farmers to get together and run a pyrolysis plant as a cooperative, but I think ultimately it makes more sense to somehow look at how I can coordinate biomass flows at communal level, at local level."[25] (B11, 35)

Also, regarding heat usage, the (joint) organization at the municipal level is seen as beneficial (B7, 23; 38-39; B11, 35). One respondent stated that cooperation will be fostered with an increased number of implemented plants (B11, 35). The need for organization might also be addressed by new companies (B11, 35).
Further, the joint operation of the pyrolysis plant was mentioned as a driver, as investment and risk are shared (B3, 42; 66; B6, 76; B7, 23, 67-68). For example, an agricultural cooperative was referred to as beneficial for organization and implementation of biochar production and use (B2, 61; B3, 42; B11, 35; B7, 67). Moreover, a machinery ring was mentioned as a promising organizational model to address the topic of energy usage and supply security (B2, 61). In Switzerland, for example, there is a machinery

[25] Translated with deepl.com, for original quote see Appendix (B11, 35)

ring where farmers collect biomass via heckling places, jointly manage and sort the material flows, and operate a pyrolysis plant (B7, 67). Farmers' associations and machinery rings were mentioned as good contact points for marketing biochar or for bringing biochar into agriculture (B7, 68). Associations, such as the FVPK or the EBI, bring the required actors together and foster cooperation among potential actors in the value chain (B1, 35; B12, 42). Furthermore, trading platforms connect biochar producers and end-users and by this contribute to biochar development (B2, 29-30; B12, 36).
It was also pointed out that different options for organization exist and that the choice depends on the individual situation, especially tax and legal aspects should be considered (B8, 46). To sum up, cooperation and joint organization were often mentioned as important and enabling aspects for biochar production (B3, 73, B7, 67-68; B11, 35; B12, 43-44).

However, also hindering aspects regarding cooperation and organization along the value chain were identified. Besides, the need for cooperation and jointly advancing biochar development competition might hinder joint progress (B12, 44-45). Further, coordination and organization involve high administrative expenses. For example, to set up a heat usage concept, one challenge is to enroll the required participants (B7, 38-39). One farmer also described the lack of opportunities for viable cooperation, as besides his willingness to cooperate no option for cooperation with a biochar producer exists (B7, 17). Moreover, a lack of actor groups initiating coordination and organization for biochar production and usage was indicated (B11, 35).

Communication and knowledge dissemination

In this section, aspects regarding communication and knowledge dissemination are described. This includes, for example, statements on communication within networks and seminars as one means for information exchange, as well as barriers regarding communication. Further, this entails the processes of disseminating knowledge, especially the dissemination of scientific findings on biochar.

The importance of communication and exchange and different means of communication were described. In general, the relevance of knowledge dissemination and information was emphasized (B6 69-70; B8, 51; B11, 56) to increase awareness and understanding (B8, 51). For example, one respondent described that the increased public and political dissemination of the relevance of negative emissions contributes to biochar development (B2, 29).
An established knowledge platform, different associations and networks, and the EBI enable communication and knowledge dissemination (B1, 35). For example, the FVPK provides a platform for communication and exchange (B10, 29). More specifically, exchange with actors and feedback based on this platform were mentioned as drivers for biochar project development (B10, 29). Further, one interviewee said that biochar as a product needs explanation, so communication can support biochar application (B11, 50; B13, 28). One biochar producing company described that its application consultants advise potential customers at the farm or at events and fairs (B11, 52). Moreover, practitioners and, more specifically, farmers can contribute by sharing their practical experience and motivating other actors to engage with biochar (B9, 38). Another

enabling agent for biochar communication are advisory groups (B11, 54). Hence, the support of biochar development via communication is enabled by motivated actors who engage in increasing information on biochar (B8, 52). Symposia and talks are one opportunity for exchange, knowledge transfer, and to create increasing interest (B2, 20; B7, 45-47; B8, 52). The following communication media were also mentioned as levers: television reports, newspaper articles and trade publications (B2.1, 2; B8, 52).
Further, during the planning, approval and implementation process, communication with key stakeholders, such as the authorities, can be beneficial (B4.1, 3). This is in line with one participant who stated that communication with involved actors (e.g., equipment manufacturers) helped to address organizational barriers (B10, 27). Hence, communication with the relevant actors contributes to the implementation of regional biochar concepts. Moreover, integrating the topic into education in the agricultural sector enables biochar development by increasing awareness in younger farmer generations (B11, 55). Another respondent mentioned the communication with the agricultural sector as a potential driver for more sustainable development of the sector, for example through the widespread use of biochar (B6, 69-71).

> "So, agriculture is not opposed to sustainability if we simply talk to it more and don't come up with blanket bans. Education is important."[26] (B6, 69)

Besides the potential of communication and knowledge dissemination, various associated barriers could be identified. Knowledge dissemination and information on the topic of negative emissions as well as on biochar, the chances and hurdles are still lacking (B11, 38, B13, 28; B9, 43-45) to foster progress and increase awareness (B11, 38; B13, 28). Another essential aspect is communicating the relevance of cascading usage (B7, 33). Regarding this, one participant mentioned that the sensibilization of disposal companies for biomass handling and pyrolysis is necessary (B1, 59).
However, information events and exchange have limited potential to increase biochar deployment as it is necessary to gain practical experience with biochar (B7, 45-47). Due to the complexity of the topic, information is needed (B1, 36). In line with this, processes and information must be presented simply to communicate them (B3, 30, 65).
Moreover, there is a need to establish a platform for information exchange on processes such as compliance with regulations or funding (B10, 29). One farmer also indicated lacking exchange with other actors (B5, 31-32). The farmer also criticized the lack of support in approval and funding procedures and the difficulty to gather relevant information (B5, 38). A summary of the identified people-related drivers and barriers is presented in Table 10[27].

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[26] Translated with deepl.com, for original quote see Appendix (B6, 69)
[27] For the extended table with the references from the transcripts see Appendix E (Table XIV and Table XV).

Table 10: Empirically identified people-related drivers and barriers

Drivers	Barriers
• Communication among the various stakeholder groups (FG[28], I[29]) • Cooperation through networks, associations and platforms (FG, I) • Symposiums, events, television reports, newspaper, trade publications (FG, I)	• Insufficient communication and information (FG, I) • Difficult communication due to complexity of biochar topic (FG, I) • Limited potential of communication due to need for practical experience (I) • Time effort for information gathering, need for platforms to enable information gathering (I)
• Education in the agricultural sector (I)	• Administrative and organizational effort for collaboration (I) • Lacking options for cooperation (I)
• P: Different options and ongoing development for coordination and cooperation (I)	• Competition hampers joint progress (I)

4.2.3 Culture

Culture depicts the attitude and values that affect biochar implementation. This category entails drivers and barriers regarding people's values, beliefs, perceptions, and attitudes. This also captures the fit with the existing social and cultural system (e.g. with farm management and working practices).

Findings based on the focus group

The following cultural drivers were identified within the focus group. One farmer explained his willingness to change the cultural system of the agricultural sector, specifically for his farm, towards a circular system (FG 190-191). Another biochar applying farmer stated that he relies on hope and plans for the long-term out of a sense of self-motivation (FG 209). Thus, he decided to use biochar despite leasing his land (FG 209). Further, the appreciation of biochar benefits in the direct marketing of food was mentioned as a potential driver (FG 193). One respondent elaborated on the practical experience gained with the application of biochar, which confirmed a positive environmental impact and hence fosters biochar engagement (FG 27).

Simultaneously, the following cultural aspects hindering biochar development were uncovered. Uncertainty, caution and a conservative attitude affect the perception of

[28] FG marks the findings from the analysis of the focus group (=FG) data.
[29] I marks the findings from the analysis of the interview (=I) data.

biochar as a carbon sink (FG 117). One respondent elaborated on this by stating that reservation hinders biochar deployment. For example, sewage sludge pyrolysis is not allowed due to this (FG 107-108). Further, in the agricultural sector, the existing cultural system is driven by productivity rather than soil benefits. This is accompanied by sticking to traditional and conservative practices (FG 190-191). Changing this cultural system is a long-term process (FG 190-191). Moreover, the leasing of agricultural land influences biochar application as the lack of secure long-term land use can prevent biochar application (FG 207, 209).

Findings based on interviews

Within the interviews, the cultural aspects were investigated either directly by, for example, asking about the acceptance of biochar or indirectly within other statements of the experts. Several cultural drivers could be identified, such as increased awareness and the agricultural system, which will be elaborated on in the following.
General societal change, reflected in increased end-user awareness of sustainability and product quality (B2.1 16; B3, 59; B7, 94; B8, 6, 29), and societal will to act were cited as facilitating factors for the use of biochar as a NET (B2.1 16; B3, 66). There is an increased acknowledgment of the necessity for carbon sequestration, especially by political actors (B2, 29; B2.1, 15; B3, 30; B8, 6). This is accompanied by a raised interest in the topic biochar. Politics, scientists and local actor groups increasingly recognize its positive impacts (B2, 15, 29; B3, 30; B4, 49; B8, 29, 50-51; B12, 56-57). Further, it was mentioned that certain actors undergo a cultural change from the general aversion and lack of openness to interest in biochar (B11, 54). One participant described that in his case, authorities contributed to the implementation process through the way they handled decision-making and their positive attitude toward biochar (B4.1, 21).
Regarding the agricultural sector, the high degree of mechanization in agriculture enables biochar production as farmers can deal with technological machinery (B8, 25). Further, farmers are familiar with handling agricultural wastes (B8, 25). Generally, the farming system affects the likeliness of dealing with biochar (B7, 45; B9, 39; B11, 22, 58). For example, the agricultural system determines the financial and time possibilities for biochar deployment (B7, 45; B9, 3; B11, 22). Hence, for example, viniculture allows for biochar adoption due to the higher value addition (B9, 3). Moreover, agriculture with special crops is characterized by longer term planning security, thus supporting the investment into biochar (B11, 22). Moreover, farmers focusing on sustainable food production, farm management, and soil health might foster biochar implementation (B9, 2-4; 39). Another respondent reported on the general openness for sustainable development in the agricultural sector (B6, 69).
Another aspect that affects the likeliness to implement biochar is the level of suffering, which is determined by regional soil properties (B7, 35). Farmers in regions with degraded soils might therefore be more likely to deal with technologies such as biochar, in other words, they show a higher likelihood to act (B7, 35). Moreover, younger generations of farmers show higher openness to biochar due to the integration of this topic into the curriculum (B11, 55).

Simultaneously, several cultural aspects hinder biochar implementation. Contrary to the stated increased interest in biochar and its strengthened relevance, various interviewed reported a lack of awareness of biochar and NETs (B2, 22; B3, 34; 55; B10, 43-44; B11, 37-38; B13, 28).

> “It is in fact the case that many people have simply not yet dealt with the issue - neither with biochar nor with negative emissions - also because the issue simply does not yet play a significant role in the public sphere. “[30] (B11, 37)

This is supported by the statement that awareness and interest are bounded to specific actor groups and not given in general (B3, 27). This aspect is strengthened by narrow mindedness (B3, 35). For example, farmer associations, focusing on other challenges, lack openness for biochar technology (B3, 34). Further, it was mentioned that the actors involved in legislation and enforcement play a relevant role that can be either enabling or hindering (B4.1, 21; B4, 30), according to the participant especially young and inexperienced employees hinder pyrolysis implementation (B4.1, 21). Moreover, public servants and authorities show a hindering attitude towards biochar, which harms approval procedures (B2.1, 15). According to one interviewee, the above mentioned increased political will is accompanied by a hindering lack of action (B2, 7, 63).
Further, a false understanding and perception of relevant topics as carbon sequestration and sustainable agriculture hamper biochar deployment (B2, 24; B6, 69; B11, 37). Regarding acceptance, negative perceptions might be driven by a lack of information (B10, 43; B11, 56). There is a lack of understanding, imagination and sensibility regarding biochar and the underlying processes (B3, 52) and related topics as waste and resource management (B1, 59; B7, 51). One respondent stated that Germany's centralized waste management system hinders biochar production as waste streams are bound to established and centralized structures (B7, 70). Moreover, the need to work with biochar and gain practical experience in order to understand and recognize the potential of biochar was pointed out (B7, 47; B12, 62).
Furthermore, values that drive trade and purchase decisions affect biochar development. Besides the mentioned positive societal change, end-consumers neglect good quality, lack environmental awareness, and recently show reluctance to buy (B2, 25; B7, 94). One interviewee mentioned that retail neglects environmental aspects and solely aims to optimize economic efficiency (B2, 29), hindering biochar adoption.
Looking at the agricultural sector, the perceived relevance of carbon sequestration is low in the agricultural sector (B7, 85-86; B9, 2-4). With a low level of suffering and relatively good soil properties, the likeliness to adopt biochar is low (B7, 34). Further, focus on short-term decisions due to high uncertainty in the agricultural sector hampers biochar adoption (B6, 67). This is accompanied by a lack of long-term planning due to given company structures (B10, 48). Moreover, as mentioned above, the farming system affects the likeliness to adopt biochar. Leased land, for example, decreases motivation for biochar investment due to a lack of long-term security (B11, 22). Depending on the farming system, lack of time and capital resources hinder biochar deployment (B4, 49; B9, 2-4; B11, 22). According to one interviewee, biochar is not an option for arable farming, the dominant agricultural system in Germany, due to lacking financial capacities (B11, 22). One interviewee stated that farmers show a low willingness to cooperate and hence impede joint operation of a pyrolysis plant (B7, 34). Generally, among certain actor

[30] Translated with deepl.com, for original quote see Appendix (B11, 37)

groups, the lacking willingness for cooperation and exchange hinders biochar deployment (B2, 24).

The risk attitude of actor groups affects biochar production and use and might hinder farmers from biochar engagement (B5, 50; B7, 23; 35; B10, 17-18; 47). This is accompanied by mistrust in politics and political funding (B7, 23). Table 11[31] summarizes the findings.

Table 11: Empirically identified cultural drivers and barriers

Drivers	Barriers
• Societal change and increased awareness of NETs and biochar (I[32]) • Appreciation of environment and biochar benefits (FG[33]) • Idealism (FG)	• Lack of awareness (I) • Reservation, caution, conservative attitude (FG) • Lack of appreciation and reward of environmental benefits (I) • Insufficient understanding and negative perceptions on biochar (I)
• Agricultural system: mechanization, experience with residues, long-term planning, ecological orientation (I) • Willingness to change the agricultural system (FG) • Ecological oriented agricultural systems (I)	• Agricultural system: short term decisions, low level of suffering, leased land (FG, I)
• Practical experience with biochar (FG)	• Focus on economic efficiency and productivity (I)
• Openness for biochar engagement e.g. along younger farmers (I) • High level of suffering increases likeliness for biochar adoptions (I)	• Low willingness to cooperate (I)
• Increased political will (I)	• Risk aversity (I)
	• Mistrust in politics (I) • Hindering attitude of authorities (I)

[31] For the extended table with the references from the transcripts see Appendix E (Table XVI and Table XVII).

[32] I marks the findings from the analysis of the interview (=I) data.

[33] FG marks the findings from the analysis of the focus group (=FG) data.

4.2.4 Technology

The category 'technology' depicts all technological aspects of biochar, including statements on the pyrolysis plant and the conversion process. Further, application-related drivers and barriers are depicted here as the application constitutes biochar technology as a NET as described in Section 2.1.

Findings based on focus group

There was consensus among the participants that the availability of pyrolysis technologies and technological development foster biochar development (FG 43, 49, 51, 54). The required technological progress was not seen as a problem but as inherently occurring within the technology development path (FG 49, 51). One advantage related to small scale pyrolysis plants is simplicity (FG 27). Depending on the feedstock, pre-treatment processes might be required. The technological feasibility of these pre-treatment processes is seen as a driver (FG 85, 89, 91-93).

However, the high labor demand for small scale systems hinders its implementation (FG 72). The costs of pyrolysis plants as well as the available sizes, are blocking aspects (FG 213). Hence, the economic viability of the pyrolysis plant depends on the income revenue or usage of excess energy, as well as on the biochar price (FG 164). There is a need to gain experience with other feedstocks as pyrolysis plants in Germany are optimized for converting woody residues (FG 70). Other needs for technological development that were mentioned are increased flexibility regarding the input material and mixing of various feedstocks to address seasonality (FG 102). In general, there is a need to adapt the feedstocks and the conversion process by mixing different inputs (FG 91-93). Moreover, the need to commercialize pyrolysis plants was mentioned (FG 27, 49).

Findings based on interviews

To identify technical barriers and drivers, the respondents were first asked in general terms about technological drivers and barriers. In detail, the stakeholders were asked, for example, about problems with the commissioning and operation of the pyrolysis plants or decisive aspects for the choice of technology. Moreover, relevant actor groups were asked about application-related aspects. Regarding the technology, the participants' statements include different pyrolysis technologies, from small scale on farm plants with relatively low throughput to more commercial plants. The following technological subcategories could be identified: 'biomass pre-treatment and suitability', 'pyrolysis', 'application' and ‘knowledge’ and will be presented in the following.

Biomass pre-treatment and suitability

First, within the category ‘biomass pre-treatment and suitability’, statements on the technological feedstock requirements, linked pre-treatment processes and the suitability of feedstocks for pyrolysis are described.

The technological feasibility of the required pre-treatment processes of different inputs and the technological suitability of certain feedstocks constitute a chance (B2, 11-13; B8, 8; B11, 68). Furthermore, the increasing progress with the pelletization of different materials enables the pyrolysis of various inputs (B10, 20).

> "And with technology, I think we're in an easier place to say we can become successful in such and such a way, or we can get a handle on all the problems we have at the moment with pyrolysis with certain raw materials. There are materials that can do that."[34] (B11, Pos. 68)

Wood chips, for example, fulfil the technical requirements for pyrolysis (B6, 65; B10, 20). Further, for example, existing equipment and established processes for biomass pre-treatment, given in waste management companies, enable biochar production. Thus, specific operator models entail potential synergies for biomass pre-treatment (B4, 25-26).

However, several interviewed mentioned biomass suitability for pyrolysis as a critical aspect (B4, 15-17; B2, 11-13, B10, 7; 20). The pyrolysis technology requires certain biomass characteristics or qualities, such as a specific dry matter content (B4, 17; B2, 11-13; B4,17; B10, 20, 25) or grain size (B4, 13-15; B5, 14) which might either exclude certain input materials or require pre-treatment processes (B4, 17) such as pelletizing (B5, 14), crushing (B4, 17, 25-26) or drying (B4, 17). Further, legal requirements lead to the need for pre-treatment of certain biomass (B4, 17). For this, additional equipment is needed (B4, 25-26).

> "(...) because for a functioning pyrolysis process there is a demand profile, which the feed material must fulfil so that it functions. (…) they are defined by the pyrolysis technique. The process is a technical process. (...) The technical process needs a so-called dry substance content in a relatively narrow corridor of around eighty percent."[35] (B2, 13)

These pre-treatment processes might hinder the economic efficiency as well as the ecological performance of the biochar system (B2, 13; B5, 14). Moreover, the current state of pyrolysis technology does not allow for much flexibility regarding the input materials, hence production with changing or heterogeneous biomass is limited (B1, 31; B4,15-17).

> "You have to make sure that the input material is as homogeneous as possible, and the difficulty is that both green waste and biowaste are not homogeneous, because everything grows differently and has to be processed accordingly."[36] (B4, 15)

The operator must ensure the continuous supply of qualitative feedstocks and, more specifically, prevent the pyrolysis of interfering substances (B8, 54). In addition, one participant reported that the technical feed of the material into the pile restricts the use of certain inputs and limits the performance of existing plants (B4, 13-15). Therefore, technological development is needed to increase flexibility regarding the convertible feedstocks, specifically to enable pyrolysis of various, heterogenous, and mixed feedstocks (B5, 14; B11, 30). For example, using straw as an input requires technological development (B11, 30). In general, there are technical hurdles for the conversion of

[34] Translated with deepl.com, for original quote see Appendix (B11, 86)
[35] Translated with deepl.com, for original quote see Appendix (B2, 13)
[36] Translated with deepl.com, for original quote see Appendix (B4, 15)

various feedstocks as the focus has been relatively narrow on woody residues (B11, 61). Adjusting the feedstock and conversion process requires time and experience (B2, 15-16, 47; B11, 61).

Pyrolysis

The second subcategory, ‘pyrolysis,’ captures all statements about the pyrolysis plant and the operation of the plant. It entails aspects such as the availability of technology, technological development, and technology costs.
The respondents described different aspects that affect the choice and viability of the plant size. First, the economic efficiency is a relevant factor (B12, 8; B13,11). It is partially affected by the required certification process, the effort required for these limits the economic viability of small plants (B13, 7). For the economic efficiency of the plant the highest possible utilization is necessary, which requires a certain throughput of biomass (B2, 17-18; B2.1, 2; B12, 8). Simultaneously the potential for regional biomass provision affects the choice of plant size (B2.1, 2; B4, 13; B12, 8, 16; B13, 7).

Most respondents agree that the level of technological development of pyrolysis plants enables biochar deployment with an increasing trend (B1, 7-9; B3, 29; 54; B4, 19-22, 471; B10, 25; B11, 39, 60-61, B13, 11). There is a fostering competition between the plant manufacturers, and accordingly, different plant options exist (B10, 25). One participant underlined this by saying that the plants are technologically at a sound stage of development, which will become even better in the future and that the plants also tend to become cheaper (B1, 7-9).
Well-functioning technologies help to produce uniform biochar products and thus enable biochar deployment (B4, 55). Pyrolysis plants have low place requirements and can be placed anywhere as containers (B2.1, 9; B8, 56). Regarding small scale systems, lower material costs and no maintenance costs are drivers for implementation (B7, 29). Further, the simple operation of these small scale systems, in other words, the simplicity of biochar production, was mentioned as an enabling and important aspect (B7, 29). Also, for medium scale systems, the simple operation is seen as a potential driver (B6, 61). One respondent mentioned that the commissioning and operation of the pile have not shown any hurdles (B4, 19-22). For medium to large biochar systems, fully automated plant operation with remote monitoring is important from the operator’s point of view (B4, 54; B5, 16). According to one interviewee, ease of use is seen to become a driver in the future (B3, 30-32).
In addition, the following statements on technological advantages were mentioned by single respondents. The plant's economic viability is enabled by product diversification with biochar-based products (B4, 55). Moreover, mobile plants might be an option for specific niche situations where an alternative option is missing (B1, 69).

Besides the general agreement on positive technological development, there are still very failure-prone plants (B10, 25; B11, 60). Moreover, the lack of suitable technologies is mentioned as a barrier (B5, 12; B7, 80). For example, for one respondent operator, only one equipment manufacturer was offering a suitable plant size (B5, 12). The costs of the technology hinder implementation, thus cost improvements are necessary (B2.1,

6; B7, 21; B13, 11). One respondent underlined this by reporting on the cost disadvantage compared to other systems, such as woodchip plants (B7, 80).
Moreover, the high maintenance effort of pyrolysis plants was mentioned (B10, 25). Further, the complexity of the technology or, more specifically, the pyrolysis process is a hindering aspect. For example, the need for re-firing after a standstill hampers ecological performance as well as automatic operation (B10, 25). Further, if the process is controlled incorrectly, the quality of the biochar can be negatively affected, such as the production of biochar with a high polycyclic aromatic hydrocarbon (PAH) content (B3, 30-32; B10, 25; B12, 32, 59). Hence, the need for adjustment, design and control of the process parameters is seen as a barrier (B3, 30-32; B10, 25; B12, 32, 59). Further, the time and labor demand for the operation of the plant as well as the need for technological knowledge, were mentioned (B7, 48; B8, 54)

Application

Biochar only becomes a carbon sink through the end application, in the case investigated within this thesis, the end application in agricultural soils. In this section, the important aspects regarding the application are presented.
Different viable options for the loading and application of biochar were described in the interviews. For the loading and the application of biochar, different options exist that are easily implementable, especially within agricultural processes (B6, 33-34, 36; B7, 51). For example, mixing with fertilizer, such as compost (B9, 14; B12, 6, 14), is an easy way of application because the biochar can be brought to the field with the usual spreading techniques (B3, 34; B9, 14; B11, 42). Biochar can be pelletized and spread with the fertilizer, thus the simplicity of the biochar as a NET and its application is seen as a driver (B3, 34).
Further, the application as a manure additive is seen as an opportunity (B3, 34, 66; B9, 2). Other options are the mixture into the litter as a viable and easily implementable option (B6, 12; 29-32; 36) and the usage of biochar in the composting process (B12, 6). Generally, the options for cascading usage are seen as a chance of biochar deployment (B3, 26, 66; B7, 33). For example, biochar can be applied with animal feeding and, by this, becomes part of the slurry (B6; 29-32; B7, 33; B9, 19). One farmer reports that the admixture to pig and chicken feed works well. Furthermore, the application is easy to implement for farms with feed mixer wagons (B7, 33).
This is accompanied by ongoing research and development to improve application methods (B11, 46).

Besides the existing and improved options for application, the respondents reported on different barriers regarding the application of biochar. One relevant hindering aspect for application is biochar costs (B11, 42; B13, 13). Further, the lack of technical know-how among end-users hinders biochar adoption (B12, 44; B13, 13). More specifically, the application can pose specific challenges, the right amount must be determined, and a way of application must be developed (B7, 33; B12, 44). This heterogeneity is strengthened by different options for application requiring clear procedures for application (B12, 51). Unloaded biochar not only causes difficulties in terms of application but also does not achieve good effects (B9, 19). Mechanical problems regarding the agricultural application were mentioned as hindering (B11, 42). Hence the technical possibilities of the application still need to be developed further (B11, 42, 45). For example, pelletizing biochar offers an option that improves application. On the other hand, powdered biochar is better for its function in the soil (B11, 46). Therefore, optimization of the application is necessary. Another example is mixing with cattle feed, as biochar does not mix well with hay (B7, 33).

Knowledge

Knowledge was identified as the next relevant sub-category within the technology element. This category depicts all statements on the knowledge level for biochar production and usage as well as on research progress and needs.

Findings from the focus group

Scientific findings indicate the agronomic benefits of biochar, more specifically straw biochar, and support biochar production and usage (FG 100, 101). In addition, there is ongoing research on innovative applications of biochar and potential feedstocks for conversion (FG 25, 108, 177, 181). One participating farmer elaborated on biochar benefits based on practical experience instead of scientific evidence (FG 5, 173).

However, there is a lack of knowledge and scientific evidence on specific biochar qualities and their fit for context-dependent soil conditions (FG 100). There is a need for scientific research on the environmental services of biochar (FG 100, 110, 121, 145-157), as well as on various biochar qualities, for example, regarding the dependence on the pyrolysis plants (FG 100). Other research needs are the carbon sequestration potential and sustainable application rates (FG 100, 169). There is a need for science-based certification and regulation (FG 108, 121). Research and development is needed to create standardized biochar products to facilitate distribution and application, guide policy making, and foster funding (FG 145-147, 169). In general, there is a need for applied research (FG 224, 226).

Findings from the interviews

The interviews revealed that the improved level of knowledge and ongoing research foster biochar implementation. First, the established level of knowledge is seen as an enabling aspect (B2, 41; B11, 56). For example, there are various scientific results for applying biochar with local differences (B12, 44). Moreover, ongoing research contributes to biochar development. For example, there are research projects on specific soil-biochar-fits and the potential benefits of the specific soil context (B2, 41; B3, 35; B4, 32). Another example is ongoing research to improve application options (B4, 32; B11, 46). It was mentioned that besides the heterogeneous scientific findings, the current state of knowledge supports biochar application, therefore more focus should be put on practice (B2, 41; B3, 35). In line with this, one participant mentions field trials as a potential driver for implementation (B7, 90).

The interviewees brought up various research and knowledge gaps as well as other knowledge-related barriers. Besides the established level of knowledge, some respondents mentioned the need to improve the level of knowledge (B6, 39-40; B10, 29, 42; B8, 52). Moreover, there is a need to synthesize the existing findings (B12, 51-53). For example, research is needed regarding the feedstock-biochar-soil-fit (B10, 29, 49), this also entails knowledge on the pre-treatment of input materials (B10, 29, 49). Moreover, the soil impact of biochar must be further investigated (B10, 29, 49) and heterogeneous findings on biochar applications hinder biochar deployment (B12, 44). One respondent mentioned the need for quantitative research to determine the impact, such as fertilizer saving (B7, 92). In addition, it was pointed out that biochar must be brought into practice instead of overdoing research (B7, 24-27). Moreover, the technical knowledge required to operate the plant and the possibility of serious operating errors is considered critical (B3, 30-32). Lack of knowledge regarding the complexity of the pyrolysis process and the associated potential errors can, for example, lead to the accumulation of pollutants (B12, 61; B3, 30-32). Regarding the application, there is a need to synthesize the existing findings and establish guidelines and recommendations for application (B12, 51-53). There is a need to gain practical knowledge on biochar application, for example, regarding the co-production of compost and biochar (B5, 20), and further to develop valid application options (B5, 20). The technology-related drivers and barriers that were presented are summarized in Table 12[37].

Table 12: Empirically identified technology-related drivers and barriers

Drivers	Barriers
• Technological development and availability of technologies (FG[38], I[39]) • P: Technological improvements (I)	• Lack of flexibility regarding feedstocks (FG, I) • Costly pre-treatment processes (I) • Difficulties with feed-in into pile (I) • Quality of feedstock (FG 102)
• Simplicity and low costs of small-scale plants (FG, I)	• High labour demand (FG, I)
• Technological feasibility of pre-treatment (FG, I) • Established pre-treatment structures and processes (I)	• Costs of technology (FG, I)
• Ease of use, fully automated operation (I)	• Lack of suitable plants regarding the offered size (FG)
• Easy loading and application options (I) • Progress in application options (I)	• Complexity of conversion process (I)

[37] For the extended table with the references from the transcripts see Appendix E (Table XVII and Table XIX).
[38] FG marks the findings from the analysis of the focus group (=FG) data.
[39] I marks the findings from the analysis of the interview (=I) data.

• Application in combination with other agricultural processes (I)	• Need for adjustment and experience with input-conversion-adjustment (I)
•	• Need to improve and optimized technical options for application (I)
• Established level of knowledge (FG, I) • Ongoing research (FG, I) • Practical experience (FG) • P: exact field trials (I)	• Research gaps (FG, I) • Biochar soil impacts considering local soil conditions and different biochar properties (FG) • Application rates and methods • Ecosystem services • Lack of applied research (FG, I)
	• Required technical knowledge for operation of pyrolysis plants and conversion process

4.2.5 Infrastructure

The category 'infrastructure' captures aspects associated with the techno-physical and organizational configuration of the system as described in Section 3.2. More specifically, it captures statements on biomass provision, storage, and transportation, as well as the distribution of biochar and the production and usage of by-products.

Findings from the focus group

According to this definition of infrastructure, the following enabling aspect were derived. The availability of potential feedstocks for biochar production is seen as a driver (FG 79-81). Especially biomass with no other usage is considered beneficial for thermo-chemical conversion (FG 77, 79-81, 99). Using residues with low value shows high potential for pyrolysis as these materials can be upcycled and the recycling of cost-free residues improves the price situation (FG 45, 77). Further, using materials with chargeable disposal is another possible option (FG 68). Straw, roots and moor biomass as well as biomass from the agroforestry, among others, are stated as innovative biomass sources and hence potential future drivers for biochar deployment (FG 79-81, 87, 101, 103-105). In addition, green waste, leftovers from food production and fiber residues were mentioned (FG 79-81).
Moreover, the operation of a pyrolysis plant requires a heat usage concept as energy usage partially determines the economic viability of biochar production (FG 43, 55, 217). Different options exist to realize this potential, for example, using the heat for biomass drying and heating of buildings, which improves the cost situation (FG 56, 70, 164). Pyrolysis plants with combined electricity generation enable higher prices and base-load capable energy supply (FG 70).

In contrast, wood is seen as an input material with limited potential due to the high usage competition, which leads to relatively high prices (FG 74, 99). Further, there is a lack of system solutions from the biomass provision to the usage of the heat (FG 43). This in line with a farmer's statement that mentions the lack of heat usage options for potential on-farm production (FG 62). Moreover, energy consumption varies with seasons, which puts another hurdle on the aspect of heat usage (FG 70). In addition, the seasonality of certain feedstocks requires mixing input materials to ensure a continuous input supply over the year (FG 102). Besides the viable option for energy production, a constant energy supply also requires a specific input supply (FG 102).

Findings from the interviews

The respondents were asked to describe a sustainable biochar system with the most important aspects according to their view. Further, the interviewees were asked more precisely about the integration of the pyrolysis technology into the broader system or into the value chain. According to the responses, three subcategories were identified namely 'biomass provision', 'energy utilization' and 'biochar distribution'.

Biomass provision

This category captures biomass availability, biomass logistics and transport. Biomass availability is described here, whereas the suitability of the various potential feedstock from a technical perspective are described within the technological category ('biomass treatment and suitability').

The respondents described the availability of residues for biochar production from different sectors, summarized in Table 13, and the advantages of recycling wastes. For example, the high availability of residual materials from the forestry and agriculture sector is seen as an enabling factor (B2, 15-16; B2.1, 2; B3, 20-21; B7, 10; B8, 25). In forestry, much dead wood is currently rotting and could be used for pyrolysis (B2.1, 13). One operator mentioned that the regional availability of agricultural residues for pyrolysis was a critical decision point for the development of the biochar business model, which could be fulfilled (B2, 15-16). Further, industrial residues, particularly residues from food production, were brought up by the participants (B 2.1, 2; B3, 20-21). In general, wastes and residues are seen as an opportunity for biomass production (B1, 4; B2.1,2; 13; B3, 18-19; B5, 8; B10, 7), as this provides economic benefits and solves disposal problems (B2.1, 2-3; B3, 18) as biochar offers an alternative disposal solution for example to combustion (B2.1, 3, B4, 40, 61; B7, 10; B10, 7). By transforming wastes into biochar, volume can be reduced, and hence transportation is improved (B3, 18; B1, 8).

Table 13: Potential biomass sources for biochar production

Sector	Examples	Interview reference
Agricultural residues	Straw, residues from viniculture, roots	B1, 31; B7, 10; B11, 30;
Forestry	Dead wood, roots	B1, 18; B2.1, 13
Industrial residues	Cherry pits, cocoa shells, spelt husks and others	B2.1, 2; B3, 18, 20-21;
Municipal and commercial waste	Green wastes, sewage sludge, landscaping materials	B1, 4, 18; B2.1, 3; B4, 13; B3, 20-21
Secondary sources	Residues from biogas plants, wastes from composting plants	B3, 65; B4, 13; 40

Regarding feedstock collection, transportation and logistics, different viable options enabling biochar deployment were described by the participants. Using regional biomass with short transportation distance enables economically and ecologically efficient biochar systems (B1, 6, 13, 42; B2, 15-16; B3, 41; B5, 8; B8, 11; B13, 5). The regional biomass provision or purchasing facilitates logistics (B2.1, 6). The company explained that they work with their own container exchange system to collect agricultural wastes from different farmers (B2.1, 6). In addition, one respondent stated that established logistics for collecting agricultural residues contribute to biochar production (B12, 16-17). This is in line with the statement that Germany's biomass structures, such as wood logistics, are well-established and support biochar development (B10, 20, 31). Further, biomass farms, with their knowledge of biomass collection and utilization, enable the coordination of biomass flows for biochar production (B12, 13).

Besides the availability of residues for pyrolysis and established beneficiary logistic structures, the following blocking aspects were identified. The respondents reported on the sustainable provision of regional biomass as a hindering factor due to the limited availability of biomass and competition with alternative uses (B1, 23-24; B8, 37; B12, 8, B11, 23; B12, 8). The potential usage competition with alternative uses of biomass will be strengthened by an expansion of the bioeconomy (B7, 41; B12, 11), especially for pellets and wood chips (B7, 41). Regarding this, the need for biomass prioritization was mentioned to foster carbon sequestration (B3, 19; B11, 65). Due to the usage competition, it can be difficult to ensure long-term supply (B8, 37). Moreover, storage options for biomass must be developed (B1, 54; B10, 27). Raising prices of input materials were mentioned as a potential hindering aspect as this negatively affects the economic efficiency of the biochar system (B7, 41; B8, 37). Other respondents pointed out uncertainties regarding biomass availability and price development as barriers (B4, 40; B7, 41). Since the quality of the biochar is partially determined by the inputs, the possible input materials for biochar with the end use in agricultural soils are limited (B7, 41). The seasonal occurrence of some feedstocks, especially in the agricultural sector, complicates biochar logistics (B1, 31, 52). It was stated that concepts for the coordination and value addition of residual materials need to be improved (B11, 33; B12, 16-17). This is in line with the statement that there is a need to implement or improve biomass sorting plants (B1, 57-59).

Energy utilization

The second subcategory that could be identified is ‘energy utilization’. All statements on the production and usage of the generated co-products are included here. According to several respondents, the usage of the energetic by-products is of high relevance for optimizing the biochar system (B1, 4; B8, 19-21; B10, 12; 39; B11, 6; B12, 5) also regarding the economic efficiency (B2, 51; B10, 13-14). In general, it can be said that the location significantly influences the possibilities for energy use, respectively the heat use possibilities are of particular relevance when selecting a location (B13, 19; B2, 51, B3, 44; B11, 6).

> "(…) in order to achieve optimal use, it is important that no matter which conversion process is in the middle to produce biochar, that all by-products are also optimally used or the heat is reintegrated. “[40] (B12, 5)

First, the associated chances are presented. The actors described different viable options for the usage of the generated energy. First, the energy released in the conversion process can be used for internal processes (B2, 51; B4, 55; B12, 5; B13, 17-19), for example, biomass drying (B2.1, 9; B4, 55).

> "Heat can also be used as process heat or in industrial processes - both are highly dependent on the location. In addition, pre-drying of the fuel with the resulting thermal energy is usually useful. Electrical energy can either be used by the plant itself, among other things to cover the power requirements of the plant systems and thus make the system self-sufficient or sold to the grid or direct consumers."[41] (B13, 38)

There are plants on the market that already provide good possibilities for the use of the resulting energy (B7,11; B8,15). As the energy produced usually exceeds the energy demand for internal processes, such as drying, feeding into local heating networks or conversion into electricity is an additional option (B1, 10; B7, 37; B12, 27; B13, 5, 17-19). Depending on the location, using the heat as process heat or for industrial processes is an option (B8, 19-20; B11, 6). Further, heat can be used for processes that need heat in summer and other processes that need heat in winter or by storing the heat in summer and using it in winter (B12, 29). Existing or planned heat grids represent an opportunity for feed-in to heat residential buildings (B8, 19). The given energy demand (B1, 20; B3, 44; B8, 19; B10, 14; B11, 6), specifically the need for alternative decentralized energy supply, fosters biochar production (B3, 44; B8, 19, B10, 14). Pyrolysis plants can play a role in developing and improving the heating infrastructure in Germany (B1, 20; B10, 22). For example, one option is to replace old oil and gas heating systems in villages with a heating network fed by pyrolysis plants (B2, 61; B3, 44; B7, 37). Hence, a self-sufficient energy supply, the associated supply security, and independence from the public

[40] Translated with deepl.com, for original quote see (B12, 5)
[41] Translated with deepl.com, for original quote see (B13, 38)

electricity grid are driving factors for biochar deployment (B4, 55; B10, 14). Decentralized pyrolysis plants allow for redundancy in power generation and enable a more flexible energy system (B12, 29).

> "The chances are that last year was a very interesting year and people want more and more security. (...) There is a chance that people will say, I want this security, I have the raw material, it's there anyway. Exactly. Why don't I put that in and have a certain risk that I might not be perfect against market prices, but I just have the security in the supply of myself."[42] (B10, 14)

In the following the associated hurdles with the usage of the generated energy are presented. The need for a heat usage concept is seen a potential barrier by various of the interviewed (B2, 51; B10, 13-14; 35; B13, 19). Heat utilization close to biochar production can be a barrier or at least limits viable biochar production locations (B1, 16; B11, 6; B12, 27). If no heat utilization concept can be implemented, valuable energy is lost (B2.1, 9; B2 51), hence a critical aspect is the need for continuous heat sink throughout the year (B12, 21; B10, 13-14). This is challenging due to the seasonality of heat demand (B12, 23). One biochar producer faces the loss of the generated energy as there is no existing grid to feed in (B2, 51). Moreover, lacking grids or large distances between potential actors hinder the implementation of heat usage concepts (B10, 39). Regarding the heat usage options, different disadvantages vary among different potential systems. For example, low-tech smaller scale systems and mobile pyrolysis plants face a lack of heat usage options (B1, 68; B7, 11). The interviewees mentioned that the heat usage concept must be aligned with the regional biomass availability to facilitate biochar system performance (B1, 58-60). One hindrance to heat utilization concepts are the available plant sizes and financial constraints, as it not economic viable to feed a small local heating network with a few houses with the larger plant sizes (B7, 80). Hence, matching the size of the system to a heat demand is a hurdle (B7, 80; B11,7). Moreover, the coordination of energy production and usage is seen as a hurdle (B12, 29). Furthermore, the development and implementation of a heat usage concept requires time and planning capacities (B3, 52). For example, the feed in into existing grids is accompanied with organizational and planning effort (B3, 51; B4, 30; B10, 17-18). There are additional problems associated with feeding the heat into the grid. The lack of a large heating network in Germany is seen as a barrier, as this means that operators cannot simply connect to an existing network (B10, 35). In line with this, one respondent mentioned the need to build heating grids (B2, 51). Another barrier for the feeding into the local heating network is the lack of standard system for feeding into heat grids (B13, 19). Often there are no heat utilization options for potential biochar production sites because of a lack of a local heating network or a lack of feed-in requirement (B13, 19). Another challenge is the necessary security of supply (B2, 51, 61) as in the case of a reactor failure, there must be a way to still guarantee security of supply (B2, 51).
In one case there were difficulties with the delivery of the micro gas turbine to convert the energy into electricity (B4, 19-22).

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[42] Translated with deepl.com, for original quote see (B10, 14)

Biochar distribution and procurement

Within this category, all statements regarding the steps after biochar production, specifically the techno-physical and logistical aspects of biochar loading, refinement, procurement, and distribution are collected. This entails, for example, the transportation from production to the application site.
The biochar loading near the production is seen as an enabling option. For example, a nearby composting plant offers an opportunity for efficient loading with short transport distances (B7, 17; B8, 17; B12, 6). Another example is biochar production close to horticulture companies, where soils are produced (B7, 17; B8, 17). Demand and various market opportunities for biochar-based products are given (B4, 51-52; B8, 32) and contribute to biochar development. For example, producing composts or soils and selling biochar-based substrates enables the distribution (B7, 77-78; B8, 17). The potential to sell biochar supra-regional is also mentioned as enabling factor, not severely affecting the ecologic efficiency of the biochar system and allowing for more flexibility (B1, 16).

> "Exactly, and the topic of heat and the topic of where the biomass comes from, that already binds me relatively strongly to a certain location. That's why I wouldn't restrict myself too much as far as the sale of biochar carbon is concerned. I can't remember the exact figure, but we're talking about less than two per cent, which is the transport emissions of biochar over 500 kilometers in relation to the carbon sink potential of biochar."[43] (B1, 10)

One respondent mentioned growing biochar distribution structures in the future as an facilitating factor for regional biochar supply (B11, 4). Further, optimized logistics and transportation of biochar can contribute to the systems efficiency and foster regionality (B11, 48).

However, according to various interviewees, biochar distribution or procurement is seen as a barrier. The lack of concepts for biochar distribution hinders biochar production in the agricultural sector (B2, 55). Generally, large-scale market penetration is seen as a barrier for new potential producers (B7, 22). Further, large-scale wholesale distribution via wholesale is limited, as biochar is still a product in need of explanation, requiring on-farm marketing, advice and sale (B7, 22; B11, 50). Local chains for biochar distribution are not well established, so that regional procurement is limited (B11, 4). Hence, there is a need to develop structures to improve distribution (B11, 4). Another participant confirmed this by mentioning the procurement of biochar as an obstacle due to the qualities and prices offered and the regional spread of biochar production (B9, 18; B4, 11). The biochar refiner and trader described the need to align biochar production with refinement at specific locations (B11, 48). Moreover, the required optimization of the transport can pose a barrier, as it is challenging to adjust and optimize the type of packaging, volume, security and time (B11, 48). The identified drivers and barriers are presented in Table 14[44].

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[43] Translated with deepl.com, for original quote see Appendix (B1, 10)

[44] For the extended table with the references from the transcripts see Appendix E (Table XX and Table XXI).

Table 14: Empirically identified infrastructure-related drivers and barriers

Drivers	Barriers
• Feedstock availability (FG[45],I[46]) • Availability and usage of residues or feedstock with no alternative usage (FG, I) with price advantage	• Usage competition e.g. for wood and hence high prices (FG, I) • Limited feedstock availability (I) • Raising price for input materials (I) • Uncertainty regarding input availability and price development (I) • Seasonality of feedstocks (FG, I)
• Established feedstock logistics and viable options for feedstock logistics (I)	• Need to improve and develop biomass logistics concepts (I)
• Heat production and options for heat usage (FG, I) • Energy demand (I) • Need to improve the energy system (I) • Decentral energy production for independent energy supply (I)	• Lack of heat usage concepts (FG, I) • Seasonality of heat demand (I) • Time, planning and organizational effort to set up a heat usage concept (I) • Lacking options for feed-in into existing grids (I) • Need for equipment for heat conversion (I) • Lack of grid infrastructure (I)
• Low transport distances for biomass and heat (FG, I) • Loading of biochar next to production (I)	• Alignment of feedstock input and energy demand (FG)
• Growing distribution structures (I) • Flexibility regarding the distance for biochar distribution (I) • Market opportunities for biochar distribution (I) • Optimized distribution logistics (I)	• Lack of local chains and distribution structures (I) • Optimization of distribution logistics (I)

4.2.6 Institutions and procedures

In this category, aspects that guide the production or use of biochar are collected. A procedure is a way of doing something, such as the methodology for quantifying carbon

[45] FG marks the findings from the analysis of the focus group (=FG) data.
[46] I marks the findings from the analysis of the interview (=I) data.

sequestration. Moreover, formal institutions are rules that determine how to do something and are also captured here.

Findings based on the focus group

Certification of biochar enables the sustainable production and usage of biochar as well as the acknowledgement of its positive impact (FG 17-18, 47, 82-83). The EBC, the mature certification system for biochar-based products and pyrolysis plants, will drive biochar deployment in the future (FG 52, 118). In general, there is an ongoing further development of the definition and standardization of biochar (FG 10-11).
Moreover, carbon crediting is seen as a potential driver for biochar adoption (FG 17-18, 47, 155, 215). There are voluntary approaches for the quantification and certification of biochar as a carbon sink for example, the sale of climate neutral products (FG 17-18, 47, 203). The existence of the voluntary certification system can support the development of the legal framework. The EU-regulation, for example, is based on the EBC system (FG, 77). One respondent stated that for the REACH ordinance, there are clear determined procedures, thus the implementation should not pose a barrier (FG 131-135). Besides that, ongoing regulative change is seen as a driver. For example, the amendment of the German fertilizer ordinance, which is less restrictive regarding the input materials, improves the cost situation (FG 75; 82-83). Furthermore, application-based funding could help boost biochar deployment (FG 148-153).

On the contrary, biochar certification requires effort (FG 63). Further, there is legal uncertainty and a lack of uniform regulation (FG 110, 127-129, 143, 144, 163) as there are regional differences and various relevant laws (FG 125, 143). For example, different options exist to legally classify a pyrolysis plant (FG 127-129). The legal situation increases the complexity and costs of planning and approval procedures (FG 163). Moreover, some policies and regulations restrict and misguide biochar production (FG, 74, 77, 110). Examples are the restriction of input materials for example, the ban on sewage sludge (FG 74), and the lack of regulatory pollutant specification (FG 77).
Regarding carbon crediting, the certification is voluntary and no legal regulation is in place, this is accompanied by uncertainty regarding the development of the CDR market and associated uncertainties regarding the allocation of roles in carbon crediting (FG 155, 215). There is a need to improve the quantification of biochar as a carbon sink and to further develop the carbon sink certification system (FG 118, 120-121). Moreover, there is a lack of funding for ecosystem services provided by biochar (FG 145-147, 148-153).

Findings based on the interviews

Three subcategories were identified with the main category ‘institutions and procedures’ based on the interview findings. ‘Regulation and certification’, ‘carbon crediting and quantification of ecosystem services’ and ‘funding’ constitute the decisive institutions and procedures for biochar systems. The first identified subcategory is ‘regulation and certification’ and will be described below.

Regulation and certification

Certification determines how biochar is used and applied such as the EBC certification for biochar as a product as well as for the pyrolysis plant. Regulations prescribe how biochar can be produced, traded and applied, for example, such as the German Fertilizer Ordinance.

Regarding regulation and certification, only a few drivers were mentioned, such as the chances associated with certification and regulative changes that foster biochar adoption. Certification is seen as a decisive aspect as it enables biochar quality and risk reduction and improves market opportunities (B4.1, 3; B8, 8; B12, 41-44). The existing EBC certification system contains different biochar qualities with varying requirements and contributes to biochar development (B8, 8). Moreover, the amendment of the Fertilizer Ordinance allows more input materials for pyrolysis and fosters broader biochar production feedstocks (B1, 42).

The respondents described various barriers associated with biochar regulation and certification, such as overregulation, bureaucratic effort, regulatory heterogeneity, and uncertainty. The EBC certification involves extensive requirements and is therefore associated with effort (B4.1, 22-25; B8, 32). This is in line with the statement that high effort for certification hinders the economic viability of smaller scale plants (B13, 7). Generally, overregulation is seen as a major barrier in Germany (B2.1, 15, B2, 7, B2 55-57; B7, 55).

One participant mentioned that the transposition of EU-regulations into national law also hinders biochar production. In contrast, other EU members contribute to biochar development by enabling the transposition of these regulations, which facilitate trade and production of biochar (B2, 44). The regulatory requirements are defined via various laws, regulations and certification systems. The complex regulatory landscape confronts and hinders regional, decentralized biochar production (B12, 56). Furthermore, in addition to international and national requirements, local legislation might restrict or prevent biochar production and use (B12, 56). Moreover, discrepancies between the European Directive and the implementation by the German Fertilizer Ordinance impede sales options, lead to uncertainty and hinder biochar development (B2, 45; B4.1, 9; B4, 41-43).

Regarding the input materials, restrictive regulations impede biochar production (B2, 45; B8, 6; B11, 30). Especially for biochar with end-use in soils, there are regulatory restrictions on the permitted input substances (B8, 6). In the past, only wood was allowed as a feedstock for biochar production (B2, 45; B8, 6; B11, 30, 58). Besides the amendment of the German Fertilizer Ordinance, pyrolysis of sewage sludge, for example, is still prohibited (B1, 40). Hence, the respondent mentioned the need to align the policies and regulations with scientific findings (B1, 40). Generally, regulatory uncertainty hinders biochar implementation (B4, 11, B10, 31; B13, 23).

The required approvals for biochar projects were mentioned as a barrier (B2, 47, 55-57; B4, 30; B7, 55; B8, 32; B10, 31; B13, 15) as they are associated with high bureaucratic effort and the risk of rejection due to minor mistakes (B2, 45; B7, 55; B10, 31; B12; 56).

> "Regulatory hurdles are, I would say, some of the biggest hurdles in project development itself. Then, of course, project planning is also affected, depending on the location, certain approval issues have to be clarified and, of course, building permits, but also emission protection permits. Then you have this certification issue

> for the biochar and of course also for the issue of carbon removal credits, which has to be addressed."[47] (B8, 32)

Further, the need for quality assurance of the biochar is important (B12, 51, 59).

Carbon crediting and quantification of ecosystem services

The second subcategory, 'carbon crediting and quantification of ecosystem services', depicts all statements on carbon crediting, such as the certification and trading procedures and statements on quantifying and monetizing the ecosystem services biochar provides. Regulations related to carbon sequestration are captured here.

Various driving aspects regarding the quantification of ecosystem services, specifically regarding carbon crediting, were identified. General, carbon removal credits for biochar are seen as a driver for biochar production and use by various of the interviewed (B2, 29; B2.1, 16; B3, 23; B7, 76; B8, 43-44; B11, 15-17; B13, 9). Since with carbon certification for biochar the ecological benefit of biochar is valued, the economic viability of biochar systems is improved (B2, 29; B3, 75; B4, 57-59; B11, 23; B10, 29; B8, 43-44, B13, 9). Carbon certification is, if implemented correctly, a chance to pay the farmers for the climate service or, more generally, for additional income generation (B3, 18; B4, 57-59; B7, 83-84). This is seen as a chance for larger farms (B7, 83-84). Carbon certificates are a political instrument to set the right incentives and to finance biochar implementation (B3, 49). Examples of viable options for voluntary carbon certification were given (B7, 67).

The existence of a mature certification system, the EBC system, for carbon sequestration of biochar in the voluntary market is an enabling factor (B1, 44-45). This system offers a viable methodology for and tracking of carbon sequestration and facilitates biochar carbon crediting (B1, 42-44; B2, 28-29). One participant explained that trading non-flammable biochar-based products, such as biochar-containing soils, enables the creation of a valid carbon sink (B2, 37-39). Future incorporation into the stately regulated carbon market is a potential driver (B1, 47). However, one respondent stated that carbon crediting in the voluntary market is seen as an advantage due to the faster feasibility (B1, 50-52). One of the interviewees mentioned that a state obligation for CO_2 neutrality could boost biochar implementation and hence might act as a driver in the future (B12, 49).

Moreover, it was stated that the high prices in the carbon markets represent the high demand and indicate a positive development regarding CDR. The demand for CDR projects fosters biochar projects (B8, 43-44). In addition, positive development in the carbon markets regarding harmonization and methodology are expected:

> "At the moment, each marketplace uses its own methodology to measure the value of the carbon removal credits and what the requirements are, and I can imagine that there will be a lot of changes worldwide. "[48] (B8, 43-44).

Besides the potential provided through trading carbon removal certificates, the participants brought up various associated barriers. One of the interviewees pointed out that the existence of different approaches for the measurement and accounting of carbon

[47] Translated with deepl.com, for original quote see Appendix (B8, 32)
[48] Translated with deepl.com, for original quote see Appendix (B8, 43-44)

sinks, ranging from low-threshold to high-threshold concepts, hinders biochar implementation and, more specifically, carbon certification for biochar (B3, 27). The lack of a uniform system for the issuing of carbon certificates as well as the complexity of carbon crediting and the certification process pose barriers (B11; 15-17; B13, 26). Carbon trading concepts must be developed and improved, especially regarding their seriousness (B3, 23) and there is a need for a uniform, overarching benchmark for carbon crediting (B13, 26).

> „CO_2 certificates for plant carbon make sense - a uniform, overarching standard would be preferable. The certificates are currently not issued in a uniform way and the market and mechanism behind it is quite complicated. Barriers could exist because the certificates need to be explained and the process of obtaining them is not easy to understand."[49] (B13, 26)

It was mentioned that carbon sequestration is not a guiding incentive for farmers' application due to the lack of financial reward for this service (B7, 6; B13, 9). The carbon sequestration potential is more relevant for biochar production as companies that produce biochar have an economic incentive by producing and trading carbon certificates (B2, 28-29; B13, 9). However, this reward structure hinders application, as the farmers who create the carbon sink by applying biochar are financially not incentivized (B13, 9). Hence, an essential aspect of carbon sequestration and carbon credits is the design of the reward structure (B13, 9; B12, 54). Data protection is critical in the tracked and verified and carbon crediting chain (B1, 47-48). Moreover, some participants mentioned the need to include biochar certification in the state carbon market (B11, 15-17; B12, 49-51; B13, 26).
Carbon crediting is accompanied by bureaucratic effort (B8, 32; B7, 7-8, 83-84; B10, 29), hindering the feasibility for small scale farmers (B7, 7-8, 83-84). Regarding the quantification of the ecosystem services provided by biochar, inconsistency in and lack of data are mentioned as hindering factors (B10, 27). Uncertainties regarding the carbon certification process were mentioned as barriers (B10, 27; B11, 68). More generally, there is a need to quantify and value the ecosystem services biochar provides to support biochar development (B3, 62-63, 66). The required knowledge regarding processes such as carbon crediting and the associated need to address these issues might pose a barrier (B3, 62; B8, 43; B10, 29).

Funding

The third identified subcategory is 'funding'. The category 'funding' comprises the processes of financial support for biochar production and application, such as subsidies. The funding of biochar production and application was identified as an important topic, which can either foster or hinder biochar deployment.
Generally, funding for biochar as a NET is an instrument to set the right incentives and boost biochar implementation (B3, 49; B10, 49). The respondents elaborated on different funding options in Germany (B2, 9; B4.1, 27-29; B8, 39-40). Moreover, potential options for designing biochar funding were mentioned (B3, 56; B9, 25; B11, 28). For example, application-related funding was suggested as a potential driver for biochar application

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[49] Translated with deepl.com, for original quote see Appendix (B13, 26)

(B11, 28). Further, a possible increase in climate-relevant funding in the future might contribute to biochar development (B8, 39-41).

However, the following funding-related barriers were identified. The lack of suitable biochar funding options was mentioned and there are no biochar or bioeconomy specific funding options (B2, 9; B3, 49). Moreover, three respondents elaborated on the failure to gain funding for their biochar projects in Germany (B4.1, 27-29; B4, 32-34). One farmer, for example, failed with two different funding options and saw the required effort and know-how as a barrier (B5, 38-42).
This in line with the bureaucratic effort mentioned as a hindering aspect (B2, 9). Further, it was mentioned that existing funding options are too narrow (B4.1, 27-29). In addition, the complexity and heterogeneity of funding options is seen as a barrier, as it is difficult to get an overview (B8, 39-41). Regarding this, the lack of consultancy opportunities was criticized by a farmer (B5, 38-42).
The lack of financial incentives for biochar production and misleading incentives hinder the implementation of pyrolysis plants (B11, 26; B13, 26).

> "On the promotion side, for example, incentives are lacking due to federal funding; pyrolysis systems are in part explicitly excluded from promotion, while pure biomass combustion is implied - this sets the wrong incentives in terms of CO_2 savings and does not promote decarbonization. Moreover, these incentives make it more difficult to purchase biomass oneself, as prices on the market are rising due to increased demand. Pyrolysis technology thus becomes less competitive."[50] (B13, 26)

Moreover, the lack of funding for biochar co-benefits, such as the reduction of nitrate leaching, was criticized (B11, 26). According to one participant, ecosystem services need to be quantified to foster political funding (B3, 69). Table 15[51] summarizes the empirically identified drivers and barriers concerning ‘institutions and procedures’.

[50] Translated with deepl.com, for original quote see Appendix (B13, 26)

[51] For the extended table with the references from the transcripts see Appendix E (Table XXII and Table XXIII).

Table 15. Empirically identified institution- and procedure-related drivers and barriers

Drivers	Barriers
• Existing certification and ongoing development (FG[52], I[53])	Bureaucratic effort for • for compliance with regulation and certification (FG, I) • funding procedures (I) • carbon crediting (I)
• Voluntary carbon certification for biochar (FG, I) • Voluntary carbon crediting concepts (I) • P: Incorporation in the state carbon market (I)	• Complexity of carbon crediting (I) • Required knowledge and information on carbon crediting (I) and funding options (I)
• Regulative change and enabling legislation (FG, I)	• Approval procedures (I)
• P: Funding (FG) • Funding as a NET and other funding options (I)	• Overregulation (I) • Legal uncertainty, lack of an enabling legislative framework, legislative heterogeneity, and complexity (FG, I) • Misleading and restrictive regulation (FG, I)
• P: quantification of ecosystem services	• Uncertainty of carbon crediting and lack of incorporation of biochar into CDR market (FG, I) • Need for improving quantification method for carbon sequestration and further develop certification system (FG, I) • Heterogenous carbon accounting methodologies (I) • Inconsistency and lack of data on carbon sequestration (I)
	• Lacking funding for ecosystem services (FG, I) • Heterogeneity and complexity of funding options and procedures (I) • Lack of suitable funding options and lack of access to funding (I)

52 FG marks the findings from the analysis of the focus group (=FG) data.
53 I marks the findings from the analysis of the interview (=I) data.

Table 16: Summary of the empirically identified relevant factors

Goals	People	Culture	Technology	Infrastructure	Institutions and procedures
• Carbon sequestration • Soil benefits • Economic goals	• Communication and information exchange • Cooperation through networks, associations and platforms	• Awareness of biochar • Acknowledgement of environment and biochar benefits • Political appreciation • Practical experience with biochar • Acceptance of biochar technology • Orientation the agricultural system • Perceived relevance of NETs	• Technological development • State of application methods • Level of scientific evidence • Technical knowledge • Costs • Required feedstock quality and associated pre-treatment processes	• Decentral production and alignment of biomass provision and energy usage • Availability of feedstocks and residues • Usage competition, uncertain price development and seasonality of feedstocks • Distribution structures • Biomass logistics • Development and realization of heat usage options	• Regulative frame • (Voluntary) carbon crediting • Bureaucratic requirements • Quantification of ecosystem services • Certification

5 Discussion

In this section, the results of the interviews are theoretically discussed and interpreted. The guiding question of this thesis is to investigate drivers and barriers of biochar production and use in Germany by applying an STS approach. The discussion of the empirical findings will answer the research questions outlined in Section 1.1 taking into account the interdependencies between the system components and relating the findings to the literature. Furthermore, recommendations for action are developed based on this discussion. Finally, the research design is critically reflected upon, and limitations are elaborated on.

5.1 Biochar value chains and associated actors

Regarding RQ1 (*What are potential regional biochar value chains and what is the associated network of actors?*), various potential value chain and actor configurations are presented in Section 4.1. The identified actor configurations range from small scale biochar systems, in which the farmer fulfils all functions of the value chain, to larger scale systems, in which various actor groups fulfil the different steps. This confirms the stated variability of vertical integration (Anderson et al., 2017).
Some of the identified value chains are already in place, and some concepts that were described are not yet being implemented. The latter were described by the interviewees as they see potential in these configurations. The indicated high complexity and variability of regional biochar value chains has the potential to contribute to the adaptation of biochar systems to different contexts, which are determined by the local biomass availability, the energy demand and other factors. Thus, in a specific context, a small scale, integrated concept with a single actor might be beneficial. In contrast, cooperation among different actors that fulfil specific value chain steps might be preferable in another context. More complex constellations with various actors might include actor groups from different industries, such as farmers, energy companies and industrial actors. The indicated complexity and variability might also partially explain why the implementation is still lagging behind. Moreover, the interviews showed that the distance between potential actors influences the performance of biochar systems. Hence, if different actors fulfil the function in the value chain, the distance between these actors might affect cooperation and biochar implementation.

De Bruijn and Herder (2009) mention that in addition to the physical-technical elements, it is “important to identify and understand the parties—or ‘actors’—responsible for the design, implementation, and operationalization of that system” (p.981). The empirical research illustrated which actor groups are regarded as viable for the implementation of biochar value chains. For example, food manufacturers are beneficial as they can act as biomass provider, biochar producer and have a constant energy demand. However, besides the various identified value chain and actor configurations in case of biochar, it is also crucial to bring together the different actors and jointly develop regional production and usage concepts. Studies on the bioeconomy support this by stating the need for aligning different actor groups from different industries and for managing collaborations to foster the bioeconomy (Mertens et al., 2019; Olsson & Fallde, 2015; Palgan & McCormick, 2016). In other words, "a network of dedicated actors" is crucial for adopting innovations (Olsson & Fallde, 2015). This is supported by this empirical research as it uncovered that the potential actor groups entail different needs and potentials. Therefore, cooperation might be needed to anticipate these needs and potentials. The potential of the industry as an agent for biochar was often mentioned, but only a few examples were given where they already engage in biochar value chains. Thus, there is a need to involve them. This might indicate that a network of committed actors still needs to be further developed. Furthermore, some interviewees pointed out the willingness to engage with biochar, but they are facing a lack of possibilities to participate. Hence, the findings might imply a lack of so-called system builders, responsible for implementing and managing a system (Hughes, 1993). Intermediary actors are described as agent to bring together two or more parties and enable the establishment of relationships (De Silva et al., 2018). System builders or intermediary actors are key agents in system development by contributing with their knowledge, skills and resources to enroll the required actors and align various system components (Hughes, 1993; Lamprinopoulou et al., 2014; Palm & Fallde, 2016). For example, Palm and Fallde (2016) mention that for the Swedish energy transformation, the local energy company was crucial as it aligned the biomass provision for biogas production and the usage of the generated by-products by enrolling the associated actor groups, namely a slaughterhouse as the waste provider and the farmers as the by-product consumers. In this case, a collaboration initiated by the system builder, the local energy company, enabled the development and functioning of the system. Also, Mertens et al. (2019) report on the relevance of actors engaging to foster relationships and coordination among the dispersed actor groups. Therefore, besides the various actors with the potential to engage in biochar systems, the insufficient implementation might be explained by the lack of intermediary actors engaging in stakeholder collaboration and system development. According to Hansson (2021), for biochar technology adoption in developing countries local intermediaries are key agents by contributing with knowledge and skills, as well as by their “bridging function” (p.5197). Apart from this, biochar literature has not yet addressed the need for an actor who initiates collaboration and organization along various actors to implement and manage a biochar system and the role of intermediary actors.

The identified associations and networks could contribute to these functions but may not have the capacity to fully perform them. This is also indicated by the fact that these alliances already provide other functions, such as information exchange and advancing standardization. Therefore, local actor groups may be needed to take on this role and focus on stakeholder integration and engagement.

5.2 Drivers, barriers and recommendations for biochar implementation

The empirical research revealed several drivers and barriers for regional biochar value chains, described in Section 4.2 and summarized in Table 16. These findings are interpreted with regards to the literature review presented in Chapter 2. Furthermore, the findings are related to each other, and inferences are drawn in order to answer RQ2 (*What are the socio-technical drivers and barriers to the development of regional value chains for biochar?*). Based on the presented interpretation, recommendations for action are derived and outlined.

Technological development and exchange with technology users

The empirical research confirmed that the achieved and ongoing technological development enables biochar development. Technical aspects needing improvement are a lesser hinderance to the implementation than other non-technological factors. However, this study revealed that there are strong differences between the offered technologies. Individual challenges were mentioned, such as the lacking suitability of the available technologies to a specific context, the feed process or the lacking provision of technical service. Addressing these technological drawbacks is the responsibility of the equipment manufacturers. The identified individual challenges regarding the available technology and the perceived lacking suitability of technology to specific contexts indicate the lacking anticipation of user needs (Weber & Rohracher, 2012). Hence, equipment manufacturers must engage with potential operators to adjust technologies to user demands. For example, it is recommended to improve the technological flexibility regarding feedstocks. Furthermore, equipment manufacturers could provide information on the conversion process, address the need for technical knowledge, and reduce the risk of the pyrolysis process. Hence, in this case, the exchange between the two stakeholder groups, the equipment manufacturers and potential operators, has twofold benefits. First, technological development can be guided by user demand and thus increase the perceived suitability of the technology. Second, the need for technical knowledge as well as the complexity of the conversion, should be addressed by improved communication. Overall, it is recommended that equipment manufacturers engage with potential operators to further developing technologies and disseminate technical knowledge.

The findings confirmed that the technological system component is not on its own decisive for the success of the biochar system, especially due to established level of technological maturity. This supports the claim that other socio-cultural and socio-political related drivers and barriers affect the implementation as described in Section 2.3. These aspects will be discussed and interpreted below.

Awareness and legitimacy

The increased interest in biochar and negative emissions is still bound to specific actor groups and far from becoming mainstream. Therefore, lack of awareness is still one major hindrance to biochar development on two different levels, the missing appreciation of the need for negative emissions in society and the lack of awareness of biochar technology and its potential. Increasing the perceived relevance of negative emissions and putting forward biochar's carbon sequestration potential can contribute to biochar development. This underlines that technology development and usage is directly linked to the provided function for society as described in Section 2.3. Society further plays a significant role in bioeconomy value chain development and is seen as a potential agent for change (Bugge et al., 2019). Hence, the function for society, climate change mitigation potential, must be highlighted and communicated. In addition, the low perceived relevance of the need for negative emissions may be linked to insufficient pressures or incentives for engagement. Moreover, lacking awareness of biochar's benefits may be connected to the legitimacy required of new technology (Bergek et al., 2008; Fuenfschilling & Truffer, 2016).

Therefore, policymakers should improve information on negative emissions and specifically on biochar to stimulate society as an agent of change and provide incentives for action and legitimacy for biochar technology. This is in line with Pourhashem et al. (2019), who argue for the need of non-financial policy support, for example through programs that highlight the benefits of biochar. Regarding the general promotion of the urgent need to reduce emissions, the European Climate Law (EU 2021/1119) legally requires negative emissions by setting the target of net zero emissions by 2050. In addition, the need for negative emissions is part of Germany's coalition treaty (SPD et al., 2021). Hence, these indicate a change in the right direction, however the specification of negative emission targets and strategies is still required to further promote their relevance.

Political commitment and clear targets

According to the literature, there is a lack of political will to foster biochar development (P. M. Rogers et al., 2022). In contrast, the interviews indicated that besides raised political interest in biochar technology, political action has been missing. The lack of an enabling policy framework at a regional level reflects this. However, the novel adoption of the EU Fertilizing Product Regulation (FPR; EU 2019/1009) allows the trade and usage of EU-fertilizing products containing biochar. For regional biochar concepts in Germany, the empirical research revealed legal uncertainty, heterogeneity, and complexity as the main institutional-related barriers. For example, inconsistencies between EU-regulations, the transposition into German law, and related uncertainties were mentioned. On the one hand, this indicates regulative change as a potential driver in the future. On the other hand, this suggests the lengthiness of such change processes. Discrepancies between policies and practical implementation might explain the empirical uncovered institutional barriers. Moreover, it shows the complexity of policies on different levels.

In general, political "commitment" is needed, as also suggested by Palgan and McCormick (2016), who identified action points for the bioeconomy transition in Sweden (p.9). This is further specified as "stable, long-term, targeted policies with clear and ambitious goals" (Palgan & McCormick, 2016, p. 9) . Also, Wilde and Hermans (2021) elaborate on the lacking political commitment to the bioeconomy and a sustainable transition, which is reflected in a heterogenous regulative landscape and policy inconsistencies. It is recommended that policymakers in Germany develop a biochar policy with clear qualitative targets to promote the role and development of biochar. These goals should then also be reflected in the implementation of EU-regulations.

Moreover, it is crucial align general perceptions and policymaking with the scientific progress achieved and therefore to disseminate the current level of knowledge. Hence, communication between different actor groups, such as policymakers, science and practitioners, is essential. The interdependence of policy development and research is highlighted in the literature as there is a need for science-based policy development (Jeffery et al., 2015). The findings from the focus group and the interviews supported this perspective by showing a need to adjust regulations to the current level of knowledge. Pourhashem et al. (2019) suggest including farmers, as the end-consumers of biochar, in policy making to close knowledge gaps. By doing this, discrepancies between policymaking and practice can be addressed. To sum up, policymakers should develop specific biochar policies with clear targets based on the communication with other stakeholder groups. This political commitment should then be further reflected in regulations that guide biochar production and application.

Communication and practical experience

In general, the literature review and the empirical data agreed on communication as a relevant measure for addressing barriers, such as lacking awareness, insufficient understanding of biochar technology and misperceptions. However, the participant's insights revealed difficulties with communication on biochar technology. The complexity of the topic of biochar and the associated carbon crediting impede communication. According to Rogers (2003) the technology's complexity, and more specifically the difficulty of understanding the innovation, partially determines the rate of adoption. Besides that, the aspect of communicational barriers is neglected in the literature. It is recommended to increase and improve communication. Communication strategies must be developed that present the bigger picture and underlying mechanisms in a simple and easily understandable way. As it was found that existing networks and associations already contribute to communication and provide a focal point for information exchange, it is advised that they further develop these services. Several measures to increase communication were mentioned, such as symposia and media. Hence, communication strategies can be developed based on these measures. It is recommended that associations and networks should increase communication to boost awareness and improve understanding. It is pivotal to focus on easily understandable communication.

The analysis of the focus group and interviews supported the research gaps that were identified within the literature review but also stressed the need to incorporate biochar into practice instead of diving too deep into rather specific research. Apart from this, research and practice agree that long-term field studies are needed. The findings suggest that gaining practical experience with biochar farmers should contribute to biochar development by initiating exchange with potential farmers. All interviewed biochar appliers reported positive effects on soil and animal health. Therefore, demonstrations can contribute by making the positive impact of biochar visible and accessible. This can also partially address the fact that practical experience is necessary to internalize the benefits of biochar. Rogers (2003) supports that by the statement that observability is another innovation factor. Moreover, Geels and Raven (2006) point out the importance of other niche developments, such as local practices and projects that lead to learning processes, adjustment of expectations, and the enrolment of new actors. According to this, the visibility of the positive effects of biochar and good experience can motivate others to engage with biochar. Hence, local experimentation and exchange are essential steps to motivate and convince other actors as well as to shape pursued goals and expectations (F. W. Geels & Schot, 2007; E. M. Rogers, 2003). Based on this, it is recommended that local pioneers that are already engaging with biochar promote biochar in the agricultural sector through local learning and knowledge transfer through demonstration.

Incentives and common goals

The empirical identification of the pursued goals among the various actors confirmed that, as described in the literature, biochar systems bring different entry points due to the multiple potential benefits such as carbon sequestration, soil benefits and resource management (Sohi et al., 2015). The identified goals vary among the different actor groups. For example, farmers emphasized the benefits for soil and animal health. Whereas other actor groups, representing science or companies, put more emphasis on carbon sequestration. Identifying stakeholders' values, perceptions, and motivation is essential as these shape human action by which they either "maintain or change aspects of ST-systems" (F. W. Geels, 2004, p. 909). The various identified goals among different actor groups indicate the need establish common goals as earlier suggested by studies on innovation and transition management (Mertens et al., 2019; Palgan & McCormick, 2016). For example, it was mentioned that biochar benefits are in line with the goals of the agricultural sector, however, communication is needed to clarify and make use of this fact. However, the findings indicate that due to the multidimensional nature of biochar, it may be a challenging task to determine common objectives. Nevertheless, the simultaneous fulfilment of several aims is also possible. Moreover, Leach et al. (2012) point out that the goals of biochar carbon crediting connects different actor groups. Negotiating and setting these goals is inevitable. Within the establishment of common goals it is vital to consider possible trade-offs that Jeffery et al. (2015) describe.
Mertens et al. (2019) state that intermediaries allow for “building a common vision that can include and merge each of their various individual goals and ambitions” (p.5). This supports the before stated hypothesis that the network of biochar actors currently lacks such intermediaries. Moreover, the findings imply that different drivers and barriers are related to the achievement of different goals. For example, the goal of carbon sequestration is driven or inhibited by carbon crediting and the perceived relevance of negative emissions. In contrast, the goal of soil benefits is affected by climate change impacts and the economic reward structure. A comprehensive table on the underlying drivers and barriers for the identified goals provided in the Appendix F. The literature neglects the linkage between driving and hindering forces and the goals pursued. Hence, the determination of common goals is vital to then anticipate the respective drivers and barriers. Agreeing and setting the goals could also partially remove the communication barriers mentioned above by enabling more direct communication focused on the goals set.
The multidimensional nature of biochar and the associated various goals partially explains the regulatory and funding heterogeneity. Policies for biomass or agricultural waste management, climate change mitigation and environmental remediation might indirectly or directly affect biochar production and usage (Pourhashem et al., 2019). This supports the need to negotiate pursued goal. To sum up, relevant stakeholder groups should collectively determine common goals. Regarding this, intermediary actors might play a vital role in enabling the establishment of a joint vision.

Lacking financial incentives to reward the farmer for the provided ecosystem services also hinders the alignment of goals. Otte and Vik (2017) support this point by stating that there is a need to turn climate mitigation goals into economic goals to enroll more actors. They point out that policies and regulations are measures that influence the intended

goals, for example by financially rewarding ecosystem services or increasing carbon prices. In this way, the goal of soil benefits can be reconciled with economic goals.
The results suggest that the configuration of the value chain affects the pursued targets as the configuration also influences which actors are involved. Furthermore, Anderson et al. (2017) state that the simultaneous fulfilment of several goals is possible but depends on the value chain configuration and specification. Thus, the value chain configuration not only influences which goals are pursued, but also which can be achieved. However, this thesis does not allow for a systemic comparison of the goal constellations associated with the various value chain and actor configurations.

Quantifying the provided ecosystem services is an important task to highlight biochar's currently unrewarded benefits. This is a decisive aspect of facilitating communication with policymakers and other stakeholders (Pourhashem et al., 2019). By doing so, inclusion in policy instruments can also be made possible. Further, the empirical research also revealed the relevance of quantifying biochar’s impact to foster the application by farmers. Quantification transforms the benefits into tangible values and thus facilitates communication to the stakeholders. The next step would be to monetize these values and convert them into a business model. Moreover, the incorporation of monetized benefits into policy frameworks plays a role (Pourhashem et al., 2019). The empirical research supports this as the lack of a unified carbon crediting system and lacking incorporation into legislated carbon credit schemes leads to uncertainty and impedes biochar development. However, existing voluntary carbon crediting options are a relevant instrument to generate additional income opportunities. For example, one farmer, has successfully turned the carbon sequestration of biochar into a business model by selling climate neutral products. To conclude, researchers should engage in the quantification of the ecosystem services provided by biochar. Based on this, actor groups, such as entrepreneurs or service providers can further develop business concepts for trading these values.

Literature states that in some cases funding contributed to biochar development (A. E. Latawiec et al., 2019; Leach et al., 2012; You et al., 2022), whereas in other cases there is a lack of funding (Kong et al., 2014; A. Latawiec et al., 2017; You et al., 2022). For Germany, this thesis revealed that the biggest problems with funding are heterogenous funding options, the complexity of funding processes and too strict requirements. Hence, there is a need to improve clarity, provide support with funding, and establish specific biochar funding options. In some cases, besides the willingness for biochar engagement, the costs pose an obstacle. Hence, financial incentives are required to foster biochar engagement (Pourhashem et al., 2019). However, some participants argued that with a viable system integration that enables the sale of surplus energy and income from carbon capture, there is no need for funding.
Apart from the fact that biochar funding and research and development on standardized biochar-based products are mentioned as essential, the need for funding for research and development has not been identified as an important driver or barrier in this study. In contrast Pourhashem et al. (2019) mention funding for research and development as essential to foster innovations, specifically for biochar technology. This gap cannot be explained because the barriers to lacking research and development have not been investigated here.

Generally, the required capacities for and difficulties with compliance, approval and funding processes were mentioned as hindering among different actors who already engage with biochar production or planned to do so. One empirically uncovered barrier to voluntary carbon crediting is the bureaucratic effort. Especially the agricultural sector lacks capacities for lengthy and complex approval and certification procedures. In line with this, Pourhashem et al. (2019) explain the low participation in funding options by the perceived complexity and lacking familiarity with these options. Hence, associations or advisory bodies are required to improve their provided services regarding information exchange and consulting. Established platforms must be further improved or new ones must be developed to increase information exchange. A study on entrepreneurial activity for bioeconomy transition already suggests the need for support with obtaining funding as skills and experience are required. According to this study, networks play a decisive role in providing the required support (Adamseged & Grundmann, 2020). Small scale farmers might even be more disadvantaged regarding the required skills and experience, so helping them with such processes and procedures is of major importance. To conclude, it is suggested that networks, associations and advisory bodies should provide support with compliance, approval and funding procedures, especially for small scale farmers. Moreover, financial incentives must be established to align the goals pursued.

Values and education

Besides the awareness, as mentioned earlier, the attitude and perception of the different stakeholder groups are decisive. It was found that enforcement of regulations and the course of approval procedures of the pyrolysis plant is highly dependent on the attitude and perception of the authorization bodies. This aspect is disregarded by the literature and suggests that addressing the authorities' culture is of major importance. As pointed out, regulations and policies partially shape human action and can affect perceptions. Further, communication can increase acceptance and improve stakeholder perceptions. According to Garcia et al. (2022) voluntary certification fosters trust in biochar technology. This already being in place may indicate the need for legislated product certification to improve social acceptance (Pourhashem et al., 2019).

Moreover, the prevailing attitude of the agricultural sector affects the decision for biochar application. The interviewed farmers mentioned their positive attitude towards the environment, which motivated biochar engagement. Further, the specific agricultural system can either enable or hinder biochar engagement. The linkage between the agricultural system and biochar engagement is economical. Farming systems not dealing with special and intensive crops do not provide sufficient resources, such as capital and workforce, to engage with biochar. This again strengthens the need for financial instruments to make biochar more attractive to these farmers. However, the effect of the agricultural system on biochar engagement is dependent on the linked values and perceptions of the farmer. As described above, the general attitude towards agriculture and the purpose pursued influence the farmer's behavior. Hence, barriers such as the lacking incentive for long-term decisions provided by leased land can be overcome by an environmentally friendly attitude resulting in long-term decision making. According to Rogers (2003) this can be explained the compatibility of an innovation with existing values and needs being another decisive factor for the rate of adoption. This underlines the need for a general cultural change towards a more sustainable society and, more specifically, a sustainable agricultural sector. Moreover, governments can, for example, foster education on biochar and by this contribute to consumers' perception and hence foster demand (Pourhashem et al., 2019).

Overall, cultural change among different actor groups was identified as a decisive factor for biochar implementation. Some interviewees indicated ongoing cultural change, whereas some also criticized the prevailing lack of environmental consciousness. The change of people's perception, values and attitudes is related to high uncertainty. However, different starting points to spur cultural change were mentioned, such as the society, end-consumers of biochar, disposal companies and the agricultural sector. These might also mutually influence each other (Wilde & Hermans, 2021). Hence, it is recommended to foster awareness of the urgency to combat climate change and related needs, for example, more efficient resource management. One measure to foster cultural change, at least for the younger generations in the agricultural sector identified within the interviews, is education. This already indicates the lengthiness of this process. Otto et al. (2020) analyze possible trigger points for social decarbonization, in other words social tipping dynamics, and state that values and norms can trigger decarbonization, but only at a very slow pace. Apart from the possibly slower impact of education, it is proposed that education is an important lever for society and more specifically for the agricultural sector to promote biochar development.

Alignment of system components and cooperation

Besides the affirmation that the availability of residues fosters biochar development, the interviews revealed that there is a need for coordination and management of biomass flows. Existing biomass logistics were mentioned as beneficiary and yet further development and improvement of biomass logistics is needed. The first statement refers to suppliers of woody residues, which are seen as less beneficiary by research and practice due to usage competition and price situation. Regarding the usage of other residues and wastes, which received less attention in the past, the existing structures need adjustments. On the one hand, there is a need for concepts to transfer unused residues in usage, on the other hand, existing material flows need to be re-coordinated. This is linked to the need for a cultural change regarding resource and waste management, as this affects the handling of residues and biomass prioritization. Further, this indicates the need for investments in new structures that deviate from the existing structures focusing on woody residues and combustion of residues. As a conclusion, the further development of biomass structures and the implementation of a biomass prioritization to foster biochar production is recommended.

The interviews revealed that heat production and usage could function as both driver and barrier depending on the specific situation. Despite several options for heat utilization having been mentioned, developing such a concept in practice often constitutes an obstacle for the involved actors and this in return limits potential locations. The design of energy usage depends on the value chain configuration and on the actors involved. For example, it was shown that the farmers are viable biomass providers and operators. However, they might lack capacities for heat usage. In contrast, industrial players have the advantage of access to biomass and the option for constant energy usage. This supports the need to align actors' potentials and requirements. Hence, the need for energy consumption may require cooperation between different actors. One option to address the lack of heat usage options could be incorporating pyrolysis plants into municipal heat plans. By this, system integration can be facilitated, and the networking of actors can be initiated. Further, this creates an income opportunity for potential biochar producers. Therefore, the development and organization of heat usage concepts may provide the potential for re-enforcing drivers within the biochar STS. Municipalities should engage in developing these concepts and incorporate pyrolysis plants in municipal heat plans.

The findings uncovered the need to align the different system components. Especially, the need for the alignment of biomass provision, biochar production, energy usage and biochar distribution as well as the involved actors was uncovered. Regarding this, decentral production was emphasized as being beneficial. However, this still requires the alignment of the system components as well as of the actors involved, also in terms of location as mentioned above. The empirical data clearly pointed out the need for the development of biochar concepts, that align these elements and provide a way for coordination of actors and resource flows. The findings already indicate that there are differences in the alignment dependent on the value chain configuration. For a medium-sized plant, for example, it may be necessary to purchase biomass in addition to the company's own biomass, which requires cooperation with a biomass supplier. One challenge in developing biochar concepts may be the high variability of options that should be considered in the specific context and based on this be adjusted. This entails a high need for organization and coordination. Basic concepts with the potential for adjustment to specific contexts must be developed. Challenging is that any potential business model requires appropriate alignment of the aforementioned system components, such as biomass provision, heat utilization and biochar distribution. Moreover, it is important to acknowledge that new businesses and the associated business concepts are interdependent on the business environment, which is constituted by institutions, knowledge and consumer preferences. Misalignments between a company and its environment might hinder business development. Adamseged and Grundmann (2020) identified the associated challenges of bioeconomy businesses and their alignment with the business environment. Their findings suggest that the development of business concepts is still dependent on the aforementioned drivers and obstacles and associated recommendations. For example, an enabling legislative framework, support with funding and approval and increased communication to raise awareness and consumer preferences would enable business development.
Further, Adamseged and Grundmann (2020) point out that cooperation among the various stakeholders is essential to provide capacities to deal with these challenges and to overcome them. Based on this, it can be concluded that cooperation is essential to address different drivers and barriers of regional biochar value chains in Germany and thus promote biochar development.
It is recommended, that entrepreneurial companies or service companies develop reproducible and adjustable biochar business models taking into account the alignment of the biochar system components.

The established associations and networks were mentioned as enabling agents for communication, information exchange and consulting. They also provide a starting point for initiating cooperation. However, the empirical research revealed that cooperation among the identified actors still needs to be fostered. Cooperation is one measure to address various identified barriers, such as lacking knowledge and information and lacking capacities for the before described approval and certification procedures (Adamseged & Grundmann, 2020). Besides the mentioned options for collaboration such as franchise systems or cooperatives, the realization of these concepts for biochar lags behind. On the one hand, existing associations and networks may further extend their capacities to initiate cooperation. On the other hand, other actor groups with sufficient capacities might need to fulfill the role of intermediary actors and initiate cooperation. The analysis of the empirical data revealed, for example, the relevance of state actors such as municipalities for initiating cooperation. The analysis of the empirical data revealed cooperation obstacles such as perceived lacking options and lacking partners for cooperation, as well as organizational effort that is associated with cooperation. Further, the lacking willingness to cooperate was mentioned. Within the scope of this work, it was not possible to answer in depth what hinders biochar cooperation. Tviza et al. (2021) analyze conditions for the formation of alliances, this might provide an interesting starting point for further investigation of biochar systems. The identified barriers to cooperation could indicate that the above-mentioned variability of the value chain may also be a hindrance because actors are unaware of their role and the possible interactions with other actors. There are no clearly defined structures and the actors first need to get an overview of the multiple options before they can determine which option is best in the particular situation and then try to develop the necessary partnerships for it. Further, the potential collaboration of novel actors from different sectors may be challenging (Mertens et al., 2019). Overall, it is essential to further identify barriers to cooperation and foster cooperation among the diverse actor groups. Developing collaborations can also create joint capacities to address other obstacles.

Levers to foster biochar implementation

To sum up, important levers could be identified, which address different drivers and barriers. A range of obstacles can be addressed with better communication (e.g. lack of awareness, lack of understanding, misperceptions, and lack of alignment of policies and scientific progress). As elaborated on before, communication between equipment manufacturers and operators, science and practice, policymakers and farmers is key to biochar development. Governmental bodies, associations, and networks provide a starting point to improve communication.

Moreover, the empirically identified actors involved in biochar development are associated with different potentials and needs regarding the fulfilment of the value chain steps. Therefore, the actor groups might need to cooperate to fulfil the required roles and outweigh their specific offers and needs. Furthermore, cooperation is one measure to address some of the identified barriers by joining capacities. This may also enable the described need to align different system components and design viable system configurations. However, this thesis does not allow for an in-depth comparison of the differences between the identified configurations. It is important to develop concepts for cooperation that optimize the system components and their alignment, taking into

account the benefits and needs of the required stakeholders. Generally, biochar development requires strong cooperation between the different stakeholder groups.
The establishment of a common vision and the setting of goals is pivotal to improve collaboration and communication. In line with the need for a common vision, political commitment and an enabling framework are needed to support biochar development. Political support can range from non-financial support to the establishment of financial incentives.

General interpretation and further advice

The described discrepancies between the perspectives found in the dominant literature and the empirical research conducted in the context of this thesis can be explained by taking into account the different contexts. In this regard there were significant differences between the reviewed studies and the investigation object of this thesis' empirical research, namely regional biochar systems in Germany as well as by the temporal scale (Kamali et al., 2022; Sundberg et al., 2020; Thengane et al., 2021; Verheijen et al., 2012). Further, these differences indicate a gap between research and practice. The chosen approach incorporated the actors' perspectives and, more specifically, the reality of experience. This is an essential contribution to biochar development. The study identified various barriers to implementing biochar as an NET, such as drawbacks in institutional support, namely the lack of enabling policies and support with approval, certification and funding procedures. This is in line with Minx et al. (2018), who point out the need to not only acknowledge the relevance of NETs but also to reflect their implementation in science and policy. Regarding this, stronger collaboration between policymakers, science and practitioners is required.

The literature review pointed to some relevant interdependencies between the enabling and hindering factors. For example, increased public confidence can spur investments. Likewise, regulations based on risk assessments can foster confidence in biochar technology (Downie et al., 2012). However, these interdependencies are not explicitly referred to in the literature. This indicates that the acknowledgement of interdependencies needs to be further encouraged. The literature review showed that research on the holistic biochar system remains scarce besides the scattered findings on single system components and related drivers and barriers. For example, the manifold techno-economic assessment of biochar implementation neglects the perception and values of relevant actors. The empirical research revealed many potential interactions between the system components and the associated drivers and barriers. This thesis contributes to biochar research by showing that incorporating these interactions is vital for designing and managing biochar systems. A mismatch between system components, such as the guiding institutions and people's capacities, can impede technology adoption (F. W. Geels, 2004). Hence, the identified interactions and the revealed need to jointly consider system components constitute a relevant contribution to the work of policymakers, actioners and scientists aiming to foster biochar deployment. For example, policymakers should not only incorporate the practical perspective on drivers and barriers into decision making but also consider the effect of policies and regulations on other system components, such as the involved bureaucratic effort and the effect on perceptions within society.

The interdependence of the drivers and barriers indicates that when appropriately addressed biochar development can be boosted by reinforcing drivers or by implementing drivers that have to potential to cancel out certain barriers. Some of the described processes have the potential to address several drivers or barriers, and this might have a strong positive effect on the transition process. This is in line with Hekkert et al. (2007), who analyzed the contribution of different system functions to successful innovation systems and technological change. They concluded that the reinforcing system functions have the potential to create a momentum of change and thus constitute "motors of change" (Hekkert et al., 2007, p. 426).

In addition, the findings suggest relevant differences between small scale biochar production and usage and medium to large scale implementation. For example, for medium scale systems, heat usage is seen as an opportunity, whereas for smaller scale system the lacking option for heat usage hinders the performance of the system. This underlines the findings from Otte and Vik (2017), who conclude that "there are also huge differences between the values of the non-technical factors that need to be addressed in the project design for biochar systems" (p.10). Hence, these differences must be considered when designing and managing biochar concepts. For example, regulation and certification affect the implementation of biochar and both should consider the system configuration. This requires, for example, that smallholders with lower capacities in particular are supported in biochar production and usage rather than hindered.

Zooming out

Regarding the potential for a socio-technical transition, the analysis indicates a mismatch between some system components that hinder the successful implementation and diffusion of biochar technology. For example, there is a lack of options to feed-in the generated energy and a hindering regulative landscape. This may imply that regulations, values and user practices are partially still aligned to the incumbent system and thus hamper biochar development (F. W. Geels, 2002). Bugge et al. (2019) state that systemic change is challenging "as routinised practices tend to become institutionalized both socially and materially over time" (p. 57). However, the empirical research shows the coevolutionary alignment processes of biochar technology as a niche innovation with the surrounding elements of the STS, which constitute the socio-technical regime. For example, the lack of supply chains was mentioned as a barrier for biochar procurement, and growing structures for biochar distribution were simultaneously identified. Also, regarding the application methods, it was reported on achieved progress and easily implementable methods and simultaneously on the need to improve (knowledge on) application methods further. These findings indicate a dynamic process where new structures are developed and aligned to biochar technology. Another example are the changes in the German Fertilizer Ordinance, which were mentioned as an enabling factor for biochar development. However, the empirical research revealed that other system components, such as technology, still need to be aligned to these changes as in the past, the focus was on the technological feasibility of wood pyrolysis. Moreover, the interviews showed that landscape pressures such as climate change and the gas crisis are likely to affect the transition in the future. Hence, this perspective offers hints on the processes involved in a socio-technical transition and by this provides a starting point on how to foster and guide this transition.

5.3 Limitations

The approach to analyze biochar development from an STS perspective and not overemphasize the technology's relevance for technology adoption is justified as the given technological development is considered as an enabling factor. Analyzing biochar as an STS helped to understand the embedding of the biochar technology into the biochar system, yielding relevant insights on the implementation. The analytical framework provided by the STS theory and adjusted to the biochar context allowed to uncover various drivers and barriers related to these system components. Through this process insights were gained regarding the interdependence of these system components and the associated drivers and barriers.

However, the method is subject to certain limitations. The rather broad scope of the thesis, depicting various biochar systems, required the development of an analytic distinction between the different system components as described in the Section 3.2 and in the coding guideline (see Appendix D). The development of these analytical distinctions and the coding process are based on the active interpretative decisions in the course of the construction. However, the coding guideline contributes to the transparency of the research method. In addition, coding was complicated by the interdependence of the system components. At the same time, the empirically confirmed interdependence is an important result of the research.
The approach and scope of the thesis did not allow for a detailed examination of the differences between the various system configurations. This thesis applied a qualitative research approach to depict a holistic picture of biochar systems incorporating the stakeholder’s perspective. Therefore, a weighting of the drivers and barriers was not possible. As also indicated within this thesis market dynamics are of relevance. However, the market dynamics were outside the scope of the study and hence were only marginally considered.

With the chosen methodological approach, it was possible to gain information on the investigation object, namely biochar as an STS, from the actors’ perspectives. However, the validity of the empirical results is limited and calls for future research. The recommendations of interview partners by persons already interviewed according to the snowballing principle may have provided an additional bias in the interview sample. With regards to the complex and various identified value chain configurations and associated actors, further interviews that incorporate other perspectives could particularly contribute to the research goal. This way, individual results could be questioned, reported in more detail, verified, discussed, or adjusted. This was impossible because of the scope of the thesis and the time and resources available.
Due to the chosen approach of semi-structured interviews with pre-formulated questions, the risk of pre-determinisms inevitably exists (Helfferich, 2014). The respondents' ability to express themselves might be limited and restrict the uncovering of new insights (Helfferich, 2014). Since only one person performed the qualitative content analysis, the subjectivity of the statements made is additionally increased. An additional coding

process of the material by another person and the discussion of possible deviating abstractions could further increase the quality of the results and reduce the risk of analytical bias (Kuckartz, 2016). Further, the identified subcategories partially represent the developed questions and might indicate a need for more openness for unexpected findings.

The limited number of interviews conducted implies a concern with regards to generalizability of findings. The sampling process was guided by the ambition to depict a holistic picture of biochar development, involving different actors representing different functions in the system. The generalizability and validity of the results could be improved by choosing several different actors performing the same functions. Furthermore, not all relevant actor groups could be represented, for example, the perspective of industrial actors could be relevant. Nevertheless, the sampling corresponds to the scope of the thesis and represents a broad range of stakeholder groups, and therefore contributes to the pursued research goals.

6 Conclusion

The goal of the thesis was to gain a better understanding of biochar implementation as an NET in Germany. To achieve this, relevant value chain as well as actor configurations were identified. These value chain and actor configurations range from small scale on-farm production conducted by a single farmer to large scale value chains, where multiple actors fulfil the different steps. RQ1 was conducted on an exploratory basis as biochar research investigating the potentially involved stakeholder groups for biochar systems remains scarce.

The study also revealed the relevance of actors which are not directly linked to a specific step in the value chain, such as associations, policymakers, certifiers etc. By doing this, this thesis provides a viable starting point for further analysis of stakeholder engagement for biochar production and usage. Such analysis may also foster cooperation and actor engagement, for example, through existing associations.

The main aim of the study was to investigate the socio-technical drivers and barriers for regional biochar value chains in Germany (RQ2). To address the research gap on socio-technical aspects affecting the biochar development, a literature review, a focus group and 13 semi-structured expert interviews were used as data sources. The semi-structured interviews constitute the core of this thesis and allowed an investigation of drivers and barriers based on different stakeholders' perspectives. Hence, the empirical research provided essential insights from the practice on drivers and barriers that affect the implementation of biochar as an NET and therefore contributes to biochar research. In general, the thesis addresses the lacking consideration of the deployment of NETs. The analysis of biochar implementation from an STS perspective allowed the holistic investigation of various socio-technical factors, such as cultural, institutional and infrastructural factors. Based on the identified drivers and barriers, recommendations for action were developed. The identified drivers and barriers and derived recommendations for actions may enable policymakers that aim to facilitate biochar implementation, and other actor groups (such as farmers or industrial players) who want to engage in biochar production and utilization, as well as by researchers, who strive at further investigating the implementation and management of biochar systems. The recommendations help to overcome the current obstacles for implementation, as accounting for stakeholder perceptions allows research to be aligned with the real situation. Overall, this thesis suggests improving the communication on biochar as an NET to address barriers of lacking awareness, insufficient understanding of biochar technology and negative perceptions. Further, it is recommended that policymakers provide an enabling framework for biochar technology, specifically, biochar-specific regulation with clear targets and financial incentives such as funding or incorporation into carbon crediting schemes. Strong stakeholder cooperation is required to address a variety of the identified barriers. It is vital to negotiate and determine common goals among the different actor groups to facilitate biochar development. The developed recommendations help to address the barriers and to leverage the drivers' full potential in order to foster biochar implementation and contribute to carbon sequestration.

Due to the scope of this thesis, a detailed analysis of the drivers and barriers associated with the different system configurations could not be provided. Nevertheless, the results already point to system differences, warranting an in-depth analysis of different biochar systems, for example of small scale on-farm and medium scale production. In particular, the importance of drivers and barriers in the different configurations should be investigated. Future analysis of existing biochar systems according to the developed STS biochar framework can provide best practice examples and concrete case studies to further incorporate the practice.
Another opportunity for future research is the in-depth investigation of the interdependencies of the drivers and barriers. By researching this, levers that catalyze biochar development can be identified. The findings indicate that certain tasks and processes can address various drivers and barriers simultaneously and by this immensely contribute to biochar system transition. Therefore, these should be further investigated.
Moreover, it is relevant to further analyze stakeholder integration and engagement to support biochar development. For example, the possible lack of intermediary actors should be examined. Future research should consider which actor groups have sufficient capacities and are capable to act as intermediary actors. Another field for future research could be the prioritization of the identified drivers and barriers, for example, through quantitative research. Regarding the neglection of market barrier effects, an interdisciplinary merge of studies to analyze economic drivers and barriers is useful. Furthermore, the above-mentioned time scale of the drivers and barriers could be examined by incorporating the strand of literature on social tipping dynamics.

Overall, this thesis investigated socio-technical drivers and barriers from the actors' perspective and addressed the research gap of non-technical aspects affecting the implementation of biochar technology. This thesis revealed important insights on the potentials and barriers of biochar technology for low carbon transitions through biochar technology.

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8 Appendix

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Appendix A: Extended literature review findings with references

Table XVII: Goals identified within the literature review

Goals
• Food security, energy provision, climate change mitigation, soil remediation (Garcia et al., 2022; A. E. Latawiec et al., 2017)
• Sustainable development of the agricultural sector (Ayaz et al., 2021)
• Waste management and productivity (Ayaz et al., 2021, 2021; A. E. Latawiec et al., 2019)
• Farmers motivation: soil benefits especially for degraded soils, productivity increase, environmental impacts (A. Latawiec et al., 2017; Mahmoud et al., 2021a; Rittl et al., 2015; P. M. Rogers et al., 2022)

Table XVIII: People-related drivers and barriers identified within the literature review

Drivers	Barriers
• P: establishment of research initiatives for coordination of research and knowledge dissemination, to foster funding and accumulate resources (Gwenzi et al, 2015) • P: transdisciplinary research collaboration (Sundberg et al., 2020)	• Need to increase awareness (Niemmanee et al., 2019; A. Singh et al., 2021) to foster investments (A. Singh et al., 2021) • Lacking media support (Niemmanee et al., 2019) • Lacking governmental promotion (Niemmanee et al., 2019)
• P: Collaboration and information exchange (Thengane et al., 2021) • P: Collaboration between science and practice (Leach et al., 2012; Thengane et al., 2021)	• Lack of communication and exchange in biochar research (Gwenzi et al, 2015) • Inappropriate and insufficient communication (Garcia et al., 2022)
• P: demonstration for knowledge provision (Bellè et al., 2022)	• Need for joint action by all stakeholder (Thengane et al., 2021)
• Biochar conferences as a means for knowledge dissemination (A. Latawiec et al., 2017)	• Need for knowledge transfer (Gwenzi et al., 2015; Zanli et al., 2022)
• Alliances for biochar development among different actors groups (Kong et al., 2014; Leach et al., 2012) • P: collaboration of biochar business, third-party testing and the government (E. Singh et al., 2022)	• Lack of education as a barrier (Karim et al., 2022; A. Latawiec et al., 2017; P. M. Rogers et al., 2022; E. Singh et al., 2022)

•	• Need for cooperation between research institutes and farmers (Zanli et al., 2022)

Table XIX: Cultural drivers and barriers identified within the literature review

Drivers	**Barriers**
• Growing interest (Thengane et al., 2021) • Farmers awareness of biochar technology (Leach et al., 2012)	• Lack of awareness (Garcia et al., 2022; Karim et al., 2022; A. Latawiec et al., 2017; Niemmanee et al., 2019; P. M. Rogers et al., 2022; Zanli et al., 2022; Zilberman et al., 2022) • Lack of farmers awareness (A. Latawiec et al., 2017; Niemmanee et al., 2019; P. M. Rogers et al., 2022; Thengane et al., 2021; Vochozka et al., 2016)
• P: positive perception of society (Kamali et al., 2022)	• Lack of openness for new practices/ to change old practices ○ (Gwenzi et al., 2015; Zanli et al., 2022) • Agricultural system (Hansson et al., 2021; Sundberg et al., 2020; Zanli et al., 2022) • Farmers risk aversity (Garcia et al., 2022; Gwenzi et al., 2015; Zanli et al., 2022)
• Agricultural system (Hansson et al., 2021) • Openness to new practices (Gwenzi et al., 2015; A. Latawiec et al., 2017), which also depends on the agricultural practices (A. Latawiec et al., 2017) • Familiarity with biochar technologies or of biochar technology with other technologies (Bellè et al., 2022; Hansson et al., 2021; A. E. Latawiec et al., 2019) • Farmers' positive attitude towards biochar production and usage (Niemmanee et al., 2019) • Acceptance (Müller et al., 2019) • Openness for new technologies (Müller et al., 2019) • Environmental consciousness (A. Latawiec et al., 2017) • Trust in biochar technology (Mašek, 2016)	• Lack of (positive) customer perceptions (Thengane et al., 2021) • Need to raise acceptance (Kong et al., 2014) • Need for public trust in biochar technology (Downie et al., 2012)

	• Misunderstanding and wrong perceptions (Thengane et al., 2021) due to lack of data • Misunderstandings, negative perceptions, reluctance due to concerns (Zanli et al., 2022) • Environmental concerns (A. Latawiec et al., 2017) • negative perceptions and lobbying e.g. due to risk of usage competition of biomass (Gwenzi et al, 2015)
	• Lack of political will (P. M. Rogers et al., 2022) • Need to change policymakers attitude towards biochar technology (Thengane et al., 2021)

Table XX: Technology-related drivers and barriers identified within the literature review

Drivers	**Barriers**
• Existing and established technologies (Garcia et al., 2022; Kong et al., 2014) • Ongoing technological development (Mašek, 2016) • Technologies with re-integration of the energy (Kong et al., 2014; Sundberg et al., 2020)	• Technological feedstock constraints, requiring equipment and costly and addition pretreatment processes (Chang et al., 2015; Downie et al., 2012; Kong et al., 2014; Roberts et al., 2010; You et al., 2022; Zanli et al., 2022) which increase emissions (Downie et al., 2012) • Pre-treatment processes (Thengane et al., 2021) • Heterogeneity and moisture of feedstocks (Thengane et al., 2021) • Suitability of feedstocks due to high water content hampers ecological performance, besides technological feasibility of pre-treatments (Gwenzi et al., 2015) • Heterogenous feedstocks hamper consistent biochar quality, hence need for technological development (Thengane et al., 2021)
• Cheap and simple small-scale technologies, easy to operate (Gwenzi et al., 2015; A. E. Latawiec et al., 2019)	• Lack of technical knowledge and skills (Gwenzi et al., 2015; Niemmanee et al., 2019; P. M. Rogers et al., 2022; Zanli et al., 2022)
• Technological knowledge (Garcia et al., 2022)	• Need to design the conversion process appropriately, to adjust

	biomass, conversion and application (Crombie et al., 2015; Sundberg et al., 2020; You et al., 2022b)
• Beneficiary when compared to other NETs due to co-benefits (Hansson et al., 2021)	• High labour demand and time effort (A. E. Latawiec et al., 2019; Müller et al., 2019; Thengane et al., 2021; You et al., 2022) • Labour demand of mobile systems (You et al., 2022)
• Reduced production costs due to technological development (Nematian et al., 2021; Song et al., 2022; Vochozka et al., 2016)	• Costs (Kong et al., 2014; A. E. Latawiec et al., 2019; Thengane et al., 2021)
• P: technological flexibility regarding inputs (Downie et al., 2012)	• Low system efficiencies (Kong et al., 2014; You et al., 2022) • Emissions (Thengane et al., 2021)
• Established research level and progress (Kong et al., 2014; A. Latawiec et al., 2017) • Lab scale scientific findings on conversion (Kamali et al., 2022) • P: Long term field research (Thengane et al., 2021) • P: transdisciplinary research (Sundberg et al., 2020)	• Lack of suitability of technology to the local context (Hansson et al., 2021) • Level of technological development hinders widespread adoption (Zilberman et al., 2022)
	• Application as a barrier as it requires technical knowledge and further resources (Hansson et al., 2021)
	• Uncertainty in predictability of biochar impacts and associated risks (Garcia et al., 2022; Gwenzi et al., 2015)(Garcia et al., 2022)
	Research gaps • Lack of field-scale research (Kamali et al., 2022; Thengane et al., 2021; You et al., 2022) • Research on application with fertilizer or compost (Kamali et al., 2022) • Research on long-term effects (Kamali et al., 2022) • Agronomic impact of biochar with different feedstocks and technologies (You et al., 2022) • Ecosystem services • Biochar's soil-specfic impacts (Garcia et al., 2022; A. Latawiec et al., 2017; Mašek, 2016; You et al., 2022)

	• Socio-economic assessments (Kamali et al., 2022) • Carbon sequestration (Garcia et al., 2022) • Quantitative assessments of biochar soil effects (Kong et al., 2014)
	• Need for systemic and standardized research (You et al., 2022)
	• Lack of knowledge on biochar technology (Kong et al., 2014; A. Latawiec et al., 2017; Maroušek et al., 2019; Mašek, 2016; Song et al., 2022; Vochozka et al., 2016; Zanli et al., 2022) • Farmers lack of knowledge (Niemmanee et al., 2019)

Table XXI: Infrastructural drivers and barriers identified within the literature review

Drivers	**Barriers**
• (Local) availability of feedstocks (Ayaz et al., 2021; Garcia et al., 2022; Mahmoud et al., 2021b; P. M. Rogers et al., 2022; Sundberg et al., 2020; Thengane et al., 2021; Zanli et al., 2022) • Usage and availability of residues (Maroušek et al., 2019; Sundberg et al., 2020; Vochozka et al., 2016; Zilberman et al., 2022) • Low cost of feedstock acquisition (Zilberman et al., 2022)	• Usage competition (Bellè et al., 2022; Garcia et al., 2022; A. E. Latawiec et al., 2017; P. M. Rogers et al., 2022; Sundberg et al., 2020; Zanli et al., 2022) • Seasonality of feedstocks (P. M. Rogers et al., 2022; Zabaniotou et al., 2015; Zanli et al., 2022)
• Decentralized production with small scale systems close to the biomass source (Maroušek et al., 2019; Roberts et al., 2010; Thengane et al., 2021; Zanli et al., 2022) and/ or application (Maroušek et al., 2019; Vochozka et al., 2016) with local energy provision (You et al., 2022) • Optimized logistics (Maroušek et al., 2019; Vochozka et al., 2016; Zanli et al., 2022) • Shor transport distance of biomass provision (Maroušek et al., 2019; Roberts et al., 2010; Zabaniotou et al., 2015; Zilberman et al., 2022) • Decentralized production is beneficiary in terms of feedstock	• Logistics (feedstock collection, transportation, storage) and related costs (Chang et al., 2015; P. M. Rogers et al., 2022; Thengane et al., 2021; You et al., 2022; Zanli et al., 2022) • Long distance of biomass transportation (Kong et al, 2014) • Relevance of logistics, e.g. storage capacities, need for coordination and organization of biomass collection (Kong et al., 2014; Montanarella & Lugato, 2013; Roberts et al., 2010; You et al., 2022; Zabaniotou et al., 2015)

heterogeneity (Thengane et al., 2021)	
• Existing infrastructure in California (Thengane et al., 2021)	• Heterogeneity of biochar qualities impedes distribution (Kochanek et al., 2022)
• Co-production and usage of heat (Downie et al., 2012; Garcia et al., 2022; A. E. Latawiec et al., 2017; Maroušek et al., 2019)	• Lack of long-term contracts between biomass provider and operator of the plant (Kong et al., 2014) • Seasonality of biochar markets leading to need of storage capacities (Garcia et al., 2022)
• Mobile system for decreased biomass hauling distance (Nematian et al., 2021; You et al., 2022)	

Table XXII: Process- and procedure-related drivers and barriers identified within the literature review

Drivers	Barriers
• Certification (Downie et al., 2012)	• Lack of enabling policies (Ayaz et al., 2021; Gwenzi et al., 2015; A. E. Latawiec et al., 2019; Müller et al., 2019; Thengane et al., 2021, 2021; Zanli et al., 2022) • Lack of guiding institutions (Rogers et al, 2021) • Need for international guidelines (Downie et al., 2012; Gwenzi et al., 2015; Kong et al., 2014; Rodrigues & Horan, 2018; P. M. Rogers et al., 2022). • Lack of regulation for biochar as a soil amendment (Garcia et al., 2022)
• Voluntary certification systems; voluntary biochar quality standards and guidelines (Conte et al., 2015; Downie et al., 2012; Garcia et al., 2022; Jeffery et al., 2017; Leach et al., 2012; Verheijen et al., 2012) support regulative development and interest into biochar (Conte et al., 2015; Garcia et al., 2022) • Existing standards such as guidelines provided by IBI (Jeffery et al., 2017; Thengane et al., 2021; Verheijen et al., 2012)	• Legal uncertainty (Garcia et al., 2022) • Heterogenous regulative landscape (Garcia et al., 2022; Montanarella & Lugato, 2013; Rittl et al., 2015) • Restrictive legislation e.g. with regard to feedstocks (Maroušek et al., 2019)

• Ongoing regulative change (Garcia et al., 2022) • P: Incorporation into policies (Azzi et al., 2021b; Hansson et al., 2021) • Regulatory procedures in all EU member states to apply for biochar application (Garcia et al., 2022) • Climate legislation in California (Thengane et al., 2021) • P: incorporation of biochar into REACH regulation (Garcia et al., 2022) • P: enabling policies (Thengane et al., 2021) • P: science based policy development (Jeffery et al., 2017; Leach et al., 2012)	• Lack of biochar standardization and certification (Kamali et al., 2022) • Need for guidelines for production and application that take into account biochar soil fit and soil implications and socio-economic aspects (Sundberg et al., 2020; Verheijen et al., 2012) • Need to improve biochar standards (Thengane et al., 2021) • Need for scientific based regulations and guidelines (Verheijen et al., 2012) • Need to extend guidelines with environmental and socioeconomic aspects that take into account site-specific aspects (Sundberg et al., 2020; Verheijen et al., 2012) • Need to establish standards and conformity assessment tools to raise demand and acceptance (Kong et al., 2014) • Need for risk assessment to ensure quality and sustainability (Downie et al., 2012; Gwenzi et al., 2015; Kong et al., 2014; Rodrigues & Horan, 2018; P. M. Rogers et al., 2022) e.g. regarding the suitability of various feedstocks (P. M. Rogers et al., 2022)
• Funding, carbon prices, rewards for carbon seq as income sources (A. E. Latawiec et al., 2019; Leach et al., 2012; You et al., 2022) • P: subsidies (Chang et al., 2015) • P: incorporation into carbon crediting schemes (A. E. Latawiec et al., 2019; Mašek, 2016; Song et al., 2022; Verheijen et al., 2012; Zilberman et al., 2022) • P: carbon crediting (Thengane et al., 2021) • Voluntary carbon crediting (Hansson et al., 2021; Leach et al., 2012; Thengane et al., 2021) • P: economic incentives can boost acceptance (Kong et al., 2014)	• Need of methodologies for carbon crediting (A. E. Latawiec et al., 2019; Leach et al., 2012; Mašek, 2016; Thengane et al., 2021; Zilberman et al., 2022) • Lack of unified methodologies for quantification of ecosystem services (Downie et al., 2012; Gwenzi et al., 2015; A. E. Latawiec et al., 2019)
• P: biochar standards to improved demand acceptance (Kong et al.,	• Costs of controlling the technology hinders viability of small scale

2014), to support biochar research (Jeffery et al., 2017; Leach et al., 2012)	systems (Downie et al., 2012; Hansson et al., 2021) • Costs of approval processes (Rogers et al, 2022)
	• Compliance with regulations and certification (Thengane et al., 2021)
	• Lack of financial support e.g. carbon crediting (Zilberman et al., 2022) • Uncertainty regarding carbon crediting regulations (Thengane et al., 2021) • Carbon credit ownership (Thengane et al., 2021)
	• Lack of funding (Kong et al., 2014; A. Latawiec et al., 2017; Zilberman et al., 2022)

Appendix B: Conducted interviews

Table XXIII: Conducted interviews with length and date

ID	Organisation	Expertise	Length (hh:mm:ss)	Date
B1	EBI	Project development and representation of interests	00:56:10	05.10.2022
B2; B2.1	Biochar start-up	Biochar production, refinement and distribution	01:27:00; 00:51:00	17.10.2022; 14.11.2022
B3; B3.1	Project developer for the agricultural sector as well as farmer association	Consulting, advocacy and project planning for agriculture	1:02:46;	18.10.2022; 21.10.2022
B4; B4.1	Disposal company	Operation of a pyrolysis plant	01:10:00; 00:23:26	18.10.2022
B5	Farmer	Agricultural expertise and engagement with the potential operation of pyrolysis plant	00:21:37	24.10.2022
B6	Farmer	Biochar application	00:50:38	
B7	Farmer	Biochar application and production	1:10:00	29.10.2022
B8	Equipment manufacturer	Plant manufacture and operation of a plant	00:57:00	04.11.2022
B9	Wine grower	Biochar application	00:29:00	04.11.2022

B10	Contracting company	Project planning and operation	00:43:55	08.11.2022
B11	Biochar trading platform	Biochar refining and trading	00:53:55	14.11.2022
B12	DBFZ; Research institute	Research with focus on bioeconomy and biomass	00:49:57	24.11.2022
B13	Equipment manufacturer	Plant manufacture and operation of a plant	In writing	26.11.2022

Appendix C: Interview guidelines

Table XXIV: Interview guideline for superordinate actors

Einleitung	*Optionale Unterfragen*
- Vorstellung meines Studiums - Vorstellung der *Landgewinn*-Projekts - Vorstellung der Forschungsziele - Vertraulichkeits- und Datenschutzerklärung	
Einstiegsfragen	
Aus welchen Gründen engagieren sie sich im Bereich Pflanzenkohle?	
Beschreiben Sie bitte Ihre Pflanzenkohle-Wertschöpfungskette und ihre Position darin. Was ist Ihrer Meinung nach besonders wichtig für eine nachhaltige Pflanzenkohle Wertschöpfungskette?	
Goals[54]	
Welche Rolle spielt die Kohlenstoffsequestrierung bei der Produktion und der Anwendung von Pflanzenkohle?	- Welche Rolle spielt die Kohlenstoffsequestrierung in der Landwirtschaft?
People	
Wer sind Ihrer Meinung nach die relevanten Akteure für regionale Pflanzenkohle-Konzepte?	- Wer sind Ihre Partner? - Bei welchen Akteursgruppen gibt es für Handlungsbedarf?
Welche Organisations- und Kooperationsmodelle funktionieren gut entlang der Wertschöpfungskette? Was wird bezüglich der Vernetzung von Akteuren bereits realisiert?	- Was gibt es für Beratungsangebote? - Was gibt es für Barrieren für die Zusammenarbeit? Wie kann Kooperation entlang der Wertschöpfungskette entwickelt und unterstützt werden? - Wie nehmen sie die Kooperationsbereitschaft verschiedener Akteure wahr?

[54] The first introductory question also refers to the topic goals.

Was gibt es für Kommunikations- und Informationsbedarfe?	- Was findet diesbezüglich bereits statt?
Technology	
Was sind technologischen Chancen und Hürden auch in Bezug auf das dazugehörige nötige Wissen zur Implementierung und Nutzung der Technologie?	- Was sind aus Sicht des Tagesgeschäfts die wichtigsten Aspekte bei der Operationalisierung eines Pflanzenkohlesystems bzw. der Pyrolyseanlage? Was sind Chancen und Hürden bezüglich der Anwendung der Pflanzenkohle?
Wenn man sich spezifischer den Betrieb der Anlage anschaut, was sind hier gängige Betreibermodelle? Welche Betreibermodelle sind aus Ihrer Sicht für eine regionale Umsetzung in Deutschland am erfolgversprechendsten?	- Was sind sinnvolle Standorte und warum? - Was sind sinnvolle Anlagengrößen?
Infrastructure	
Was gibt es für logistische Herausforderungen bei der Integration der Technologie in die Pflanzenkohle Wertschöpfungskette (von der Biomassebereitstellung über, Transport und Lagerung, zur Abnahme der entstandenen Wärme und Pflanzenkohle)?	- Was waren die größten Probleme bei der Umsetzung Ihrer Position in der Wertschöpfungskette? Wie wurden diese adressiert? - Welche Probleme bestehen aktuell? - Was gibt es bei der Gestaltung und Planung eines Pflanzenkohle Konzepts zu beachten? - Was bereitet hier Schwierigkeiten? - Welche Schnittstellen bereiten Probleme?
Optional: Was ist seitens der Biomasse zu beachten?	- Wie schätzen sie Zugang und Verfügbarkeit von Biomasse für Pflanzenkohle Herstellung ein? - Wie sieht es mit der Konkurrenz zu alternativen Verwendungen von Rohstoffen aus? - Welche existierenden Strukturen sind förderlich für die Bereitstellung und Nutzung

	von Biomasse? - Was gibt es für logistische Hürden bezüglich der Biomassebereitstellung?
Optional: Was gibt es bezüglich der Nutzung der entstehenden Energie für Möglichkeiten?	- Was sind Herausforderungen? - Welche Energienutzungskonzepte werden bereits umgesetzt? - Was gibt es für Infrastrukturen zu Energienutzung? - Für welche Energienutzungskonzepte sehen Sie das größte Potential?
Optional: Was gibt es für bestehende Verkaufsstrukturen?	- Wo sehen Sie die größten Chancen für den Verkauf? - Was gibt es für (logistische) Herausforderungen?
Culture	
Wie schätzen Sie Bewusstsein und Akzeptanz für Pflanzenkohle ein?	- Was ist aus Ihrer Sicht am wichtigsten, um die Akzeptanz zu fördern? - Was sind Treiber oder Barrieren in den bestehenden gesellschaftlichen / landwirtschaftlichen/ industriellen Systemen für Pflanzenkohle?
Institutions and procedures	
Wie beeinflussen die aktuellen politischen Rahmenbedingungen die Herstellung und Anwendung von Pflanzenkohle? Was ist hemmend und was ist fördernd? Was sehen sie die diskutierte Anrechnung von Pflanzenkohle CO_2 Zertifikaten?	- Was gibt es für Fördermöglichkeiten? - Was für Bedarfe gibt es hier? - Welche Veränderungen sehen Sie durch die Novellierung der Düngemittelverordnung auf sich zukommen?
Abschluss	
Was halten Sie für besonders wichtig für die zukünftige Entwicklung regionaler Biokohle-Wertschöpfungsketten bezüglich der bestehenden Chancen und Hürden?	

Table XXV: Interview guidelines for actors that represent one specific step in the value chain[55]

Einleitung	
- Vorstellung meines Studiums - Vorstellung der Landgewinn-Projekts - Vorstellung der Forschungsziele - Vertraulichkeits- und Datenschutzerklärung	
Einstiegsfragen	
Aus welchen Gründen engagieren sie sich im Bereich Pflanzenkohle?	
Beschreiben Sie ein aus ihrer Sicht vielversprechende, nachhaltige Pflanzenkohle-Wertschöpfungskette von der Biomassebereitstellung über die Verarbeitung bis zur Anwendung	
Goals	
Welche Rolle spielt die Kohlenstoffsequestrierung bei der Produktion und der Anwendung von Pflanzenkohle?	
People	
Wer sind Ihrer Meinung nach die relevanten Akteure für regionale Pflanzenkohle-Konzepte?	- Bei welchen Akteursgruppen gibt es für Handlungsbedarf?
Welche Organisations- und Kooperationsmodelle funktionieren gut entlang der Wertschöpfungskette? Was wird bezüglich der Vernetzung von Akteuren bereits realisiert?	- Was gibt es für Beratungsangebote? - Was gibt es für Barrieren für die Zusammenarbeit? Wie kann Kooperation entlang der Wertschöpfungskette entwickelt und unterstützt werden? - Wie nehmen sie die Kooperationsbereitschaft verschiedener Akteure wahr?
Was gibt es für Kommunikations- und Informationsbedarfe?	Was findet diesbezüglich bereits statt?

[55] This guideline entails different options for the specification of the interview with regard to the function the respective actor represents.

Technology	
Was sind technologischen Chancen und Hürden auch in Bezug auf das dazugehörige nötige Wissen zur Implementierung und Nutzung der Technologie?	
Wenn man sich spezifischer den Betrieb der Anlage anschaut, was sind hier gängige Betreibermodelle? Welche Betreibermodelle sind aus Ihrer Sicht für eine regionale Umsetzung in Deutschland am erfolgversprechendsten?	- Was sind sinnvolle Standorte und warum? - Was sind sinnvolle Anlagengrößen?
Infrastructure	
Was gibt es für logistische Herausforderungen bei der Integration der Technologie in die Pflanzenkohle Wertschöpfungskette (von der Biomassebereitstellung über, Transport und Lagerung, zur Abnahme der entstandenen Wärme und Pflanzenkohle)?	- Was gibt es bei der Gestaltung und Planung eines Pflanzenkohle Konzepts zu beachten? - Was bereitet hier Schwierigkeiten? - Welche Schnittstellen bereiten Probleme?
Optional: Was ist seitens der Biomasse zu beachten?	- Wie schätzen sie Zugang und Verfügbarkeit von Biomasse für Pflanzenkohle Herstellung ein? - Wie sieht es mit der Konkurrenz zu alternativen Verwendungen von Rohstoffen aus? - Welche existierenden Strukturen sind förderlich für die Bereitstellung und Nutzung von Biomasse? - Was gibt es für logistische Hürden bezüglich der Biomassebereitstellung?
Optional: Was gibt es bezüglich der Nutzung der entstehenden Energie für Möglichkeiten?	- Was sind Herausforderungen?
Culture	
Wie schätzen Sie Bewusstsein und Akzeptanz für Pflanzenkohle ein?	- Was ist aus Ihrer Sicht am wichtigsten, um die Akzeptanz zu fördern? - Was sind Treiber oder Barrieren in den bestehenden

	gesellschaftlichen / landwirtschaftlichen/ industriellen Systemen für Pflanzenkohle?
Institutions and procedures	
Wie beeinflussen die aktuellen politischen Rahmenbedingungen die Herstellung und Anwendung von Pflanzenkohle? Was ist hemmend und was ist fördernd? Was sehen sie die diskutierte Anrechnung von Pflanzenkohle CO_2 Zertifikaten?	- Was gibt es für Fördermöglichkeiten? - Was für Bedarfe gibt es hier? - Welche Veränderungen sehen Sie durch die Novellierung der Düngemittelverordnung auf sich zukommen?
Abschluss	
Was halten Sie für besonders wichtig für die zukünftige Entwicklung regionaler Biokohle-Wertschöpfungsketten bezüglich der bestehenden Chancen und Hürden?	

Appendix D: Coding guidelines

Table XXVI: Coding guideline for main categories

Category	Definition	Coding rules with exclusion criteria	Examples
Goals	This category depicts the driving motivation and purpose to engage with biochar. This includes the highest valuated advantages of the actors involved for biochar implementation.	It captures the goals pursued and not the general attitude or values.	Carbon sequestration, soil benefits
People	This category depicts statements on the (social) interaction between people.	This category captures relationships, interdependencies and interactions between actor groups. It does not include statement on needs or potentials of specific actor groups that do not relate to interaction with other actor groups.	Networks enable communication and information exchange
Culture	This category entails drivers and barriers regarding the values, belief, perception, and attitudes of people. new knowledge.	Statements on the fit with the existing social and cultural system (e.g. with farm management and working practices) are included here. Further,	Lacking awareness, lacking openness for biochar technology

		awareness is part of this category as this describes how people behave towards potential	
Technology	All aspects regarding the biochar technology, meaning the production of biochar as well as its application.	All technological aspects that directly belong to biochar technology as a NET are captured here, this also entails application. Statements on pre-treatment of feedstocks and all statements on feedstock quality and suitability as this directly linked to the technology.	Technological maturity
Infrastructure	The category infrastructure depicts the value chain related aspects, this refers to everything that goes beyond the plant itself. It is about the techno-physical and organizational configuration of the system. More specifically it captures statements on biomass provision (resource availability and provision, storage, and	Biomass provision and feedstock logistics are included here, whereas biomass quality, suitability and biomass pre-treatment are included within the technology as they are directly linked to technology.	Biomass availability, short transportation distance of feedstocks

	transportation) as well as the distribution of the biochar and the production and usage of by-products.		
Institutions	In this category aspects that guide the production or use of biochar are collected. A procedure is a way of doing something as for example the (methodology for the) quantification of carbon sequestration. Moreover, formal institutions are rules that determine how to do something and are also captured here.	This category depicts the formal institutions that govern biochar systems. Informal institutions, that are unwritten, and comprise norms and values belong to the category culture.	Biochar certification, German Fertilizer Ordinance

Table XXVII: Coding guideline for subcategories

Category	Subcategory	Def. of subcategory	Not to include
Goals	-	-	-
People	Cooperation and organization	All statements on how people jointly engage in biochar technology, and how they organize.	Statements on communication
	Communication and knowledge dissemination	All statements on exchange and dissemination of information.	Statements on the level of knowledge
Culture	-	-	-
Technology	Biomass treatment and suitability	All statements on the technological feedstock requirements, linked pre-treatment processes and general the suitability of feedstocks for pyrolysis.	Statements on biomass provision, feedstock logistics
	Pyrolysis	All statements on the availability of technology, technological development, and costs of technology. This also includes technical knowledge.	Statements on general knowledge level and research Statements on technological determined feedstock requirements and statements on the biomass-conversion-fit Statements on energy production and usage
	Application	Biochar only becomes a carbon sink through the	Statements on application knowledge

		end application, in the case investigated within this thesis the end application in agricultural soils. In this category, the important aspects regarding the application are presented.	
	Knowledge	All aspects concerning the knowledge level, research and research gaps regarding biochar technology.	Statements on knowledge on other procedures, such as carbon crediting and funding Statements on knowledge dissemination Statements on knowledge regarding other processes, such as carbon crediting, are coded in the respective category
Infrastructure	Biomass provision	All statements on the biomass provision. This entails biomass acquisition, storage, transportation. Further feedstock availability.	Statements on regulations with regard to input, technological requirements with regard to inputs Statements on pre-treatment of biomass, feedstock suitability for conversion Statements on cooperations for biomass provision
	Biochar distribution	All statements on the techno-physical and logistical aspects of biochar	

		loading, refinement procurement and distribution. It is not about who is selling it, but about how biochar is sold.	
	Heat utilization	All statements on the use of the generated co products are included here.	Statement on actors that can fulfil the role of the energy consumer
Institutions and procedures	Regulation and certification	All statements of regulations that affect biochar development as well as on associated certification are depicted here. Certification determines how biochar is used and applied. Regulations prescribe how biochar can be produced (under which requests) and how it can be applied.	Statements on the certification of biochar as a carbon sink
	Carbon crediting and quantification of ecosystem services	Statements on procedures of and knowledge on the quantification and monetization of ecosystem services	
	Funding	Statements on financial support for biochar producers and appliers, such as subsidies or	Statements on carbon crediting as a financial support instrument

		biochar funding programs.	

Appendix E: Extended tables of the findings with references

Table XXVIII: Goals (based on focus group)

Goals
• Climate change mitigation (FG 1, 9, 17, 27, 29)
• Environmental and animal health benefits besides climate mitigation such as soil benefits (FG 3, 27, 183-184, 203, (FG 3, 5, 9, 14). • Healthy food production (FG 9)
• Economic motivation (FG 54, 207)

Table XXIX: Goals identified (based on interviews)

Goals
• Climate change mitigation (B1, 2, 6; B13, 32; B3, 2; B11, 2; B12, 15; B9, 22; B1, 2; B3, 30; B13, 13; B8, 6; B3, 2; B3, 57).
• Environmental co-benefits (B1, 43; B3, 2, 19, 26, 30; B5, 52; B7, 63; B9,10; B12, 40; B13, 13, 32).
• Resource management, circular economy (B1, 43; B3, 12; B4, 5-7, 9; B12, 2-3, 15)
• Combination of various benefits (B3, 19; B13, 13)
• Energy provision (B2, 50; B8, 18)
• Economic goals (B12, 15; B13, 2, B11, 2; B10, 5; B2, 2-3; B4, 5-7)
• Idealistic motivation (B6, 69, B7, 6; B10, 5; B11, 21; B13, 2)

Table XXX: People related drivers and barriers (based on focus group)

Drivers	**Barriers**
• Ongoing discussions, negotiations, knowledge exchange (FG, 48, 109-11, 221, 223, 224)	• Need for education on biochar (FG, 48, 121)
• Cooperation e.g. in forms of networks and association as well as between these (FG 9-7, 17, 121, 223)	• Communication due to complexity of biochar topic (FG 48, 121)
• Symposiums, events etc. for exchange of information (FG, 221-222)	

Table XXXI: People related drivers and barriers (based on interviews)

Cooperation and organisation	
Drivers	**Barriers**
• Ongoing development of cooperation (B8, 46) and existing options for organization of biochar concepts (B8, 46)	• Competition hampers joint progress (B12, 44-45)
• Organization on the municipal level (B7, 38-39, B11, 35)	• Administrative and organizational effort for collaboration (B1, 29-30; B7, 38-39)
• Joint operation as for example by an agricultural cooperative (B2, 61; B3, 42; 66; B6, 76; B7, 23, 67-68).	•
Communication and knowledge dissemination	
Drivers	**Barriers**
• Communication via networks and associations, symposia, talks to increased information and awareness and publicity of biochar (B8, 52, B1, 36-37, B2, 20, B8, 52; B7, 45-47; B11, 54; B13, 29-30)/ • Existence of platforms, associations etc for exchange and knowledge dissemination (B1, 36; B11, 54-56; B10, 29; B8, 52, B1, 36-37)	• Need to increase communication and information (B11, 38, B13, 29-30; B, 50-52, B9, 43-45)
• Television reports, newspaper, trade publications as means for information (B2.1, 2; B8, 52)	• Complexity of topic impedes communication (B1, 38; B3, 30, 65)
• Education (B11, 55)	• Time effort for information gathering, need for platforms to enable information gathering (B10, 29)
• Increased communication to foster relevance of NETs (B2, 29)	• Limited potential of communication due to need for practical experience (B7, 45-47)
• P: Information and communication with the agricultural sector enables sustainable development (B6, 69-71)	

Table XXXII: Cultural drivers and barriers (based on focus group)

Drivers	Barriers
• Practical experience with biochar (FG 27)	• Reservation, caution, conservative attitude (FG 107-108, 117)
• Idealism (FG 209)	• Agricultural system driven by (short-term) productivity (FG 190-191), leasing
• Willingness to change the agricultural system (FG 190-191)	• Lack of awareness of regulations (FG, 131)
• P: Appreciation of biochar benefits in the direct food marketing (FG 193)	• Lack of appreciation and reward of environmental benefits in society (FG 193)

Table XXXIII: Cultural drivers and barriers (based on interviews)

Drivers	Barriers
• Societal change (B2.1 16; B3, 59, B7, 94; B8, 29), • Increased awareness of NETs and biochar (B2.1 16; B3, 66).	• Lack of awareness (B2.1, 15; B2, 22; B3, 27, 34; 55; B10, 43-44; B11, 37-38; B13, 29-30).
• Agricultural system: mechanization, experience with residues, long-term planning, ecological orientation (B7, 45; B8, 25; B9, 39; B11, 22, 58).	• Lack of understanding and negative perceptions on biochar (B2, 24; B6, 69; B11, 37, B10, 43, B11, 56)
• Openness/ likeliness for biochar engagement: • High level of suffering increases likeliness for biochar adoptions (B7, 35) • Younger farmers show increased likeliness (B11, 55)	• Agricultural system: short term decisions, low level of suffering, leased land (B7, 34; B7, 85-86, B9, 2-4, B11, 22)
• Increased political will (B2, 29)	• Low willingness to cooperate (B7, 34)
	• Risk aversity (B5, 50; B7, 23; 35; B10, 17-18; 47)
	• Mistrust in politics (B7, 23)
	• Lack of environmental awareness and valuation of product quality among the end-consumers, purchasing decision is rather guided by cheap prices (B2, 25)

Table XXXIV: Technology-related drivers and barriers (based on focus group)

Drivers	Barriers
• Technological development and availability of technologies (FG 43, 49, 51, 54), ongoing technological progress (FG 27, 49)	• Costs of technology (FG 213)
• Simplicity of small scale plants (FG 27)	• High labour demand (FG 72)
• Technological feasibility of pre-treatment (FG 85, 89, 91-93)	• Suitability of available plants (FG 72)
• Scientific findings and ongoing research (FG 25, 100, 101, 181)	• Need to improve biomass-conversion-fit and flexibility for feedstock conversion (FG 70, 91-93)
	• Need for research e.g. on environmental benefits • As well as on biochar qualities depended on the pyrolysis plants (FG 100, 110, 121, 145-157)

Table XXXV: Technology-related drivers and barriers (based on interviews)

Biomass pre-treatment and suitability	
Drivers	**Barriers**
• Technological feasibility of feedstock pre-treatment and adjustment of conversion (B2, 11-15, B11, 68)	• Technological requirements regarding the input materials (B4, 15-17; B2, 11-13, B5, 16; B10, 7; 20) and associated pre-treatment processes (B4, 17, 25-26, B5, 14, 16, B2, 13)
• Feasibility of feedstocks (B10, 20)	• Lack of flexibility regarding inputs (B1, 32; B4,15-17; B5,14, 16) • Need for technological development (regarding convertible inputs) (B11, 30, 61)
• Established pre-treatment structures and processes (B4, 25-26)	• Suitability of feedstock (B7, 41)
	• Feed-in into pile (B4, 13-15)
	• Need for adjustment and experience with input-conversion-adjustment (B2, 15-16, B11, 61)
Pyrolysis	
Drivers	**Barriers**

• Technological development and maturity (B1, 9-11; B3, 29; 54; B4, 19-22; B10, 25; B11, 39, 60-61, B13, 11-12).	• Costs (B13, 11-12)
• Simplicity and low costs of small-scale plants (B7, 29)	• Complexity of conversion process (B3, 30-32; B10, 25; B12, 32, 59)
• Ease of use, fully automated operation (B2, 41; B3, 35; B4, 19-22, 32, 54; B5, 16, B3, 30-32)	• Failure prone plants (B10, 25; B11, 60) • Lack of suitable plants (B5, 12; B7, 80)
• P: exact field trials (B7, 90)	• Labor and time demand for operation (B7, 48; B8, 54) • Need for technological knowledge (B7, 48; B8, 54)
	• High maintenance effort (B10, 25)
	• High energy demand (B12, 8)
Biochar application	
Drivers	**Barriers**
• Easy loading and application options, progress in application options, combination with other agricultural processes and equipment (B3, 43, 66; B6, 33-34, 36; B7, 51; B9, 2, 14; B11, 42, B12, 6, 14)	• Costs (B11, 42; B13, 12-13).
• Ongoing research and development (B11, 46)	• Lack of technical know-how (B7, 33; B12, 44; B13, 12-13).
	• Heterogenous scientific findings on biochar application (B12, 44)
	• Need to improve and optimized technical options for application (B7, 33; B11, 42, 46)
Knowledge	
Drivers	**Barriers**
• Level of knowledge and ongoing research (B2, 41; B11, 56).	• Need to improve level of knowledge/ research needs (B6, 39-40; B7, 92; B10, 29, 42; B8, 52; B12, 44)
	• Need of/ lack of technical knowledge on pyrolysis process (B3, 3-32, B12, 61; B3,30-32)
	• Need for synthesis of findings on application B12, 51-53)

Table XXXVI: Infrastructure-related drivers and barriers (based on focus group)

Drivers	Barriers
• Feedstock availability (FG 79-89), residues or feedstock with no alternative usage (FG 45, 77, 87, 79-81, 99, 101, 103-105) due to price advantage e.g. straw, left-overs from food production	• Usage competition e.g. for wood and hence high prices (FG 74, 99)
• Options for heat usage (FG 56, 70)	• Lack of heat usage concepts (FG 43, 62, 70)
• Low transport distances for biomass and heat, system configuration with location of pyrolysis plant close to biomass provision and heat demand (FG 164)/ Regionality/ decentral production (FG 56, 58, 60, 139)	• Seasonality of feedstocks (FG 102)
	• System configuration regarding feedstock input and energy demand (FG 102)

Table XXXVII: Infrastructure-related drivers and barriers (based on interviews)

Biomass provision	
Drivers	**Barriers**
• Availability of feedstocks (B2, 15-16; B2.1, 2; B3, 20-21; B7, 10; B8, 25)	• Raising price for input materials (B7, 41; B8, 37; B13, 11)
• Usage of residues (B1, 8, 18; B2, 2-3, 15-16, B2.1,2; B3, 18, 20-21)	• Uncertainty regarding input availability and price development (B4, 40; B7, 41).
• Short transportation distance (B1, 8, 13, 42; B2, 15-16; B2.-1, 6; B3, 41; B5, 8; B8, 11; B13, 5; 6-7).	• Lack of availability and usage competition (B1, 23-24; B8, 37; B12, 8, B11, 23; B12, 8) as well as seasonality of feedstocks (B1, 32)
• Established logistics (B12, 16-17; B10, 20, 31) • And viable options for logistics (B12, 3)	• Need to improve and develop logistics concepts (B1, 62; B11, 33; B12, 66-67)
Energy utilisation	
Drivers	**Barriers**

• Heat production and heat usage options (BB1, 6; 2, 51; B2.1, 9; B4, 55; B12, 5, 27; B13, 5, 18-19, 38)	• Need for heat usage concepts (B1, 11, 16; B2, 51; B10, 13-14; 35; B11, 6; B12, 27; B13, 38).
• Energy demand (B1, 20; B3, 44; B8, 19; B10, 14; B11, 6),	• Seasonality of heat demand (B12, 23)
• Need to improve energy system, decentral energy production for independent energy supply (B2, 61; B3, 44; B4, 55; B8, 19, B10, 14).	• Time, planning and organizational effort for heat usage concept (B3, 52)
	• Feed-in into existing grids (B10, 35; B3, 51; B4, 30; B10, 17-18; B13, 38)
	• Need for equipment for heat conversion (B4, 19-22)
	• Need of grids (B2,51; B13, 38)
Biochar procurement and distribution	
Drivers	**Barriers**
• Loading of biochar next to production (B8, 17; B12,6)	• Need for distribution concepts (B2, 55; B7, 22)
• Market opportunities (B4, 51-52, B8, 32)	• Lack of local chains (B11, 4)
• Flexibility regarding the distance (B1, 14-17)	• Lack of distribution structures (B11, 4)
• Growing structures (B11, 4)	• Optimization of logistics (B11, 48)
• Optimized logistics (B11, 48)	

Table XXXVIII: Institution- and procedure-related drivers and barriers (based on focus group)

Drivers	Barriers
• Existing certification and ongoing development (FG 10-11, 52, 82-83, 118)	• Effort for compliance with regulations and certification (FG 63)
• Voluntary carbon certification for biochar (FG 17-18, 47, 155 203)	• Legal uncertainty, lack of an enabling legislative framework, legislative heterogeneity and complexity (FG 110, 125, 127-129, 143, 144, 163)

	• Misleading and restrictive regulation (FG 74, 77, 110)
• Regulative change (FG 74, 82-32), enabling legislation (FG 111-114)	• Uncertainty of carbon crediting and lack of incorporation of biochar into CDR market (FG 155, 215) • Need of quantification method for carbon sequestration and further develop certification system (FG 118, 120-121) • Verification and quantification of carbon crediting (FG 117)
• P: Funding (FG 148-153)	• Lack of funding for ecosystem services (FG 145-147, 148-153)

Table XXXIX: Institution- and procedure-related drivers and barriers (based on interviews)

Certification and regulation	
Drivers	**Barriers**
• Certification (B1, 62; B8, 8; B3.1, 3; B12, 41-44) and the EBC system (B8, 8)	• Overregulation Germany (B2.1, 15, B2, 7, B2 55-57) and restrictive regulation (B1, 43; B2, 45; B8, 6; B11, 30; B3.1, 9; B4, 41-43).
• Regulative change, more specifically the amendment of the fertilizer ordinance (B1, 42)	• Bureaucratic effort for compliance with regulation and certification (B3.1, 22-25; B8, 32; B13, 6-7).
	• Heterogenous regulative landscape (B12, 56)
	• Regulative uncertainty (B4, 11, B10, 31; B13, 25)
	• Approval procedures (B2, 47, 55-57; B4, 30; B8, 32; B10, 31; B13, 14-16)
Carbon crediting and quantification of ecosystem services	
Drivers	**Barriers**
• Carbon crediting (B2, 29; B2.1, 16; B3, 23; B7, 76; B11, 15-17; B8, 43-44; B13, 25; B13, 27-28).	• Heterogenous carbon accounting methodologies (B3, 27; B13, 34)
• Established certification system (B1, 44-45; 47-48, B2, 28-29)	• Complexity of carbon crediting (B13, 34)
• Voluntary carbon market (B1, 50-52)	• Need to improve carbon crediting systems (B13, 27-28)

• P: Incorporation in the state carbon market (B12, 49)	• Need for incorporation into state market (B11, 15-17)
• Demand in the carbon market (B8, 43-44)	• Bureaucratic effort (B8, 32; B7, 7-8, 83-84; B10, 29)
• Progress in carbon markets (B8, 43-44)	• Inconsistency and lack of data (B10, 27)
• P: Need for quantification of ecosystem services (B3, 62-63, 66)	• Required knowledge and information on carbon crediting procedures (B3, 62; B8, 43; B10, 29).
Funding	
Drivers	**Barriers**
• Funding as a NET (B3, 49; B10, 49) and other funding options (B2, 9; B3.1, 27-29; B8, 39-40).	• Need for funding (B3, 56)
	• Effort and know-how for funding procedures (B2, 9; B5, 40)
	• Lack of suitable funding options (B3.1, 27-29)
	• Heterogeneity and complexity (B8, 39-41, B5, 40)

Appendix F: Goals and underlying drivers and barriers

Table XL: Goals and underlying drivers and barriers

Goal	Drivers	Barriers
Carbon sequestration	• Carbon crediting • Perceived relevance of needed negative emissions • Positive attitude towards environment and society • Idealism • Co-benefits	• Lacking perceived relevance of negative emissions in the agricultural sector • Lacking economic reward for carbon sequestration
Soil benefits	• Negative climate impacts and degraded soils • Indirect economic benefits • Idealism	• Costs • Lacking economic reward • Good quality soils • Environmental challenges such as water stress
Economic goals	• Carbon crediting • Productivity increase • Business diversification	• Lack of sufficient productivity increase • Lacking economic incentives
Resource management	• Disposal problems • Cascading usage	
Energy provision	• Energy demand • Need for decentral and self-sufficient energy production • Gas crisis	• Lack of concepts • Lack of infrastructure for energy usage

9 Declaration of independence

HUMBOLDT-UNIVERSITÄT ZU BERLIN

Faculty of Life Sciences

Albrecht Daniel Thaer Institute of Agricultural and Horticultural Sciences

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Zoe Hoffmann