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How Can Biochar Systems Achieve Financial Viability in the Current Market Setting While Maintaining Their Environmental Impact? – Evaluation and Assessment of a Biochar System: The Case of Cascais

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Abstract:

Biochar systems present a promising solution for climate change mitigation through carbon sequestration and sustainable resource use. However, adoption faces the challenge of variable financial viability, leaving the biochar market underdeveloped. To address the question, *“How can biochar systems achieve financial viability while maintaining their environmental impact?”*, we extensively analyzed market enablers, barriers, and cost-revenue dynamics, foundational for our primary research. Interpreting expert interviews through deductive and inductive analysis methods, we developed 10 principles to guide financially viable biochar systems. These principles, demonstrated through a Cascais case study, offer context-sensitive strategies to navigate market complexities and promote broader biochar adoption.

Keywords:

Biochar, Biochar System, Carbon Dioxide Removal, Financial Profitability, Environmental Impact, Sustainability, Strategy Development, Eco-Innovation

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1 Introduction

This thesis explores the potential of biochar as a financially viable solution for addressing climate change through carbon capture and storage. The introduction provides a foundation for the study, starting with the problem statement outlining the urgency of climate action and the need for innovative solutions such as biochar. This is followed by the research objectives, which define the scope and purpose of the study.

1.1 Problem Statement

Climate change, fueled by increasing greenhouse gas (GHG) emissions, presents a critical challenge to global ecosystems, human health, and economic stability. Although this threat has long been acknowledged and the underlying reasons are well understood, emissions from human activities continue to rise, leading to higher atmospheric GHG concentrations and global surface temperatures. These changes already have widespread impacts on various sectors, including the weather, health, food systems, and the economy with significant consequences for livelihoods worldwide (Calvin et al. 2023).

In response, national and international frameworks, such as the Kyoto Protocol, the Paris Agreement, and the UNFCCC, have been implemented over recent decades. These frameworks have driven policy development and target-setting at multiple governance levels to control atmospheric GHG concentrations by limiting emissions. These initiatives have led to positive outcomes through technology-push policies and behaviour-driven incentives, such as reduced prices for low-emission technologies and increased financing for climate mitigation and adaptation. Consequently, some countries have achieved notable progress in reducing production-based CO_2 emissions and absolute GHG levels over the past decade (Calvin et al. 2023).

Despite these advances, current global efforts remain insufficient in mitigating climate change to a manageable degree. Without additional commitments or accelerated actions, the likelihood of limiting global warming to below 1.5°C becomes increasingly uncertain, with projections suggesting a potential rise beyond 2°C (Calvin et al. 2023). Additionally, scenario analyses have demonstrated that merely reducing GHG emissions will not suffice to keep global warming within the targets set by the UNFCCC and the Paris Agreement. Even the most ambitious emission reduction plans fall short of achieving these targets without substantial atmospheric Carbon Dioxide Removal (CDR) (Beerling et al. 2020). While the specific amount of CDR needed varies across different mitigation scenarios aligned with the Paris Agreement, ranging from several hundred to over a thousand gigatons of CO_2 throughout the 21st century, all scenarios consistently indicate a critical need to scale up CDR efforts. This consensus underscores the importance of advancing and adapting existing CDR methods to effectively meet global climate targets (Powis et al. 2023).

Biochar is one of the emerging proven technologies to capture carbon dioxide from the atmosphere and its potential is attracting a growing interest from investors and organizations worldwide (Fawzy et al. 2020). Driving its attractiveness, Biochar Carbon Removal (BCR) can have lower land, water, energy, and cost requirements than comparable CDR methods such as Direct Air Capture (Smith 2016). In addition to its carbon removal benefits, BCR systems produce biochar and energy, both of which are valuable resources. These outputs can generate additional revenue streams while replacing less sustainable practices in sectors such as agriculture, construction, and energy. While biochar´s capability to sequester carbon is widely accepted, it is unclear what role it could play in mitigating climate change, and its financial viability is still questionable. This uncertainty has resulted in underinvestment, limiting the widespread adoption of the technology (Campbell et al. 2018; Thengane et al. 2021).

1.2 Research Objectives and Purpose of the Study

This study aims to address the research question: "How Can Biochar Systems Achieve Financial Viability in the Current Market Setting While Maintaining their Environmental Impact?" While biochar is often considered a promising solution for carbon capture, its actual role in mitigating climate change remains uncertain. Assessing this role requires a comprehensive examination of the opportunities and limitations of biochar systems within their broader operational landscape. This research contributes by investigating the factors that shape biochar's potential, including market dynamics, technological innovations, operational challenges, regulatory frameworks, and stakeholder engagement. By understanding these interconnected elements, this study seeks to evaluate the extent to which biochar can achieve both financial sustainability and meaningful environmental impact, fostering its broader adoption. Ultimately, this thesis aims to offer guidance to organizations seeking to develop biochar systems that achieve financial sustainability while maintaining their environmental benefits within the current market context.

This paper begins with an assessment of biochar's role in mitigating climate change. We then examine the biochar market alongside the technological, operational, and regulatory factors that influence the success and scalability of biochar systems. Drawing from this analysis and existing literature, we then formulate hypotheses to address key challenges and opportunities. Subsequently, we will outline our data collection process and methodology. The data collection process involves gathering insights from experts across various fields to understand the practical realities of biochar systems, while the methodology employs both deductive and inductive analysis to evaluate the data. Following, we present the results of our deductive analysis, interpreted in the context of the hypotheses, with a discussion that reflects on the reviewed literature. Additionally, the inductive analysis in the results section explores new insights that extend beyond the scope of the hypotheses. Ultimately, the hypotheses will be refined to reflect the findings of our dual analysis, and culminate in a set of principles designed to guide the development of financially viable biochar systems. After, a case study on Cascais Municipality is presented to demonstrate the application of these principles and their potential impact. Lastly, we will discuss the limitations of our study and potential future directions for research.

While technical aspects play a crucial role in the efficiency of biochar setups, the principles developed will not focus on the technicalities of biochar systems. Instead, they will emphasize key opportunities and considerations regarding the project development that significantly contribute to financial performance, growth, and overall sustainability. Similarly, these principles will not delve into driving specific market changes, despite the young market's potential for growth. Rather, they will focus on how the characteristics of the current market impact biochar system setups and how these can or should be leveraged to ensure success. These principles will serve as a guideline for the development of future biochar systems and optimization of existing systems, increasing their chances for success. By providing a clear framework for how to build successful biochar systems in alignment with the market, technology, operations, policy compliance, and ecosystem engagement, these guidelines aim to motivate and support more organizations in adopting biochar technology.

2 Biochar and its Potential to Mitigate Climate Change

Biochar has emerged as a powerful tool in the fight against climate change, with its potential to sequester carbon and mitigate environmental impacts placing it at the forefront of sustainable solutions. This chapter assesses biochar's role as a carbon dioxide removal (CDR) method, exploring how it can effectively contribute to addressing global climate challenges. To provide the necessary context, we begin with an overview of biochar technology, including its production process, key outputs, and wide-ranging applications. This foundation is critical for understanding the mechanisms that enable biochar to mitigate climate change and drive its growing importance in sustainable development.

2.1 Biochar Production Process

Biochar, simply put, is a charcoal-like material produced intentionally by heating organic biomass at high temperatures in the absence of oxygen. Biochar has a long-standing history, with its earliest documented references tracing back to the mid-nineteenth century. However, it was not until the 1990s that its potential to mitigate climate change began to receive significant attention (Kamarudin et al. 2022). With growing global pressure to reduce carbon emissions due to the intensifying impacts of climate change, interest in biochar has recently surged, accelerating technological advancements in its production. In contrast to its historical origins, contemporary biochar production methods now employ advanced industrial tools, resulting in a more controlled and efficient process (Köves et al. 2024). Biochar can be produced through several thermochemical conversion methods, including pyrolysis, hydrothermal carbonization, gasification, and torrefaction, all of which rely on heating biomass in a controlled environment (Yaashikaa et al. 2020). As pyrolysis is the most commonly employed technique for biochar production, this discussion will primarily focus on pyrolysis technology. Furthermore, for clarity and readability, the term *‘pyrolysis’* will represent other thermochemical conversion techniques throughout this thesis.

During the pyrolysis process, biomass acts as the main feedstock, with almost any organic material—ranging from wood and agricultural residues to manure—being suitable when processed in compatible machinery and systems. However, the properties of the resulting biochar are influenced by the specific feedstock used, making it essential to consider factors aligned with the intended application. Key considerations include the presence of potential toxins such as heavy metals, as well as the carbon and nutrient content of the biomass (Filiberto and Gaunt 2013).

The pyrolysis process consists of three fundamental stages. Initially, moisture is removed from the biomass, followed by the thermal decomposition of its primary components. Finally, secondary reactions occur, further breaking down the resulting material into simpler compounds (Köves et al. 2024). In this thesis, however, we will not explore them in further detail, as they are not essential for building the foundational understanding necessary for this business-focused research. In summary, pyrolysis involves drying the biomass and then heating it to temperatures ranging from 300°C to 900°C in an oxygen-free environment, preventing combustion and enabling the conversion into biochar (Köves et al. 2024). Depending on the feedstock type and the desired biochar application, additional preparatory steps, such as drying and cutting, may be required prior to pyrolysis. Likewise, post-processing steps may be necessary to tailor the biochar for specific applications. The pyrolysis process is both sensitive and highly adaptable, with the resulting biochar characteristics influenced by factors including feedstock composition, moisture content, and use of additives (Thomas 2021).

In addition, the pyrolysis process conditions—such as temperature, heating rate, residence time, particle size, and reactor design—play a critical role in determining the characteristics of the resulting biochar (Köves et al. 2024). This highlights the importance of understanding these variables and aligning them with the overarching goals of the biochar system to optimize its effectiveness and suitability for specific applications.

Next to biochar, modern pyrolysis systems yield syngas, bio-oil, and other valuable by-products. Given the high costs associated with storing and transporting syngas, it is commonly (partially) combusted on-site to supply the necessary heat for the pyrolysis process. However, syngas also presents opportunities for external utilization. It can be repurposed to provide heat for nearby applications or to generate electricity for grid integration. In contrast, bio-oil is more manageable in terms of storage and transportation and holds potential as a replacement for fuel oil or diesel in stationary applications, making it an attractive resource for the energy sector. Additionally, bio-oil serves as a source for producing a range of valuable chemical products (Biochar International n.d.).

2.2 Biochar Characteristics and Application Cases

Beyond its carbon-capturing capabilities, the main pyrolysis output biochar is also valued for its highly porous structure, with a surface area spanning 10 to several hundred square meters per gram (Thies and Rillig 2009). The characteristics and degree of porosity in biochar are influenced by the pyrolysis process, which can be adjusted to meet specific application requirements by controlling parameters such as temperature and heating rate during pyrolysis. This way biochar’s structure and surface area can be tailored, allowing it to provide maximum benefits for particular applications. This adaptability makes biochar a versatile material for a diverse set of application cases.

One of the most common applications of biochar is its use as a soil additive. Its porous structure enables it to adsorb soluble organic matter, gases, and inorganic nutrients, which enhances soil quality and improves nutrient retention (Thies and Rillig 2009). By enhancing soil health, biochar reduces the demand for synthetic fertilizers, which are a significant source of the powerful greenhouse gas nitrous oxide. These key benefits of biochar in soil lead to a strong focus on soil-related applications. According to the Global Biochar Market Report by Gray, Smith, and Maxwell-Barton (2024) five of the ten most popular end-use markets are connected to soil enhancement. In a survey conducted by the International Biochar Initiative and the US Biochar Initiative for this report, biochar producers identified the following soil-related applications as primary use cases for their biochar: agriculture (crops) at 70%, horticulture at 28%, soil remediation at 21%, reforestation at 11%, and landscaping at 8%.

Biochar’s remarkable ability to absorb various substances makes it an ideal material for various applications beyond soil enhancement. In water filtration systems, this absorbent property allows biochar to be effectively used in treating wastewater, including stormwater, municipal, agricultural, and industrial effluents (Quispe et al. 2022). In the Global Biochar Market Report (Gray, Smith, and Maxwell-Barton 2024), 11% of biochar producers identified water filtration as a primary application. Additionally, biochar’s inclusion as a feed additive in livestock agriculture —cited by 24% of producers as a key use case— offers numerous benefits, such as deactivating digestive toxins, supporting beneficial intestinal flora, and improving overall animal health and growth performance (Schmidt et al. 2019).

One of the more recently explored use cases is the application of biochar in construction materials. The construction sector recognizes its potential for carbon storage, leading to an increasing incorporation of biochar as an additive in materials like concrete, asphalt, and other building materials to reduce industry emissions. The role of biochar in construction supports carbon sequestration by locking carbon into durable materials, providing long-term stability. Additionally, incorporating biochar into construction materials provides several technical advantages, including humidity and heat regulation, thermal insulation, noise reduction, improved air quality, and electromagnetic shielding, further motivating its application in construction (Zhang et al. 2022).

This versatility, combined with its carbon-sequestering capabilities, positions biochar as a transformative material that can significantly support the decarbonization of various sectors, from agriculture and water management to construction and beyond.

2.3 Biochar Systems

To fully understand biochar production, we must view it within a larger framework that considers the interdependencies between processes, materials, and stakeholders. Crombie et al. (2015) proposed dividing this system into three phases: biomass, conversion, and use. These phases highlight the steps involved in transforming organic biomass into biochar and unlocking its environmental benefits.

A biochar system is built by aligning key components across its three phases: biomass supply, conversion, and use. This includes materials like feedstock and production machinery, as well as processes such as pyrolysis settings and transportation. These components are closely connected to stakeholders like biomass suppliers and end users. Depending on how the system is configured, it can integrate with broader frameworks like waste management or land-use strategies. The system’s success depends on carefully selecting and combining its elements to ensure stability and maximize economic and environmental benefits (Crombie et al. 2015).

Figure 1. provides a simplified representation of the biochar system, highlighting only the primary materials and the pyrolysis process. Pyrolysis is emphasized as it represents the core process through which biochar is produced, forming the central component of all biochar systems.

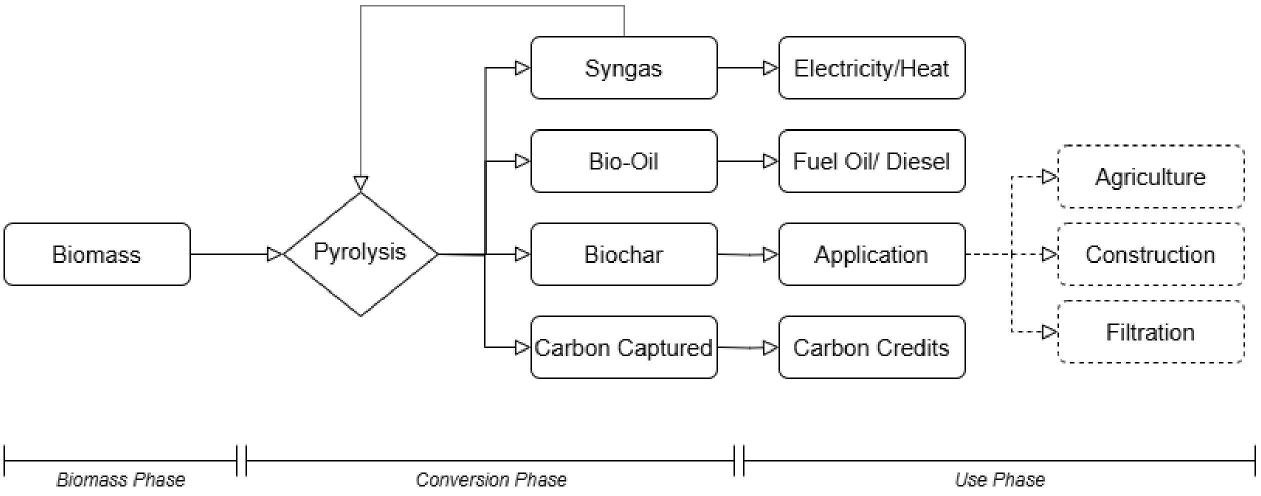

Figure 1: Simplified Biochar System Model

Note. This figure outlines the biochar production process across three phases: biomass, conversion, and use. Biomass undergoes pyrolysis, producing syngas, bio-oil, biochar, and captured carbon, each with specific applications like energy generation, fuel, agriculture, and carbon credits. Pyrolysis is highlighted as the core process that transforms biomass into various outputs for diverse uses.

In addition to the availability of the components, the underlying motivation of the biochar system plays a crucial role in its analysis. A biochar system offers several key advantages: (1) climate change mitigation, (2) waste management, (3) energy production, and (4) specific biochar characteristics tailored to particular use cases, each of which can serve as the system's primary motivation. The system can be strategically structured to maximize one of these outputs, with different building blocks selected accordingly to achieve the desired outcome (Lehmann and Joseph 2015).

2.4 Biochar Ecosystems

The biochar ecosystem is a complex network of interconnected stakeholders, each playing a critical role in the production, distribution, and utilization of biochar. From feedstock supply to end users and supporting actors, this ecosystem showcases the intricate interdependencies necessary for advancing biochar as a sustainable solution for carbon sequestration, soil enhancement, and economic development.

At the core of the value chain are *biomass producers and suppliers,* who provide the essential feedstock for biochar production. These may include farmers, who supply agricultural residues such as crop stubble and husks, forestry companies that provide wood waste, and municipal waste managers, who contribute organic waste streams. The availability and quality of these feedstocks are pivotal to the efficiency and scalability of biochar production, forming the foundation of the entire system. Often, these biomass suppliers are directly connected to *biochar producers*, who transform these raw materials into biochar through pyrolysis processes. Producers are central to the ecosystem, converting biomass into biochar and additional by-products such as bio-oil and syngas (Salo et al. 2024; Thengane et al. 2021). These by-products add economic value and can be sold to *pyrolysis by-product buyers*, who utilize them for renewable energy generation or industrial applications (Mohammed et al. 2024).

The role of *pyrolysis equipment manufacturers* is critical in enabling the production process. These manufacturers design and supply the specialized machinery needed to convert biomass into biochar, influencing the efficiency, quality, and environmental footprint of the production (Salo et al. 2024; Thengane et al. 2021).

Once biochar is produced, it is either sold directly to clients or moves to *biochar distributors*, who act as intermediaries, ensuring its delivery to end users. Local cooperatives play an important role in rural areas, connecting small-scale producers with farmers and community-level end users, while commercial distributors cater to larger industrial markets, including export (Mohammed et al. 2024; Thengane et al. 2021). These distributors can be instrumental in linking producers with *biochar consumers*, who utilize the product for various applications (Salo et al. 2024; Garcia et al. 2022).

Supporting these market interactions are *carbon accounting firms*, which provide essential services in quantifying and verifying the carbon sequestration achieved through biochar projects. These firms play a critical role in enabling producers and consumers to participate in carbon credit markets by certifying the amount of carbon removed from the atmosphere. *Carbon credit buyers*, such as corporations and institutions, purchase these credits to offset their emissions, providing a significant financial incentive for biochar production and contributing to the fight against climate change (Mohammed et al. 2024; Price, Morris, and Morris 2024).

Ensuring the quality and credibility of biochar products are *biochar labs and certifiers*, which test and certify biochar for compliance with established standards. Their work builds trust in the market and enables producers to meet regulatory and consumer expectations (Thengane et al. 2021).

Complementing this are *biochar consultancies*, which provide specialized advisory services to new and existing players in the industry. These consultancies guide stakeholders on project development, technology selection, and market opportunities, addressing logistical and technical challenges while facilitating the integration of biochar projects into broader sustainability strategies (Biochar Zero 2024 ; BioFlux Biochar Consulting Services n.d.)

The ecosystem is further shaped by *investors*, who provide the capital necessary to finance production infrastructure, purchase pyrolysis machinery, and expand operations. By supporting biochar producers, these investors stimulate innovation and help scale the industry to meet growing global demand (Thengane et al. 2021). Finally, *advocacy groups and research networks* play a pivotal role in promoting biochar as a sustainable technology. These actors conduct scientific research and create awareness, laying the groundwork for biochar's integration into climate action frameworks and economic development strategies (Mohammed et al. 2024). The influence of *policymakers* in the biochar industry is crucial in shaping regulations and incentives that promote biochar production and use. They set standards and create economic incentives, such as subsidies or tax breaks, that make biochar projects more attractive to investors and end users (Pourhashem et al. 2019)

Together, these interconnected players form a dynamic system that leverages biochar's potential for environmental and economic benefits. Figure 2 provides a visual representation of these players, showing how their roles interconnect and how material, knowledge, and influence flow through the ecosystem**.** By coordinating their efforts, they create a sustainable and resilient value chain that contributes to climate change mitigation, soil health, and sustainable development.

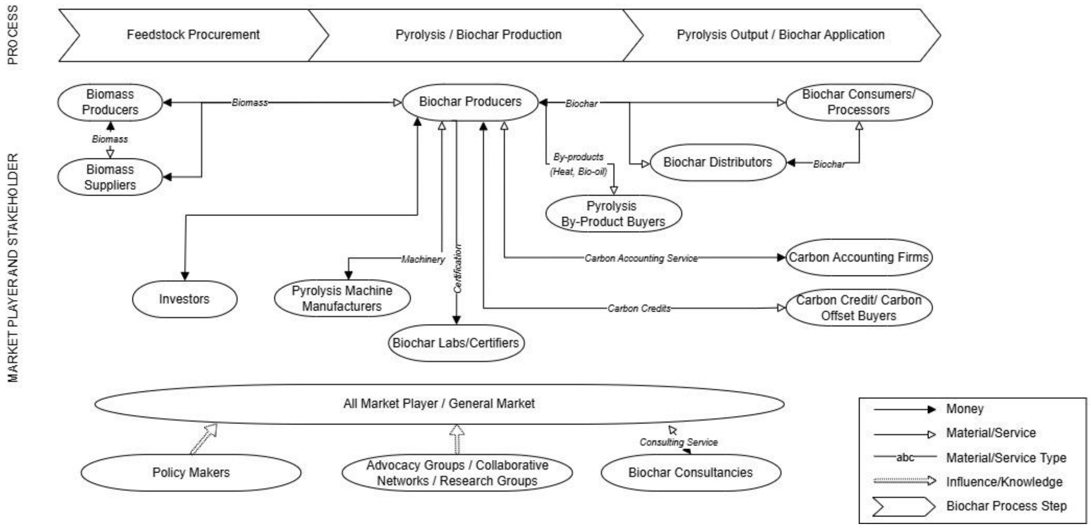

Figure 2: Biochar Ecosystem Visualization

2.5 Biochar and Carbon Capture

The Intergovernmental Panel on Climate Change (IPCC) identifies biochar as a negative emission technology (NET) with the potential to capture carbon and reduce atmospheric CO2 levels (Zhang et al. 2022). During growth, all plants absorb CO2 in the process of photosynthesis. While this captured carbon would naturally be released back into the atmosphere when the biomass is burned or decomposed, the transformation into biochar breaks this cycle and stores the CO_2 in a stable, decomposition-resistant form. Depending on the feedstock and production method, biochar can sequester an average of 2.1 to 4.8 t CO_2 per ton of biomass (Fawzy et al. 2020).

With global frameworks aimed at reducing atmospheric CO_2 levels developing and organizations increasingly aiming to reduce their emissions, the climate benefits of biochar production can now be monetized. For every ton of CO2 captured, they can sell carbon credits, typically used to offset internal emissions, directly to organizations or offer them on voluntary carbon markets (VCM).

To realize this opportunity, biochar production methods require independent certification by a third party, validating the carbon sequestration achieved through BCR and ensuring adherence to established carbon credit standards. Transparency is crucial in this process to prevent double counting of carbon credits, ensuring that each unit of sequestered carbon is accurately tracked and only credited once (Delaney and Hawkes 2005). Due to the high market value of carbon credits, almost all leading biochar producers actively sell these credits, leveraging biochar's carbon sequestration potential to generate additional revenue (Salma, Fryda, and Djelal 2024).

In carbon accounting for captured carbon, several key principles must be considered, with the main ones being *additionality, leakage, and permanence. Additionality* assesses the impact of an intervention by comparing it to a baseline scenario that models what would happen to carbon fluxes without the project. *Leakage* refers to the risk of unintended carbon emissions resulting from the project, which could reduce the net benefits of carbon capture (Nolan, Van Paasschen, and Field 2024). Finally, *permanence* or *durability* emphasizes the need for long-term storage solutions to prevent carbon from re-entering the atmosphere, ensuring sustained sequestration over time (Byrne 2024). Adhering to these principles ensures that biochar projects deliver credible and measurable climate benefits.

The concept of additionality is closely connected to the selection of the right feedstock as a foundation of the biochar system. Biochar production must use sustainably sourced biomass to maximize carbon capture and prevent negative environmental impact. Biomass sourced through harmful practices, such as clear-cutting forests or improper agriculture on peatlands, fails to provide additional carbon sequestration value. Instead, sustainable feedstocks, including agricultural residues, biomass from managed forests, and organic waste from food processing, are more viable choices that maintain existing carbon stores. This careful selection process ensures that the carbon captured by biochar production adds to existing environmental benefits rather than detracting from them (Schmidt, Kammann, and Hagemann 2020).

Permanence, or the long-term storage of carbon, is crucial for biochar’s effectiveness in sequestering carbon. To provide lasting climate benefits, biochar must be stored safely, either in soils or incorporated into materials, with minimal risk of carbon release. Applications like co-firing in biomass power plants or using biochar in steel production can release stored carbon, undermining its sequestration benefits. Therefore, stable, long-term applications that minimize these risks are essential for biochar to serve as a reliable climate solution (Schmidt, Kammann, and Hagemann 2020).

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These considerations underscore the complexity of carbon capture and highlight how it is tied to operational decisions. Every stage—from selecting sustainable feedstocks to managing emissions during pyrolysis and ensuring safe, long-term storage—affects biochar's overall carbon capture potential. This interconnectedness emphasizes that successful carbon sequestration through biochar depends on the material itself and the responsible and controlled management of its entire lifecycle.

2.6 Potential of Biochar to Mitigate Climate Change

Biochar has emerged as a tool for addressing climate change. This section builds on the foundational understanding of biochar's carbon capture capabilities outlined in Section 2.5, further examining its potential to mitigate climate change through carbon sequestration and reductions in GHG emissions. The discussion highlights biochar's scalability, contributions to global CO2 removal targets, and its integration into climate mitigation frameworks.

The fight against climate change necessitates significant carbon dioxide removal (CDR) to complement emissions reductions. According to the Intergovernmental Panel on Climate Change (IPCC), achieving the global target of limiting temperature rise to 1.5°C requires the removal of 100 to 1000 gigatons (Gt) of carbon dioxide (CO2) from the atmosphere by the end of this century

(IPCC 2022). This immense challenge underscores the need for scalable and cost-effective CDR solutions, among which biochar emerges as a promising option.

Biochar has a significant potential to contribute to climate change mitigation. Estimates suggest that biochar systems could sequester between 3.4 and 6.3 gigatons of CO2 equivalents (CO2e) annually, depending on factors such as feedstock availability, pyrolysis efficiency, and policy support (Lehmann et al., 2021). Over a 100-year period, this could result in the removal of 100 to 200 Gt CO2e, which is equivalent to 10–20% of the total CO2 removal needed to stabilize atmospheric CO2 levels. Importantly, these benefits are achieved without impacting food security or land conservation, as biochar production utilizes agricultural residues, forestry waste, and other biomass by-products (Woolf et al. 2010).

Among various CDR technologies, biochar stands out for its relative maturity, cost-effectiveness, and co-benefits. Emerging alternatives such as direct air capture (DAC) and enhanced weathering offer significant theoretical potential but face substantial barriers in terms of energy consumption, land requirements, and financial feasibility. DAC systems, for instance, often require $100 to $600 per tonne of CO2 captured due to the energy-intensive processes involved (Realmonte et al., 2019). Enhanced weathering, while potentially cost-competitive, necessitates large-scale mining and land application, raising concerns about environmental degradation and resource use (Lefebvre et al. 2020).

In contrast, biochar systems can capture CO_2 at costs ranging from $52 to $131 per tonne under optimized conditions, depending on the feedstock and pyrolysis technology used **(**Fawzy et al., 2021**).** This cost advantage, combined with biochar’s ability to sequester carbon in a stable form for decades to millennia, makes it a uniquely attractive solution.

The scalability of biochar systems further distinguishes it as a viable CDR method. Regional studies demonstrate its potential to offset substantial emissions. For example, in China, sustainable use of agricultural residues for biochar production could mitigate approximately 455 million tonnes (Mt) of CO2e annually, offsetting croplands' methane and nitrous oxide emissions (Xia et al. 2023). In biomass-rich regions such as South America, parts of Africa, and Eastern Europe, biochar could offset over 10% of national emissions. (Lefebvre et al. 2023).

Moreover, biochar production and application have additional benefits. When applied to agricultural soils, biochar not only stores carbon but also reduces emissions of non-CO2 greenhouse gases (GHGs) such as nitrous oxide (N2O) and methane (CH4). Studies have shown that biochar can lower N2O emissions by up to 80%, largely through microbial activity shifts and chemical stabilization, and suppress CH4 emissions in anaerobic environments such as rice paddies (Lehmann et al. 2021; Woolf et al. 2010). These reductions are particularly impactful in the agricultural sector, which accounts for a significant share of global GHG emissions.

Biochar offers transformative potential as a sustainable technology with diverse applications and significant environmental benefits. This chapter explores its production processes, unique characteristics, and broad use cases, highlighting biochar's role as a versatile solution for carbon capture, soil enhancement, and resource efficiency. By sequestering carbon and reducing greenhouse gas emissions, biochar plays a crucial role in mitigating climate change and aligning with global efforts to stabilize atmospheric CO2 levels. Additionally, its scalability and integration into sectors like agriculture, construction, and waste management emphasize its importance in both environmental and economic contexts.

3 Biochar Industry Landscape and Economic Insights

Having assessed the technologies´ fundamentals and potential for mitigating climate change, this chapter provides a comprehensive analysis of the economic realities of biochar systems on a market and system level. First, a general market overview is described, outlining its size and growth stage. This analysis highlights significant regional variations in biochar markets, guiding a detailed exploration of the market enablers and barriers that influence the profitability of biochar systems and, consequently, the adoption of BCR.

While market conditions play a crucial role in the financial viability of biochar systems, the subsequent section on profitability emphasizes that individual system configurations can also be key to achieving financial sustainability, even in less favorable markets. This discussion examines the cost and revenue components of biochar systems, highlighting the potential for innovative setups to optimize economic performance. The analysis concludes with the proposal of seven hypotheses for building financially viable biochar systems, derived from the findings and previous research, which will guide the methodology in subsequent chapters. This market analysis lays a critical foundation for the primary research to follow, addressing strategies to improve the financial viability of biochar systems.

3.1 Market Overview

This section provides an overview of the current biochar industry, exploring market size, growth trends, and regional variations. Importantly, the market development stage will be contrasted with biochar´s potential for carbon capture in climate change mitigation scenarios, raising questions about the opportunities and barriers affecting the growth of BCR´s role in mitigating climate change and its broader applications in agriculture, construction, and environmental remediation.

According to the Global Market Report of the International Biochar Initiative (2024), 350,000 metric tons of biochar were produced in 2023. These are predominantly used in the agriculture sector, leveraging its benefits for soil health, water retention, and nutrient efficiency, while more recent developments such as applying biochar for construction or water filtration are not as widespread yet (Gray, Boritzke Smith, and Maxwell-Barton 2024). For 2023, the market was valued at approximately $610 million, this number entailing the global revenue of biochar producers, distributors and value-added producers, and equipment manufacturers.

The market grew at a remarkable Compound Annual Growth Rate (CAGR) of 91% between 2021 and 2023. Furthermore, the fact that 39% of the biochar market consists of revenue generated by equipment manufacturers, indicates that substantial investments are being made into biochar systems and that this rapid growth is expected to continue before stabilizing at a lower rate. Projections suggest the market could reach nearly $3.3 billion by 2025 (Gray, Boritzke Smith, and Maxwell-Barton 2024; Biochar International 2024). While the key enablers and barriers to the growth of the biochar market will be discussed in detail later in this chapter, this rapid growth highlights increased interest in carbon capturing and climate change mitigation (Fawzy et al. 2022).

The adoption of biochar varies significantly across regions, shaped by differences in production methods, market maturity, and enabling conditions. North America leads global production at nearly 50%, driven by industrial-scale systems and advanced technologies (Gray, Boritzke Smith, and Maxwell-Barton 2024). Europe follows with 16%, supported by favourable policies and abundant forestry residues, with countries like Germany and the Nordic nations accounting for the majority of output. In Asia, biochar production ranges from traditional small-scale methods to emerging industrial facilities, particularly in China and India, where its use in agriculture and soil remediation is growing. South America contributes 11% of global production, dominated by a few large-scale systems, while Africa and Oceania focus on small, community-based operations with untapped potential due to abundant agricultural residues (Gray, Boritzke Smith, and Maxwell-Barton 2024).

Globally comparing biochar with other methods, it is the leading CDR technology by many metrics. In 2023, biochar systems contributed 59% of all carbon captured through durable CDR, and according to the carbon removal database CDR.fyi (2024), biochar carbon removal accounted for 94% of the delivered carbon credits in 2023. These figures and the market´s steep growth trajectory are impressive. However, comparing them to biochar´s potential for mitigating climate change, detailed in the previous chapter, it becomes clear that the market is still underdeveloped. In 2023, BCR sequestered only 0.02% of the minimum potential of 3.4 Gt CO2e it could contribute to stabilize atmospheric CO2 levels (Lehmann et al. 2021).

This stark contrast of the gap between biochar's current market performance and its potential for mitigating climate change along with the regional variations in markets, raises important questions: What factors enable the biochar markets to grow, and what challenges do they face? Are the leading companies driving technological innovation and scaling efforts, or are external factors such as policies, resource availability, and infrastructure playing a more significant role? Understanding the market enablers and barriers is crucial for identifying pathways for biochar to fulfil its role in mitigating climate change.

3.2 Market Enablers and Barriers

External market forces form the landscape within which biochar systems operate and can significantly influence their financial viability and performance. While growing environmental concerns have propelled interest in biochar technology and led to significant growth in the past decade, the biochar industry still faces significant market challenges acting as barriers for its development. Specifically, a combination of regulatory uncertainties, limited biomass availability, low awareness for biochar, and technological challenges create a disjointed landscape where potential investors are hesitant to engage, leading to underdeveloped markets that represent a complex setting for players trying to navigate and capitalize on opportunities (Salo et al. 2024). The following sections will examine the market dynamics that act as enablers or barriers to the financial viability of biochar systems. This analysis will focus on the interaction between regulatory, operational, technological, and economic factors that shape the financial success and, consequently, the adoption of biochar systems.

3.2.1 Environmental and Climate Considerations

Growing global awareness of the urgent need for climate action is a key driver of the biochar market, sparking interest in climate technologies among policymakers, private companies, researchers, and consumers (Lehmann and Joseph 2015). As a result, the biochar market is emerging as a leading solution for carbon capture and climate mitigation (Woolf et al. 2010). This heightened focus on climate action is accelerating market growth in several ways: Policymakers are increasingly incentivizing carbon capture systems and penalizing emissions, investors are prioritizing sustainability, and companies are seeking to offset their emissions (Lehmann et al. 2021). Most notably, it serves as a key motivation for early adopters to enter and develop the biochar market. Salo et al. (2024) found that while economic factors play a role, climate benefits remain the primary driver for most biochar stakeholders.

The growing public shift toward sustainability is driving demand not only for carbon capture solutions but also for sustainable products and practices more broadly. As discussed, pyrolysis offers climate benefits while producing valuable outputs such as biochar, bio-oil, and syngas. These outputs can be used across various sectors, including agriculture, construction, and energy, replacing less sustainable alternatives. In agriculture for instance, the use of biochar enhances soil structure, retains moisture and nutrients, and ultimately increases crop yields, aligning with global efforts to reduce reliance on chemical fertilizers and promote sustainable agricultural practices (Schmidt et al. 2022). Its increasing adoption in organic farming, along with regulatory support such as the European Biochar Certificate for soil application, is expected to further accelerate market growth (Grand View Research 2023). By displacing more carbon-intensive products and aligning with circular economy principles, converting agricultural waste, wood residues, and urban biomass into valuable resources, biochar systems are well-positioned to thrive in the growing market for low-carbon and sustainable solutions (Mašek, Brown, and Bakshi 2024).

3.2.2 Regulatory and Policy

The regulatory and policy environment plays an important role in shaping the biochar market. Policymakers increasingly recognize the potential of biochar systems to support decarbonization, with initiatives such as government subsidies for carbon capture systems and growing pressure on public and private institutions to reduce their carbon footprints. These measures have the potential to drive higher adoption and increase demand for carbon credits. However, the current regulatory landscape presents significant challenges alongside its benefits. Industry actors often view existing incentives for biochar production and application as insufficient, while the lack of effective centralized frameworks for regulating carbon markets further hampers progress. Additionally, certain regulations actively restrict the implementation of biochar systems, posing further barriers to market development (Salo et al. 2024).

To achieve the goals of the Paris Climate Agreement and frameworks like the European Green Deal, governments and international organizations have introduced policies aimed at supporting the development of biochar systems, particularly for carbon reduction and capture (Lehmann and

Joseph 2015; European Commission 2021). In the European Union, the Common Agricultural Policy (CAP) provides subsidies to encourage farmers to adopt sustainable agricultural practices. By improving soil health and enabling carbon sequestration, biochar allows farmers to qualify for these subsidies. In the United States, the Department of Agriculture (USDA) promotes biochar through its Conservation Innovation Grants Program, which funds innovative technologies aimed at improving soil health (USDA 2020). Additionally, the California Air Resources Board (CARB) supports biochar development by incorporating it into carbon offset programs, allowing companies to invest in biochar projects as a means of offsetting their emissions (Spokas et al. 2012).

In alignment with climate change initiatives like the Paris Climate Agreement, policies at regional, national, and international levels should prioritize reducing emissions while advancing technical solutions for carbon removal (Salo et al. 2024). A key challenge is the lack of centralized frameworks and standardized practices for voluntary carbon markets, which have so far been predominantly shaped by the private sector. Although platforms for carbon offsetting have been adopted by major companies such as Microsoft and Spotify, instances of fraud and non-transparent carbon accounting have undermined trust in these markets and the broader concept of emissions offsetting. Establishing centralized markets and regulatory oversight, such as those proposed by the EU, could restore confidence among market participants and support their progress toward achieving net-zero targets (Salo et al. 2024).

Similarly, no government-approved standards currently exist for biochar operations and applications. However, the industry has independently developed widely respected standards. The European Biochar Certificate (EBC) sets rigorous requirements for biochar production and quality, ensuring sustainable sourcing and biomass production, adherence to emission limits, and environmentally friendly storage practices (European Biochar Foundation 2021). Similarly, the

International Biochar Initiative (IBI) has established guidelines for biochar quality standards, focusing on safe applications in soils and food production systems (International Biochar Initiative 2015). To further support the development of biochar markets, participants in Salo et al.'s (2024) study advocated for measures such as implementing legally binding carbon removal targets, emission reduction schemes, and a definitive CO2 pricing mechanism. They also emphasized the need to transition from voluntary to compliance-based carbon markets and to increase incentives for biochar applications in both agriculture and industry (Salo et al. 2024).

In addition to the absence of policies and regulations that could foster further growth in the biochar market, some existing policies actively restrict its potential. For instance, legal constraints on materials like wastewater sludge, classified as waste, limit their use as feedstocks despite their potential to enhance the benefits of biochar systems (Raj et al., 2021). Similarly, regulations can hinder certain applications of biochar, such as in packaging, where existing standards may not accommodate biochar-enhanced materials. Integrating established scientific knowledge into industry standards and policies is crucial to overcoming these barriers and facilitating market growth. This underscores the need for further research, particularly long-term studies, to provide the evidence base necessary for these regulatory shifts.

3.2.3 Feedstock Availability

Another key factor limiting the growth of biochar markets is the availability of feedstock. In regions like Europe and North America, agricultural and forestry residues are already utilized efficiently, creating competition between biochar producers and other uses such as composting or further manufacturing. This scarcity presents a significant barrier to biochar production, driving up acquisition costs. For centralized, modern systems, consistent and reliable feedstock supply is particularly critical to justify the substantial capital investments **(**Hossain et al. 2011**)**.

While virtually any biomass can be converted into biochar, the choice of feedstock is crucial for both the operational efficiency and financial viability of biochar systems. The suitability of a feedstock depends on its intended application and the operation’s primary goals. For example, sewage sludge, with relatively few alternative uses, may be considered a low-interest feedstock. However, its low carbon content makes it less suitable for operations aiming to maximize environmental benefits. Although a more detailed cost-benefit analysis of biochar production will be provided in the next chapter, the competition, limited availability, and high costs of feedstocks often outweigh the monetizable benefits of biochar, posing a significant barrier to the industry’s adoption and investment growth **(**Faragò et al. 2022**).**

3.2.4 Technology Development

The maturity and characteristics of biochar pyrolysis technology are key factors influencing the market. The diffusion of biochar technology is following the classic innovation lifecycle, where early adopters and innovators lead the market, gradually paving the way for wider adoption by the early majority (Kapoor, Dwivedi, and Williams 2014). In its current phase, the biochar market is transitioning from research-driven innovation to early-stage commercialization. However, as Horbach (2008) notes, eco-innovations—defined as innovations that deliver both environmental and economic benefits—like biochar rely heavily on supportive environmental policies rather than market forces alone to drive adoption. Regulatory incentives, carbon pricing, and policy frameworks will therefore play an essential role in accelerating the industry’s growth and helping biochar systems overcome existing economic and technological barriers.

Although the process of heating biomass without oxygen has been practiced since the 19th century, purpose-built technology for biochar production has only been developed since its potential for carbon storage was recognized in 2005 (Lehmann & Joseph 2015). According to the Technology

Readiness Level (TRL) framework, a standardized tool used to evaluate the maturity of a technology from basic research (TRL 1) to fully operational and commercially deployed systems (TRL 9), biochar technologies remain in a mid-development phase. While some pyrolysis systems have reached operational viability (TRLs 7-9), many applications, such as soil amendments, are still at lower readiness levels (TRLs 1-2) (Möllersten and Naqvi 2022).

Recent data indicates that biochar producers employ a variety of technologies, with stationary augers and rotary kilns being the most widely used, accounting for 37% of systems. Portable kilns, valued for their flexibility and lower upfront costs, represent 24%, while stationary batch reactors and mobile carbonizers constitute smaller shares. These preferences reflect the scale and specific requirements of biochar production, with larger, industrial systems more common in North America. In contrast, portable kilns are particularly important in Africa and Asia, where lower capital costs and adaptability to local feedstocks make them more suitable (Gray, Boritzke Smith, and Maxwell-Barton 2024).

As pyrolysis technology and the biochar market mature, prices for equipment are expected to decline further (Woolf et al. 2010). Advances in automation are also poised to accelerate industry growth. However, high capital expenditures for advanced pyrolysis machinery remain a significant barrier for many potential early adopters. This issue is compounded by the sector's need for systems that are finely tuned to specific feedstocks and desired outputs, often requiring custom-made machinery. As a result, manufacturers face difficulties in standardizing and mass-producing equipment, which further hinders scalability and affordability (Zilberman et al. 2023). Notably, 54% of producers currently build their own equipment, underscoring the bespoke nature of the technology. As the industry scales, this trend is likely to shift toward more standardized, turnkey systems, particularly in developed markets where efficiency and high productivity are key priorities (Gray, Boritzke Smith, and Maxwell-Barton 2024).

3.2.5 Demand Uncertainty

Biochar producers also encounter market-driven uncertainties related to the revenue side of their operations. While carbon credits, as discussed in the Regulatory and Policy section of this chapter, represent one revenue stream, the market for biochar—the primary output of pyrolysis systems—remains underdeveloped (Salo et al. 2024). One contributing factor is the high cost of biochar, driven by the high costs of feedstock sourcing and pyrolysis equipment, as outlined earlier. This high price point significantly impacts its adoption, particularly among cost-sensitive farmers and industries like metallurgy and construction, where large volumes are required **(**Srinivasan et al., 2015**).**

In addition to cost, limited awareness of biochar’s benefits poses a significant barrier. Farmers, who are currently the primary buyers and users of biochar, as well as industry professionals, often lack knowledge about its applications and advantages. Peronne et al. (2023) applied the extended Technology Acceptance Model (TAM-2) to study biochar adoption among agricultural workers in northern Italy, finding that adoption is hindered by technical and knowledge gaps as well as resistance to change. Furthermore, while recent research has demonstrated that biochar delivers optimal results when matched with the right climate, crop, soil, and biochar type, earlier agricultural trials with mixed outcomes have contributed to hesitancy. Emerging applications in construction and metallurgy are even less established, leaving many potential clients unaware of the benefits biochar can provide **(**Jellali et al. 2021**).**

3.2.6 Lack of Funding

The factors outlined above make the financial viability of biochar systems uncertain in this early-market stage. While early adopters are often willing to accept these risks to achieve carbon capture, their systems represent high-risk investments with significant capital requirements. As a result, many existing players face limited funding from both public and private sources, while potential new entrants struggle to gain a foothold and make an impact on the market (Salo et al. 2024). This funding gap affects not only biochar producers and operators but also the broader ecosystem of the biochar market. It creates a "chicken-and-egg" dilemma: the technology is not yet advanced enough to make the market viable and attract investment, but sufficient investment is necessary to develop the technology further. Current levels of private and public financing for establishing biochar production remain inadequate, constraining the industry's growth and long-term potential (Salo et al. 2024).

3.3 Key Drivers of Profitability

The profitability of the biochar industry varies significantly, with only some producers currently operating profitably. As discussed in the previous chapter, market conditions play a crucial role in determining financial viability, as regions with supportive regulatory frameworks, ample feedstock resources, and favorable market dynamics offer greater opportunities for producers to thrive. Campion et al. (2023) emphasize that profitability is highly case-specific, aligning with previous research that identifies factors such as location-specific policies, market positioning, feedstock availability, production technology, scale, and reliance on by-products as key determinants (Byden and Fridlund 2020; Campbell et al. 2018; Shrestha et al. 2023). Nevertheless, the case-specific nature of biochar systems highlights their adaptability in design and operation. This means that even in less favorable market settings, producers can configure their systems in innovative ways to achieve financial viability despite challenging external conditions.

This adaptability highlights the need to analyze how individual firms can navigate their specific market environments and employ system specific strategies to become profitable. Understanding what players can do within their unique contexts is essential, as the widespread adoption of biochar and its potential to mitigate climate change relies on demonstrating its financial viability across diverse settings. As market-wide changes, such as improved regulations or increased subsidies, may take years to materialize, it is essential for firms to focus on leveraging existing opportunities and optimizing their operations within the current market landscape. Proactively addressing these challenges is key to accelerating the adoption of biochar and unlocking its full potential as a climate solution.

The economic viability of biochar systems hinges on a complex interplay between cost management and revenue generation. Key cost drivers include feedstock procurement, pyrolysis equipment and scale, operational expenses, and additional logistical considerations. Effective strategies for minimizing these costs can enhance the financial prospects of biochar production. On the other side, the revenue potential of biochar systems is shaped by several key drivers, including biochar sales, carbon credits, energy production, and in more rare cases waste management savings. While biochar and carbon credits represent the primary revenue streams, co-products need to be monetized to subsidize production. These cost and revenue factors, which individual firms can creatively adapt to enhance the financial viability of their biochar systems, are explored in detail in the following subchapters and subsequently serve as the groundwork for the development of principles to enhance the financial viability of biochar systems.

3.3.1 Cost Drivers

This section examines the key components influencing production costs, including feedstock, pyrolysis equipment, and operational expenditures. Each of these factors plays a significant role in shaping the economic feasibility of biochar systems, from sourcing and transporting biomass to the choice of technology and day-to-day operational decisions. By analyzing these cost drivers, we aim to identify opportunities for cost optimization and strategies to enhance the financial sustainability of biochar production while maintaining its environmental benefits.

Feedstock

According to Biochar Zero (2024), feedstock is the primary cost driver for most biochar businesses, as it includes not only the cost of acquiring the material but also transportation and preparation expenses. These feedstock-related costs significantly impact the overall economics of biochar production, in most cases accounting for 50-70% of total project costs (Shackley et al. 2015). The type of biomass, its availability, and the distance to the production site are key factors influencing costs. Feedstock prices vary widely based on regional supply and demand, directly impacting profitability. For instance, yard waste may be nearly cost-free, whereas agricultural residues like corn stover range from $59.4 to $83 per ton, and wood waste averages around $88.9 per ton (Shackley et al. 2015).While various feedstock options exist for biochar production, factors such as quality, carbon content, homogeneity, and price must be carefully evaluated. High-value feedstocks, such as spent grains or beetle-killed pine, can introduce substantial opportunity costs due to their alternative uses or high harvesting expenses, making them financially prohibitive in some cases (Field et al. 2013). Alternatively, biomass can be sourced externally often coming at a higher price and more impurities that require additional processing steps and ultimately result in higher expenses (Biochar Zero 2024).

As biomass can account for up to one-third of total production costs (Sessions et al. 2019)., focusing on lower-value feedstocks, particularly waste materials, has emerged as a practical solution to reduce costs. In some cases, waste feedstocks can even generate revenue through tipping fees, turning a traditional cost into a financial advantage (Ibarrola et al. 2012). While demand for organic waste has increased in recent years, driving up prices for some biomass types, low-interest waste streams like yard waste or forest thinning may still present cost-stable alternatives (Zilberman et al. 2023). Additionally, prioritizing waste feedstocks aligns with sustainable practices, further supporting biochar's role in resource recovery and waste management (Roberts et al. 2010).

Moreover, after selecting and acquiring suitable feedstock, transportation to the biochar production facility becomes a critical cost consideration, often involving the movement of several hundred tons. Transportation costs vary widely depending on factors such as regional labor prices and the distances involved. Roberts et al. (2010) highlight the sensitivity of costs to distance, showing that each 10 kilometers traveled adds $0.80 per ton to the total feedstock cost. Similarly, Kung et al. (2009) examined poplar tree feedstocks and calculated that an average transportation distance of 14.75 kilometers results in an added cost of $5.96 per ton, accounting for approximately 11 percent of production costs. McCarl et al. (2009) take a broader view, estimating that hauling costs can represent as much as 20 percent of the overall feedstock expenses. Although specific estimates vary, the studies consistently show that transportation costs can significantly impact the economic feasibility of biochar systems making it essential to minimize distances wherever possible. These findings highlight the strategic value of sourcing feedstock locally to minimize transportation costs and improve the sustainability of biochar production.

The high transportation costs can be addressed through the framework of shared value, a concept introduced by Porter and Kramer (2011), which emphasizes creating economic value while generating social and environmental benefits. In the context of biochar, this principle aligns with the development of local cluster systems, where businesses partner with local farmers, waste management companies, and government agencies to establish regional production hubs. These hubs not only reduce transportation distances but also contribute to local economic resilience and environmental sustainability (Pandit et al. 2018). By investing in local infrastructure and capacity-building, businesses can "drive productivity improvements in their value chain while also enhancing the social and economic conditions of the regions in which they operate" (Porter and Kramer 2011). Integrating the shared value framework into biochar systems provides a pathway to addressing transportation costs while achieving broader sustainability goals, such as waste management, greenhouse gas sequestration, and local economic development.

While acquisition and transportation are often the most apparent cost drivers, feedstock typically requires several pre-handling steps that can further increase costs. These steps may include drying to achieve suitable moisture levels, removing impurities, and adjusting the particle size to match the requirements of the pyrolysis machinery. Seasonal variations in feedstock availability may also necessitate the construction of appropriate storage facilities, adding to the overall costs. McCarl et al. (2009) estimate secondary storage and handling expenses at $25 per ton, while Shackley et al. (2015) estimate existing farm storage costs at $0.50 per ton for small pyrolysis units. For medium and large units, purpose-built storage is required, with annualized costs estimated at $22.50 per ton. Additionally, Kung et al. (2013) suggest that pretreatment processes account for approximately 6% of total production costs across both slow and fast pyrolysis systems. These combined costs highlight the importance of optimizing feedstock preparation and storage to improve the financial viability of biochar production.

Pyrolysis Equipment and Scale

The choice of pyrolysis technology and the scale of operations are critical factors influencing both capital expenditures and operating costs, as these depend on the technological complexity and level of automation. According to Biochar Zero (2024), equipment represents the largest capital expense for biochar producers, with the cost of establishing a pyrolysis facility varying widely based on the sophistication and scale of the equipment. Average estimates indicate that small to medium-sized units typically require an investment of $300,000 to $2 million, while large-scale industrial plants range from $3 million to $30 million (Biochar Zero 2024). These costs include the pyrolysis plant and pre- and post-processing equipment. For instance, gas turbines and generators used for energy production can alone account for over $1 million.

Overall, the biochar market remains characterized by diverse machinery configurations, as no dominant design has yet emerged (Shackley et al. 2015). While off-the-shelf equipment is available, custom-built or modular setups tailored to specific needs introduce uncertainties and complicate financial planning. Nonetheless, as pyrolysis technology matures, capital costs are expected to decline, resulting in more efficient and cost-effective equipment (Pierson et al. 2024).

Operational Expenditures

Operating costs are a critical factor in determining the economic feasibility of biochar production and significantly impact the financial performance of pyrolysis facilities. These costs include direct expenses such as labor and energy, as well as more complex elements like maintenance, overhead, and the effects of economies of scale. However, cost estimates in the literature are limited and vary widely. For instance, Brown et al. (2010) reported annual operating costs of $11.1 million and $18.8 million for slow and fast pyrolysis scenarios, respectively, both processing 2000 tons of feedstock per day. Operational costs are often estimated as a percentage of capital costs, with Bridgwater (2009) and Shackley et al. (2015) applying a rule of thumb that operational costs represent approximately 12% of total capital expenditures. Estimates for operating expenses range from $50 to $120 per ton of feedstock processed, depending on factors such as scale and energy integration (Pierson et al. 2024).

The scale of a pyrolysis operation significantly influences operating costs, with larger, centralized facilities typically achieving lower per-unit production costs by leveraging economies of scale. This efficiency arises from spreading fixed costs, such as labor and facility overhead, across higher output levels, making large-scale plants more economically efficient. Two studies on fast-pyrolysis production analyzed economies of scale by comparing the profitability of different capacity setups (with all other parameters constant) resulting in larger-scale plants being more economic per unit (Granatstein et al. 2009). While specific data for slow pyrolysis is limited, similar principles are likely to apply. However, this cost-efficiency may be offset by logistical challenges, such as increased transportation distances for feedstock or more complex maintenance requirements.

Labor, maintenance, energy, and overhead costs collectively form significant components of operating expenses in biochar production, with their magnitude varying based on facility size and technology. For example, labor costs depend heavily on the level of automation; highly automated, continuous-feed systems require fewer operators, while smaller, batch-style units demand more hands-on management. Skilled labor is also essential for maintaining and repairing pyrolysis equipment, particularly for new or custom-built technologies that may require specialized parts and expertise, further driving up costs. Moreover, maintenance and repair expenses, including routine servicing and unexpected repairs, add to the operational complexity by ensuring efficient system performance and minimizing downtime. Energy costs are another critical factor, as the pyrolysis process is energy-intensive, requiring substantial heat to maintain high temperatures. Facilities that integrate energy recovery systems, such as utilizing syngas produced during pyrolysis, can offset fuel needs, reduce net energy expenses, and even generate additional income, whereas those lacking such systems face higher costs. Finally, overhead expenses, such as facility upkeep, insurance, and regulatory compliance, while relatively fixed, can become disproportionately burdensome for smaller operations, further impacting their financial sustainability.

In summary, the operating costs of a biochar production facility are influenced by several key factors, including scale, labor, energy, maintenance, and overhead expenses. Facilities that can optimize these aspects through energy integration, economies of scale, and efficient maintenance practices are more likely to achieve cost-effective operations. However, as with many emerging technologies, significant variability remains in these cost components, reflecting the evolving nature of biochar production.

3.3.2 Revenue Drivers

This section examines the diverse revenue streams of biochar systems, including biochar sales, carbon credits, energy production, and waste management fees. A report by Biochar Zero (2024) reveals that median revenue distribution among producers typically consists of 53% from biochar sales, 26% from carbon credits, and 21% from heat or energy. Similarly, research from Nordic countries highlights carbon credits and biochar as primary outputs of pyrolysis, with heat identified as a key co-product (Salo et al. 2024). These figures underscore the importance of these outputs in biochar economics, although actual returns depend on market demand, regulations, and technological capabilities. By examining these revenue streams, this chapter seeks to uncover strategies to maximize financial returns and support the economic sustainability of biochar systems while preserving their environmental contributions.

Biochar Revenue

Studies have consistently shown that the price of biochar is a critical factor for the profitability of biochar production. Sensitivity analyses from multiple researchers, including Campbell et al. (2018), and Clare et al. (2015) demonstrate that biochar prices significantly impact the financial feasibility of pyrolysis systems. Despite this, stakeholders’ perspectives on biochar pricing differ. While Salo et al. (2024) found that Nordic researchers view biochar's high market price as a barrier to adoption, business stakeholders cite a lack of public awareness and practical experience as more pressing challenges.

Biochar itself is often the primary revenue source, with market prices varying widely depending on factors such as quality, production location, and intended use. Charcoal at the factory gate in Europe can sell for $600 to $1,200 per ton for high-quality domestic sources, while imported or lower-quality biochar may be priced between $350 and $800 per ton. Examples of reputable sellers include Sonnenerde in Austria, which markets biochar at around $600 per ton, Humko Bled in Slovenia at a similar price, and Yorkshire Charcoal in the UK, where prices reach up to $1,200 per ton. Chinese bamboo biochar producer SEEK offers prices ranging from $400 to $800 per ton, with the higher end reflecting granulated forms (Shackley et al. 2015). Over time, biochar prices will likely decrease as market availability grows and production costs decline due to technological advancements and increased competition (Pierson et al. 2024).

Moreover, the variability in biochar prices is also influenced by product strategies. Biochar can be sold as a commodity, used internally within an organization, or incorporated into higher-value products like premium planting soils. The chosen product strategy affects the achievable price per ton and, consequently, the overall revenue. Leveraging emerging applications for biochar, such as its use in fertilizers, construction materials, or other specialized products, offers a pathway to create added value by targeting specific market segments. By designing biochar products to meet precise quality and quantity needs of these markets, producers can charge a premium for customized biochar. This approach involves close collaboration between biochar designers, producers, and customers to ensure that the biochar's specifications align with market demands (Lehmann and Joseph 2015). Given the variety of feedstocks, conversion methods, and potential end uses, biochar is likely to remain a differentiated product, appealing to niche markets rather than becoming a widely traded commodity (Campbell et al. 2018).

Research highlights that the slow adoption of biochar systems is partly due to low awareness of biochar’s benefits and the absence of a stable market signal for biochar products. Despite its many benefits, uncoordinated marketing efforts have created uncertainty among end users about its optimal applications, limiting widespread use. Addressing this issue requires establishing clearer market signals and providing practical guidance on biochar applications to encourage broader adoption (Lehmann and Joseph 2015). Latawieck et al. (2017) emphasize the importance of stakeholder education in promoting biochar adoption. Their study on Polish farmers revealed a strong link between familiarity with biochar and willingness to use it, with adoption likelihood increasing from 19% to 27% when farmers were informed. Effective education strategies should transparently communicate both the benefits, such as improved soil quality, and potential drawbacks, such as cost concerns, to foster trust and confidence among stakeholders.

Carbon Credits and Climate Benefits

Carbon credits are another significant revenue driver, linked to biochar's potential for long-term carbon sequestration. The recognition of biochar as a negative emissions technology by the IPCC has made it attractive for carbon markets. The revenue potential for carbon credits depends on several factors, particularly the carbon content of the feedstock and the concept of "additionality" which considers the alternative fate of the feedstock and the emissions profile if the biochar operation did not exist (see Chapter 2.5 for a more detailed explanation). Biochar producers typically sell carbon credits either directly to commercial buyers or through carbon credit marketplaces. The choice of distribution channel can affect the final price achieved for these credits, with direct sales potentially offering higher returns than marketplace transactions.

The market for biochar carbon credits has included high-profile corporate buyers like Microsoft, JPMorgan Chase, Swiss Re, and Nasdaq. Prices for carbon credits have reached as high as $200 per ton of CO2 equivalent, with the average price in 2023 around $150, according to the MSCI Carbon Market. These high prices reflect the relative permanence of biochar-based carbon removal compared to nature-based solutions such as reforestation. However, the sustainability of current price levels is uncertain. Modelling by the MSCI Carbon Market suggests that increased competition and margin compression may cause prices to soften by 2026, with potential recovery by 2035 (Salma et al., 2024).

Heat and Energy Production

The pyrolysis process produces by-products like syngas and bio-oil, which can contribute to the economic sustainability of biochar systems through energy production. Syngas can be used to generate heat or electricity, reducing costs by replacing externally sourced energy within an organization. Excess electricity can be sold to the grid at market prices, further increasing revenue. Additionally, government subsidies for renewable energy, where applicable, can enhance the economic viability of energy production as a key driver for biochar systems. Bio-oil, although produced in smaller quantities during slow pyrolysis compared to fast pyrolysis, also offers a revenue opportunity. Fast pyrolysis projects globally have reported bio-oil revenues ranging from $0.17 to $0.65 per liter, providing a useful benchmark for slow pyrolysis operations (Shackley et al. 2015).

This approach of utilizing pyrolysis by-products to enhance the economic sustainability of biochar systems aligns with the strategy of redefining productivity in the value chain. This is a concept introduced by Porter and Kramer (2011) emphasizing improving resource efficiency and reducing environmental impact to enhance economic outcomes. Applied to biochar systems, this strategy involves optimizing processes to reduce costs while increasing sustainability. For example, businesses can adopt energy-efficient pyrolysis techniques that capture and reuse waste heat, improving energy efficiency and lowering operational expenses. As Porter and Kramer (2011) highlight, addressing social and environmental constraints can directly enhance productivity, creating a "win-win scenario where environmental improvements lead to cost savings." By integrating these principles, biochar businesses can maximize the economic value of by-products while advancing environmental and operational efficiencies.

Waste Management Savings

Biochar production can offer cost savings in waste management, particularly when residual biomass such as forest slash or agricultural waste is used as feedstock. This provides an environmentally friendly disposal method, reducing costs associated with burning or landfilling. However, the extent of these savings depends heavily on regional waste management regulations and practices. In Europe, for example, legal constraints can complicate the use of biomass classified as waste (Salo et al. 2024), potentially limiting revenue opportunities from this source.

3.4 Hypotheses for Financial Viability

Building on the insights gained from the analysis of market dynamics, profitability, and cost-revenue structures in previous sections, this chapter introduces the hypotheses developed to address the research question: *"How can biochar systems achieve financial viability in the current market setting while maintaining their environmental impact?"* These hypotheses explore the interplay between market enablers and barriers, such as regulatory frameworks, feedstock availability, and technological readiness, while emphasizing the adaptability of biochar systems to navigate diverse market conditions. The focus lies on identifying how unique configurations of cost and revenue drivers can enhance financial sustainability while maintaining environmental impact. By leveraging opportunities like by-product monetization, the hypotheses aim to provide actionable principles for optimizing biochar systems.

The proposed hypotheses are derived from the literature on biochar markets, as outlined in the preceding sections, and reflect the balance between external market conditions and internal system-specific strategies. These serve as a foundation for exploring how biochar producers can align their operations to achieve both financial and environmental goals within the complexities of the current market landscape.

H1: Source feedstock from low-interest waste streams to reduce costs and enhance sustainability by introducing circularity into the system.

With feedstock being one of the primary cost drivers in biochar projects, it becomes an essential focus for cost reduction efforts. One of the most effective ways to minimize these expenses is to source feedstock from low-interest waste streams, which have lower demand and thus a reduced risk of price increases. As previously mentioned, this approach can even turn a potential cost into a revenue stream if the feedstock is accompanied by a tipping fee, whereby the project is compensated for handling waste materials. Furthermore, using waste feedstock transforms the biochar project into a circularity initiative, aligning it with principles of sustainable resource management. This strategy not only decreases input costs but also enhances the project's environmental value, strengthening its appeal to investors and stakeholders interested in circular economy solutions. By utilizing waste materials effectively, biochar projects can achieve both economic and ecological gains.

H2: Target stakeholders with shared sustainability values to foster a strong ecosystem.

A biochar system involves a diverse array of stakeholders, and the specific types of stakeholders can vary significantly from one project to another. In most cases, these projects depend heavily on the commitment and cooperation of these stakeholders, making it essential to engage those who share a common vision of sustainability. By targeting stakeholders who prioritize environmental goals, biochar projects can foster a cohesive ecosystem grounded in shared values. This alignment encourages deeper engagement, long-term commitment, and a greater willingness to invest in or pay for biochar solutions. For instance, research has shown that biochar buyers who value sustainability are willing to pay a premium if they perceive the project as aligned with their own environmental values. By cultivating partnerships with like-minded stakeholders, biochar projects can create a supportive network that enhances both financial viability and environmental impact.

H3: Design biochar systems to align emission reduction with cost savings and revenue opportunities.

The high interdependencies between processes, materials, and the overarching goals of a biochar project provide a unique opportunity to establish a system that strategically maximizes both financial and environmental outcomes. Given the interconnected costs and their influence on project results, designing the system with careful consideration of these factors becomes essential. For instance, adjusting the process setup and selecting specific source materials can directly impact both carbon capture efficiency and operational costs, reinforcing the need for a comprehensive approach. As mentioned in the sections above, the carbon capture potential of biochar can vary significantly depending on the source materials, technology used, and specific production setup. Since the sale of carbon credits is one of the primary revenue drivers for biochar, optimizing the system to maximize carbon capture could significantly enhance its financial viability. This approach not only supports increased revenue from carbon credits but also amplifies the sustainability impact by maximizing the carbon sequestration potential of the system. Therefore, aligning biochar systems to minimize carbon leakage that aligns with cost savings and revenue-generating opportunities is crucial. For example, prioritizing high-carbon feedstocks increases the amount of captured carbon, thereby generating more carbon credits and creating additional revenue potential, further justifying strategic feedstock choices. Additionally, ensuring production facilities are located close to feedstock sources can help reduce transportation costs, lowering operational expenses while reducing emissions associated with logistics. This alignment between cost-saving and sustainability measures reinforces the dual benefits of such an optimized biochar system.

H4: Develop an ecosystem where assets and services are shared among multiple stakeholders.

With a strong ecosystem of diverse stakeholders united by a common sustainability goal, biochar projects can leverage this network to develop a collaborative framework where assets and services are shared. This ecosystem could involve shared access to essential infrastructure, such as pyrolysis facilities, transportation networks, and storage facilities, allowing stakeholders to optimize resource use and minimize redundancy. By pooling resources, stakeholders can distribute financial burdens and reduce individual capital expenditures, creating a more resilient and financially sustainable biochar system. This collaborative model not only lowers costs but also reinforces the interconnected nature of the project, with each stakeholder's contribution strengthening the system's overall stability and long-term viability.

H5: Educate stakeholders on biochar technology and its benefits to increase awareness, and drive adoption.

Education is considered as a critical driver for the adoption of biochar technology, particularly given the limited awareness and understanding of its diverse applications and benefits. Stakeholders often lack familiarity with how biochar can address specific environmental and economic challenges, which can hinder its broader implementation. By providing clear, transparent information about biochar's advantages—such as improving soil quality, reducing greenhouse gas emissions, and generating co-benefits—while also addressing potential concerns like costs, stakeholders can build confidence in its use.

H6: Leverage partnerships with customers to develop biochar into high-value products.

As with any business, aligning the product to customer needs is essential, and in the case of biochar, this alignment is particularly critical due to its variable characteristics. Biochar properties must be carefully tailored to meet specific application requirements; otherwise, it risks adding little to no value for the end user. Given the substantial capital investment associated with biochar systems, it is crucial not only to understand who the customers are but also to have an in-depth knowledge of their unique needs. Due to the complexity of biochar and its diverse applications, biochar producers may even need to know customer needs better than the customers themselves, educating them on how biochar can address their specific challenges. This approach calls for close collaboration, emphasizing the importance of building partnerships with customers to co-develop biochar into high-value products that effectively serve their intended purposes.

H7: Diversify revenue streams by internalizing all benefits of biochar and its by-products.

Biochar systems are capital-intensive, with various costs related to feedstock sourcing, processing, technology, and operations. These costs, alongside potential revenue, are highly dependent on the specific setup of each biochar project, making the economic profile of each project unique. While there are documented and well-established biochar projects operating proficiently, profitability data remains highly variable. This fluctuation reflects the significant interdependencies within the system, which can increase financial risk. However, biochar systems offer the advantage of multiple revenue streams, enabling risk mitigation through diversification. Beyond the sale of biochar itself, by-products such as bio-oil and syngas can also be monetized, supporting income stability and maximizing the system’s outputs. Although initial investments are high, the multiple revenue streams can improve long-term sustainability and profitability, balancing upfront costs with future gains. Given this potential, it is crucial to explore all possible revenue opportunities, aiming to generate income not only from the primary biochar product but also from its by-products. By capturing the full spectrum of biochar’s benefits and internalizing revenue from each output, projects can balance initial investment costs with long-term sustainability, ultimately improving the financial resilience of biochar systems.

Together, these hypotheses offer a roadmap for overcoming the biochar industry’s current obstacles and enhancing its economic and environmental impact.

4 Methodology

This chapter outlines the methodological framework used to address the research question. The methodology combines qualitative insights from expert interviews with deductive and inductive thematic analysis. This approach enables the identification of key patterns, challenges, and opportunities in the sector, ultimately guiding the development of principles to enhance the financial viability of biochar systems while preserving their environmental impact. The chapter outlines the research procedures for data collection, sampling, and analysis, while also addressing the study's limitations and key considerations.

4.1 Data collection

To answer our research question, we interviewed experts from the biochar industry using a semi-structured format with pre-planned questions and open-ended prompts to encourage detailed responses. Each interview lasted 30 minutes to 1 hour to cover all necessary topics (See Appendix A for the standard interview protocol and questions). Interviews were conducted via Teams or similar platforms, with one interviewee and two interviewers, and were recorded and transcribed with the participant's consent (See Appendix B for an example transcript). Participants were informed about the interview's purpose, and oral consent for research use was obtained.

As recommended by research, we aimed to create a comfortable environment where the conversation would flow naturally and be rich in detail, allowing the interviewee to speak with minimal interruptions and take as much time as needed to elaborate on a given topic. The interview structure followed best practices suggested by literature starting with an introduction and explanation of the interview's purpose, followed by easy warm-up questions to ease the participant. The core topics of the study were then discussed, after which simpler questions were used to conclude. The interview ended with the interviewer expressing gratitude for the participant's valuable input (Alsaawi 2014).

4.2 Sample

Given the depth of the interviews, we aimed for a sample size of 10 to 20, anticipating saturation of information within this range. The number of interviews was determined by the sufficiency felt by the interviewer and the saturation, which occurs when the same information is repeated across interviews (Alsaawi 2014). To ensure diverse perspectives, we selected reputable interviewees from various backgrounds and roles in the biochar field, focusing on experts and projects in different geographical locations.

We identified leading experts in the field by using insights from a work project last semester, where we built relationships with industry players and interviewed over 30 individuals, along with the scientific literature reviewed for this thesis. Additionally, we identified biochar projects and their members through internet searches (Google and LinkedIn) and snowballing techniques. To guide our outreach, we used Figure 2 describing the biochar ecosystem and their relationships, aiming to contact experts from each role to ensure comprehensive perspectives were represented in our findings. While the risk of overlooking a relevant expert exists—especially given the market's early maturity and informal nature—we are confident that our sample represents a diverse and knowledgeable group of industry experts, each with substantial experience in their respective roles.

After identifying the biochar experts, 17 interviews were conducted from September to November 2024. Table 1 presents the demographics of each participant, including their area of expertise, years of experience, and geographical location. The interviewees bring diverse expertise in production, consulting, investment, and carbon credits, with experience ranging from 3 to 28 years.

Geographically, they are based in Europe, Asia, Australia, and the United States, providing a broad international perspective on the biochar industry.

Table 1 Interviewee Demographics

Interviewee ID	Expertise	Years of experience	Location
1	Biochar Producer, Carbon Accountant	3	Netherlands
2	Biochar Consumer	3	United Kingdom
3	Biochar Producer, Pyrolysis Machine Producer	6	India
4	Biochar Producer	3	Germany
5	Biochar Consultant	3	Germany
6	Biochar Producer	3	United States
7	Biochar Producer	15	Australia
8	Biochar Producer	28	Finland
9	Biochar Consultant	14	Sweden
10	Carbon Accountant	15	Sweden
11	Biochar Consultant, Biochar Producer	2	Germany
12	Biochar Investor	1	United Kingdom
13	Biochar Marketplace Operator	3	Switzerland
14	Biochar Consultant, Biochar Producer	4	Thailand
15	Biochar Scientist	5	Finland
16	Biochar Advocate	13	United States
17	Biochar Scientist	5	Mexico

Note: The table presents the assigned interviewee ID to protect the identity of the interviewees, each interviewee's area of expertise in the biochar ecosystem, the approximate years of experience they have in the biochar industry, and their or their projects' geographical location.

4.3 Research Approach

The data obtained from the interviews was analyzed using a combination of deductive analysis and inductive thematic coding. The deductive analysis examines the interview data based on predefined hypotheses and existing literature. This method enables an in-depth exploration of topics identified as significant by prior research, allowing us to assess whether our findings align with, or challenge established theories. In contrast, the inductive thematic coding ensures that new and emerging themes, not captured by the predefined hypotheses, are not missed. The thematic coding followed Clarke and Braun’s six-step framework, a widely used tool for analyzing interview data. This framework begins with familiarization, where the researcher immerses themselves in the data to understand its depth and breadth. Next, codes are generated to represent meaningful aspects of the data. The codes are then combined into broader themes, capturing patterns within the dataset. These themes are reviewed for coherence and accuracy. Next, the significance of each theme is assessed in relation to the research objectives. Finally, the findings are reported, presenting the themes and insights derived from the analysis (Alsaawi 2014). Both inductive and deductive methods were applied with the assistance of AI, specifically OpenAI´s ChatGPT. To ensure accuracy, rigorous cross-checking was performed at all stages.

4.4 Limitations

A limitation of our data collection process is the geographic restriction to Europe, Asia, Australia, and the United States, which may limit the generalizability of our findings to regions with less mature biochar markets. While we aimed to cover a broad range of roles, the reliance on snowball sampling could introduce selection bias, as initial interviewees' recommendations may reflect similar perspectives or industry connections. Further, logistical constraints limited our interviews to a virtual format, which may affect the depth of engagement, and the quality of non-verbal cues compared to in-person interviews. Additionally, with a sample size of 17 interviews, there is a risk that certain nuanced perspectives within the emerging and rapidly evolving biochar field may be underrepresented.

While interviews provide valuable, real-world insights and flexibility, they have limitations. Research suggests that a researcher’s identity, background, and relationship with participants can influence data collection, potentially affecting the validity and reliability of the results (Alsaawi 2014). The subjective nature of interviews means that the researcher’s interpretations may influence the analysis, and factors like interview context and location can shape participant responses. Transcribing the interviews was employed to minimize interviewer bias by allowing multiple team members to independently review the data, providing a more balanced perspective on the analysis. Leveraging AI-driven tools like OtterAI for transcription reduced human error and provided a more detailed basis for analysis. However, they should be used with caution, as they may occasionally misinterpret specific terms or phrases.

Moreover, aligning our findings with existing hypotheses and literature may have constrained the generation of novel theoretical insights specific to the biochar industry, as it limited the flexibility to explore unique or divergent patterns in the data. The deductive thematic analysis, in particular, could have introduced confirmation bias, emphasizing aspects that align with established theories while potentially overlooking alternative perspectives. Although Clarke and Braun’s six-step framework provided a structured approach to identify themes beyond our predefined hypotheses, it may still have restricted the capture of unexpected insights or emerging patterns outside the established categories. Given these limitations, future studies could incorporate supplementary methods, such as surveys or questionnaires, to validate findings across a broader sample and improve the overall reliability of the research.

5 Results and Discussion

This study aimed to explore how biochar systems can achieve financial viability while maintaining environmental benefits in a dynamic market. To answer this question and develop comprehensive principles for financial viability, a combined deductive and inductive analysis approach was used. First, interview data were examined for evidence supporting or refuting hypotheses derived from the literature. In the deductive results section, evidence related to each hypothesis will be analyzed and discussed. Then, a thematic analysis was conducted to ensure that no recurring themes from the interviews were overlooked. This inductive method involved identifying initial codes from transcripts, which were grouped into broader themes to uncover key patterns and insights. Finally, the insights from both analyses were synergized to inform the formulation of our strategic principles.

5.1 Deductive analysis

For the deductive part of our analysis, our interview findings are examined in contrast to the hypotheses derived from the existing literature on the financial viability of biochar systems. The following section examines and discusses each hypothesis and the related results in detail.

5.1.1 Waste as Feedstock

H1: Source feedstock from low-interest waste streams to reduce costs and enhance sustainability by introducing circularity into the system

The third hypothesis suggests using feedstock from low-value waste streams, contributing to cost reductions while enhancing sustainability by promoting circularity. Our results widely discuss ideal feedstocks, and the hypothesis is largely supported by the interviews. Topics discussed include cost of feedstock, competition in use, use of virgin feedstock, and other feedstock characteristics.

Nearly all interviewees agreed that *feedstocks derived from waste streams* are desired as they align with the principles of circular economy, have little to no competition in use, and are cheaper than other options. Interviewee 9 described that “the perfect feedstock for biochar is, of course, a feedstock that is not used for anything else”. Interviewee 7 stated that “much of the financial savings in biochar production comes from using waste biomass that would otherwise have to be disposed of, such as straw or sawdust.” This aligns with the common consensus among interviewees that the cost per ton of feedstock is a major factor in biochar production expenses, with price volatility posing risks for long-term planning. Interviewee 4 stated that “the lower the cost of the feedstock, the higher the margins for biochar production, especially if it is locally available and can be used immediately”, highlighting that one might benefit from using low-cost or even free waste materials, by reducing potential waste disposal costs of the feedstock supplier. These findings align closely with the literature by Sessions et al. (2019) and Ibarrola et al. (2012), who suggest that sourcing lower-value waste materials is an effective strategy for reducing feedstock costs.

In line with circular economy principles, reusing waste streams as feedstock has not only financial benefits, but also clear environmental gains. The waste biomass materials are prevented from going to landfill or being incinerated, which helps reduce greenhouse gas emissions. Interviewee 7 indicated that “the environmental importance of biochar is mainly about the use of waste materials. Virgin feedstocks, although sometimes having higher carbon content, involve a larger carbon footprint due to land use and raw material extraction.” Several interviewees advocated for policies that encourage the use of agricultural residues and industrial by-products. Interviewee 2 stressed that “regulation that supports the use of waste biomass can help promote more sustainable biochar production and reduce pressure on natural resources.”

While evidence supporting the cost-savings and environmental benefits of using low-value waste streams was very strong, the interviewees also indicated that exclusive use of waste feedstocks is not always feasible or optimal. In some cases, proximity, availability, characteristics, or reliability of the feedstock may make it necessary to use virgin biomass. Several interviewees pointed out that although waste materials are generally cheap, the logistics of collection, transport, and processing can negate the potential savings from using waste-stream feedstocks. Interviewee 6 stressed that “transporting bulky, low-value biomass over long distances can cancel out the cost advantages, making proximity a crucial factor in feedstock selection.”, while interviewee 8 noted that “in remote areas, where agricultural residues are scarce, using sustainably managed forest biomass may be the only viable option.”

Some interviewees emphasized the critical link between feedstock quality and the resulting biochar. Interviewee 5 noted that “the most suitable feedstocks for biochar production are often woody biomass with high lignin content, which offer better carbon retention but are usually not considered waste materials.” This indicates a potential conflict between the pursuit of cost savings and the production of high-quality biochar, highlighting that a balance between feedstock selection and the desired end application is essential. Similarly, especially for higher value applications of biochar, the importance of consistency of feedstock quality and characteristics was highlighted, an important factor as waste biomass may be more inconsistent and difficult to control.

Moreover, other practical considerations such as seasonality, reliability, and availability of waste streams were mentioned. Interviewee 3 highlighted that seasonally dependent feedstocks can disrupt medium-to large scale operations, making it essential to select options that enable year-round continuous production. In addition, Interviewee 5 underscored the risk of relying on a single feedstock supplier, advocating for diversified sourcing to prevent costly production interruptions.

Another interesting topic was discussed by Interviewee 1 on the scarcity of biomass in the Global North, where nearly all biomass has local alternative uses, making sourcing for biochar production competitive. In contrast to this, interviewee 10 noted that globally, biomass supplies were abundant, rendering the virgin-waste debate less critical.

Overall, the results highlight that using feedstock from low-value waste streams can indeed contribute to cost reduction and sustainability by promoting circularity, therefore the third hypothesis can be largely confirmed. However, the validation of this hypothesis appears nuanced, with important trade-offs and regional differences to consider. The interviews highlighted an important tension between cost-effectiveness, sustainability and operational realities. While using low-value waste streams was unanimously said to offer cost advantages and environmental gains, the interviews showed that practical considerations, such as availability, carbon content, seasonality and reliability of the feedstock, must be carefully considered to achieve a profitable and sustainable operation. Interviewee 5 summed this up by stating that “ideally the priority should be waste feedstocks, but in practice one has to consider what is locally available and meets the quality requirements for the intended application.”

5.1.2 Sustainability Objectives

H2: Target stakeholders with shared sustainability values to foster a strong ecosystem

The fourth hypothesis suggest that having stakeholders with shared sustainability values enhances the strength and resilience of biochar ecosystems, as cohesive, collaborative relationships can be fostered, tensions between environmental and economic interests can be better navigated, and the systems market appeal can be amplified. However, the results highlight significant limitations and challenges associated with this approach, particularly in the context of an emerging market like biochar.

Interviewees discussed several reasons why biochar systems may prefer engaging with partners and investors who align well in terms of valuing sustainability. Interviewee 5, emphasized that value chain integration is smoother when all partners are motivated by shared environmental goals, which reduces conflicts and enhances decision-making processes. Other interviewees also noted a growing preference among customers for projects that provide full, traceable value chains. In interview 8, the respondent highlighted that targeting sustainability-minded stakeholders may help to meet this market expectation and create trust in the biochar market. They also highlighted that engaging with stakeholders who prioritize sustainability values can also strengthen the project's storytelling and market appeal, making it more attractive to potential buyers and investors. It was mentioned that early movers motivated by sustainability and climate considerations may be more likely to engage with biochar systems despite their precarious profitability and success rates than their conventional counterparts. These findings are closely aligned with those of Salo et al. (2024), who observed that although economic factors play a significant role for biochar market actors, the primary motivation for most stakeholders remains the climate benefits.

Despite these potential advantages, the evidence also indicates that there might be significant challenges in implementing Hypothesis 4, particularly regarding system effectiveness and scalability. This stems primarily from the limited pool of potential partners, resulting from factors owed to the early development stage of the market such as low awareness of biochar and the mixed financial viability of biochar systems, but also inherent factors such as the required locality of ecosystem players. In this context, it is difficult to quickly find and engage sustainability-minded stakeholders, and narrowing the focus to them entirely would further limit this pool of potential partners. While project cohesion may be increased if this strategy is successful, the ecosystem could be less effective overall if the biochar players disregard other factors such as reliability, locality, or size when engaging with stakeholders. Our participants consistently prioritized practicality over values. Interviewee 2 for example, stated that they didn´t rely on environmental aspects to significantly contribute to their value proposition, and that their customers had primarily economical motivations. Especially for scaling biochar systems, focusing exclusively on sustainability-driven partners may significantly restrict the speed of business establishment or market expansion.

In conclusion, while the hypothesis is supported in terms of its potential to enhance cohesion, trust, and market appeal, significant challenges remain. The early-stage nature of the biochar market, the limited pool of sustainability-driven stakeholders, and the prioritization of practicality and economic motivations over shared values suggest that this approach may not always be feasible or scalable. Therefore, we partially accept the fourth hypothesis.

5.1.3 Emission Excellence

H3: Design biochar systems to align emission reduction with cost savings and revenue opportunities

The second hypothesis suggests a linkage between increased economic performance and carbon capture efforts, enabled through monetizing carbon sequestration. By selecting carbon-rich materials and optimizing the production process, biochar systems can capture more carbon, reduce emissions, and earn more from carbon credits. Carefully designing the biochar system and value chain helps minimize production emissions. Our findings primarily focus on reducing emissions through feedstock choice, operational processes like transportation emissions, and application cases that ensure durability. Multiple interviewees emphasized that transporting feedstock over long distances should be avoided due to its high volume and weight, which not only drive up costs but also significantly increase emissions, ultimately reducing carbon credit revenue. Instead, the interviews strongly suggested that biochar systems should be designed around the feedstock, prioritizing locality to reduce emissions and costs while addressing potential logistical bottlenecks. This aligns with the view that feedstock supply is often a critical constraint in biochar systems (International Biochar Initiative 2024).

In addition to feedstock considerations, locality was discussed in relation to other system components, though interviewees provided mixed feedback. Some described the ideal biochar system setup as entirely local, minimizing transportation emissions for all components. For example, Interviewee 4 noted that the more local the entire system, the better it will be. However, practical constraints, such as limited local demand for biochar, often require broader distribution. In these cases, transporting biochar itself was considered by some interviewees to be less emission-intensive than transporting biomass, due to the significant reduction in weight post-pyrolysis.

Beyond locality and transportation emissions, interviewees raised concerns about proper feedstock choice and storage. Proper feedstock not only needs to meet emission reduction and carbon capture goals but should also have a high carbon content. Project developers must consider the potential alternative uses of the biomass if it were not used for biochar production. For example, if the biomass were used for biogas production, the carbon capture effect would be less than if it were burned, following the principle of additionality. Moreover, appropriate biomass storage was considered crucial to prevent emissions from biomass decomposition prior to pyrolysis. Interviewee 8 highlighted the challenges of using seasonal feedstock, as the necessary storage could lead to decomposition, compromising emission management. Lastly, several interviewees emphasized the importance of using high-quality machinery to control potential methane emissions during the pyrolysis process.

In the production process of biochar, interviewees advocated for using the energy produced from pyrolysis directly within the biochar facility. Interviewees 1 and 6 explained that biochar production requires considerable energy input, so capturing and reusing pyrolysis-generated energy for internal operations – such as powering continuous processing temperatures – can reduce dependency on external energy sources and lower emissions and operational costs. Interviewee 5 further suggested that on-site energy utilization aligns with sustainable practices by improving the energy efficiency of biochar production and potentially replacing electricity stemming from non-renewable sources. They further highlighted the importance of emission reduction across biochar's entire value chain, from feedstock processing to application. To fully realize biochar's environmental and economic potential, the interviewee stressed that biochar must be used in a durable manner, safeguarded against burning, which would release the captured CO2 back into the atmosphere.

Minimizing carbon leakage is crucial for maximizing carbon capture in biochar systems, but interviewees noted that its effectiveness depends on the system's complexity and interrelated factors. The results highlight steps to align emission reduction with cost savings and revenue generation, particularly through localized feedstock sourcing and system design. However, compromises are often needed to address market constraints and operational realities. Therefore, the second hypothesis is accepted, as the findings confirm the importance of designing biochar systems to reduce emissions and leverage carbon capture revenue, but full alignment with cost savings is not always feasible due to logistical challenges and limited local demand.

5.1.4 Shared Assets and Services

H4: Develop an ecosystem where assets and services are shared among multiple stakeholders

The fifth hypothesis indicates that sharing assets and services, such as pyrolysis facilities, transportation networks, and storage facilities, with other stakeholders of the ecosystem can be beneficial in developing financially viable biochar systems. The concept of developing an ecosystem where assets and services are shared among stakeholders was briefly touched upon in the interviews. While the results discuss the potential benefits of such an approach, the insights gained suggest that its applicability may vary significantly based on project-specific factors.

Some respondents recommended collaborating with resource-sharing partners to reduce costs and enhance operational synergy. For example, Interview 1 underscored the benefits of engaging farmers in the global south directly in the value chain, hence participating directly in both costs and revenue streams resulting in greatly simplifying operations. Similarly, Interviewee 3 pointed out the advantages of shared resources, particularly for smaller operations, stating, " [Sharing resources and machinery] also depends on the size of your project. You know, if it's a small plant, it does not make sense for you to buy a biomass chipper, right? It does not make sense for you to buy a loader." They highlighted that outsourcing certain functions, such as biomass sourcing and supply, could be an effective strategy, while still emphasizing that the feasibility of such arrangements depends heavily on the specific project setup, including size, location, and existing infrastructure.

Overall there was little evidence supporting shared ecosystems across the interviews, indicating that while this strategy could mitigate high investment costs for some, it may not broadly applicable. For projects working with well-defined setups, such as those involving municipal waste processing plants, this approach may hold limited relevance. Therefore, the fifth hypothesis is only partially with an emphasis on high context dependency. The concept appears to hold promise in certain scenarios, particularly for smaller projects seeking to reduce upfront costs while for larger, well-structured setups, its relevance may be limited.

5.1.5 Education on Biochar

H5: Educate stakeholders on biochar technology and its benefits to increase awareness, and drive adoption.

The seventh hypothesis suggests that educating stakeholders about biochar technology and its benefits is crucial for increasing market demand and driving adoption. Findings from the interviews strongly support this hypothesis, with multiple respondents highlighting the low level of awareness and understanding of biochar among potential ecosystem players, including customers, suppliers, and local stakeholders. Several interviewees discussed that this lack of knowledge creates a significant barrier to adoption, making education a critical step in building confidence in technology and fostering broader acceptance. This aligns with the existing literature such as Latawieck et al. (2017), which demonstrated a direct correlation between familiarity with biochar and increased willingness to adopt it, underscoring the critical role of education in bridging knowledge gaps and driving adoption.

Moreover, interviewees consistently emphasized the importance of targeted education efforts to address this challenge. For example, interviewee 2 noted that “It's like an educational step that we need to do every time we start a conversation is to debunk some of the myths around [Biochar].” Similarly, interviewee 4 mentioned the importance of educating local stakeholders to create a shared understanding of biochar’s benefits and enhance the project’s storytelling potential and market appeal. Additionally, these interviewees stressed the critical *role of customer education* in promoting biochar’s co-benefits. They argued that biochar should be marketed in conjunction with compelling narratives around carbon credits to maximize its perceived value. Interviewee 10 highlighted the importance of aligning biochar applications with carbon credit storylines, emphasizing that this synergy enhances the marketability of the entire biochar ecosystem. They noted that "customers want full value chains with good traceability; they want to see the full ecosystem develop around the biochar," underscoring the demand for transparency and a holistic approach to biochar production and sales.

Overall, the findings strongly support the hypothesis that education is a crucial driver for the adoption of biochar technology, hence hypothesis 5 is accepted.

5.1.6 Customized Biochar

H6: Leverage partnerships with customers to develop biochar into high-value products

Our sixth hypothesis emphasizes the importance of collaborating with customers to develop biochar into high-value products, enhancing its market attractiveness and adoption rate. The results highlight the crucial role of close collaboration between biochar producers and customers in aligning biochar quality and securing premium prices.

Interviewees 2, 8, and 10 consistently emphasized that understanding customer needs and aligning biochar quality with the application case enables producers to create and capture value. Interviewee 3 also highlighted the potential for co-development partnerships to address customer-specific challenges, such as integrating biochar into agricultural feedstock blends or tailoring physical properties like particle size for optimal performance in construction. These insights highlight that collaboration can lead to technical solutions that enhance biochar's utility and position producers as indispensable partners.

Interviewees emphasized *the importance of aligning feedstock choices with the intended use or customer demands for biochar*. Biomass types influence biochar characteristics, which should be tailored to the end use. The trade-off between cost savings and biochar quality was highlighted, with Interviewee 4 noting, “The quality of biochar is highly dependent on the carbon content of the feedstock, and low-grade agricultural residues may not meet the desired carbon standards for high-value applications.” However, the idea of developing biochar into high-value products, as proposed in the hypothesis, was not seen as essential by the interviewees. Interviewees 2 and 9 noted that while value-added products like fertilizers or plant bedding could enhance financial sustainability, this strategy is more relevant for the future, when biochar production scales up. These findings suggest that while co-developing high-value products may add value, it is not essential for financial viability. The immediate priority for biochar producers is ensuring that their biochar closely aligns with the specific needs of their customers. These findings align with the existing literature, namely Lehmann and Joseph 2015 who highlight biochar applications—such as in fertilizers, construction materials, and other specialized products—as a way to generate added value by targeting specific market niches. However, as noted by the interviewees, these markets are still emerging and may become more relevant in the future as production scales and markets mature.

Our sixth hypothesis on leveraging partnerships with customers to develop biochar into high-value products is partially supported. The results highlight the critical role of close collaboration between biochar producers and customers, but this collaboration mainly focuses on tailoring biochar to meet specific quality requirements, rather than co-developing high-value products.

5.1.7 Revenue streams

H7: Diversify revenue streams by internalizing all benefits of biochar and its byproducts.

The first hypothesis suggests that monetizing all benefits and byproducts of biochar production is critical for financial sustainability. Biochar's potential for soil improvement and industrial applications is widely recognized, with established markets globally (Gray, Boritzke Smith, and

Maxwell-Barton 2024). Meanwhile, carbon credits, though volatile, are a crucial income stream, aligning with global sustainability goals (Blaufelder et al. 2021). Several interviewees discussed revenue diversification, focusing on biochar, carbon credits, and heat and energy, partially aligning with previous research on biochar systems.

Experts highlighted that carbon credits, along with heat and energy generated during the pyrolysis process, are valuable byproducts that can enhance the profitability and sustainability of biochar business models. While utilizing heat and energy can create additional revenue streams and improve operational efficiency, it also presents strategic, technical, and market-related challenges. Namely, multiple interviewees identified storage and transport as *significant obstacles to fully capitalizing on pyrolysis-generated heat and energy.* Heat, as an inherently local resource, is difficult to store or transport over long distances without significant energy loss or high costs. Interviewee 3 noted that this limitation restricts potential buyers to those near the biochar production site, limiting market options for heat sales. Additionally, Interviewee 8 pointed out that while pyrolysis energy could theoretically be converted to electricity for wider distribution, the conversion process involves high costs and low energy efficiency, around 8-10%.

Interviewees expressed that the profitability of heat and energy sales largely depends on local infrastructure and demand. Interviewee 5 emphasized that proximity to potential heat consumers, such as district heating systems, agricultural operations, or industrial facilities, is crucial for maximizing the economic value of this byproduct. Interviewee 3 noted that many biochar projects fail to capitalize on heat due to limited infrastructure, particularly in remote or rural areas with limited access to district heating networks or industrial heat users. In these cases, finding alternative uses for heat or focusing on other revenue streams becomes necessary. Some interviewees proposed innovative approaches to overcome these limitations. For example, Interviewee 1 suggested partnering with neighboring facilities or agricultural operations to share heat, reducing storage requirements and capitalizing on localized demand. Interviewee 10 emphasized that heat and energy utilization strategies should be adapted to the local context, focusing on "right-sizing" energy systems to match nearby demand rather than pursuing one-size-fits-all solutions.

Regarding local demand and infrastructure for heat, Interviewee 8 argued that integrating pyrolysis-generated energy on-site could be challenging for smaller facilities due to the high initial investment in energy recovery technology. In contrast, larger biochar production plants may find it more economically feasible to develop closed-loop energy systems, reducing external energy requirements and potentially leading to long-term cost savings and a lower carbon footprint.

Utilizing heat and energy byproducts from pyrolysis offers *environmental and social benefits* that enhance the overall value proposition of biochar projects. By offsetting fossil fuel use in local heating systems or reducing reliance on external electricity, biochar facilities can contribute to local decarbonization and energy independence. Interviewee 6 highlighted that when biochar projects supply heat to local communities, they gain support from residents and regulators, facilitating smoother implementation and greater social license to operate. Interviewee 8 argued that incorporating heat recovery into the business model could boost the environmental credibility of biochar projects, aligning with Interviewee 5, who emphasized that well-integrated systems leveraging byproducts support carbon removal and circular economy goals.

While interviewees agreed on the importance of biochar, carbon credits, and heat or energy as byproducts, the relevance of minor by-products like wood vinegar and wood tar was deemed financially insignificant for most operations, echoing findings by Salo et al. (2024). This is mainly due to limited knowledge of their potential applications and the underdeveloped markets for these by-products.

To conclude, biochar and carbon credits are referred as the main revenue drivers in a biochar production system. The importance of heat as a co-product is consistently emphasized, with several interviewees (e.g., Interviewees 3, 5, 10) highlighting heat as a key by-product, particularly where district heating networks or nearby heat demand from third parties, such as greenhouses or food processing industries, exist. This aligns with Interviewees 5 and 8, who stressed that the local availability of infrastructure determines the feasibility of leveraging heat as a revenue stream. Other by-products, such as wood vinegar and wood tar, were deemed financially insignificant for most operations, as the costs likely exceed the revenue generated, making these streams unattractive in terms of profitability.

While not all outputs need to be monetized, diversifying revenue streams is essential. Producers should focus on maximizing value by targeting a select set of high-demand outputs during operational planning, while deprioritizing by-products with limited market potential. Practically, this means prioritizing biochar, carbon credits, and strategically relevant by-products tailored to local market demands and infrastructure capabilities. Efforts to recover and market low-demand by-products may exceed their financial value, making them less viable. Therefore, the hypothesis that a financially viable biochar system relies on monetizing all outputs of the pyrolysis production process is partially disconfirmed. While the research findings validate the importance of diversifying revenue streams, they do not confirm the necessity of monetizing all byproducts.

5.2 Inductive analysis

This chapter presents the results and discussion of the inductive thematic analysis, which involved identifying initial codes from the interview transcripts and grouping them into broader themes to uncover key patterns and insights. Conducting an inductive analysis allows for the exploration of themes and topics that extend beyond the hypotheses, capturing additional insights that emerged during the interviews.

Table 2 presents selected examples of the outcomes of the second step of the thematic analysis, highlighting the initial codes derived from the interview transcripts (see Appendix C for the full table of these results). Notably, the codes discussed in the deductive analysis appeared more frequently. For instance, *Diversifying Revenue Streams* emerged as particularly significant, with multiple participants emphasizing these topics, aligning closely with the findings of the deductive analysis. Interestingly, the codes *Local Biomass Sourcing* and *Local Ecosystem Integration* appeared with relatively high frequency, despite not being explicitly addressed in our hypotheses. Discussed by nine and seven interviewees respectively, these codes underscore the importance of tailoring biochar operations to local conditions, particularly by ensuring close proximity to feedstock sources.

Moreover, the inductive analysis revealed codes such as *Contractual Agreements*, *Storytelling*, and *Decentralized Biochar Systems*, which were not explicitly addressed in the hypotheses. While these codes appeared less frequently than those covered in the deductive analysis, their presence remains noteworthy. For instance, *Storytelling* was discussed by four interviewees, while *Contractual Agreements* were highlighted by three interviewees.

Table 2 Example of Inital codes of Thematic Analysis

Initial code	N of participants contributing	N of transcript excerpts assigned	Sample quote (interview)
Diversifying Revenue Streams	8	15	"every investor in the biochar common rule projects looks at the diversification of the revenue streams " (3)
Local Biomass Sourcing	9	12	"you have to have a lot of feed stock readily available and not too far away, because you don't want to be transporting it by truck 100 kilometers away" (14)
Local Application of Biochar	4	4	"always looking at it from a perspective of, what can I actually sell locally" (3)

Local Ecosystem Integration	7	9	"you have to adapt the biochar Production According to the local conditions " (9)
Local Carbon Credits	2	2	“a lot of companies see it as a positive, that it's local, ... we have clients interested in only buying from the Nordic countries” (9)
Contractual Agreements	3	8	“Have continued access (to feedstock) for the life of the project, so it's all well and good having a contract for feedstock” (2)
Storytelling	4	7	"You have to have a compelling story to be able to sell it (CDR) and get a premium.” (8)
Decentralized Biochar Systems	5	12	"For every one centralized biochar project, there should be 100 decentralized projects " (1)

Note: This table displays examples of the initial codes identified during the first stage of thematic analysis. For each code, it shows the number of participants who contributed relevant data, the total number of transcript excerpts assigned to that code, and an illustrative sample quote. This summary provides an overview of key themes that emerged in the interviews, indicating the frequency and distribution of each topic across the participants and providing a representative example of the perspectives shared. The table focuses on findings beyond the deductive analysis.

Table 3 provides a summary of the results derived from the third, fourth and fifth step of the thematic analysis where the codes were organized into broader themes, refined to ensure distinctiveness, and assigned descriptive labels. While all themes were covered by the hypothesis, several additional insights among these themes were discovered with the inductive analysis.

Feedstock Challenges and Opportunities emerges as a key theme, highlighting the complexities of biomass sourcing, including seasonal availability and competition with other industries. Several interviewees emphasized the need for locally sourced biomass to reduce transportation costs and environmental impact. *Financial Viability and Revenue Streams* was another prominent theme, underlining the importance of diversified income sources for biochar projects. Codes within this theme aligned closely with our deductive analysis results.

Technological and Operational Efficiency captures the recurring challenges faced by biochar producers, with participants frequently highlighting issues such as scaling pyrolysis technology and managing unplanned maintenance. Several interviewees emphasized the importance of employing contractual agreements to secure long-term partnerships for feedstock procurement and biochar application. A central theme across multiple interviews was the integration of biochar operations into local contexts to enhance the sustainability and efficiency of these systems.

Biochar Application and Impact focuses on the diverse uses of biochar across various sectors, including agriculture, urban infrastructure, and water filtration. Interviewees emphasized the potential of transforming biochar into value-added products leveraging the co-benefits of biochar to boost market demand and increase its price. Additionally, local application of biochar emerged as an important topic under this theme.

The Market Growth and Awareness theme highlights the need for greater education and advocacy to promote biochar adoption. Participants pointed to unclear policy frameworks as significant barriers and emphasized the vital role of government incentives in expanding the market. Although these insights offer limited direct guidance for biochar businesses operating in the current market, many interviewees stressed the importance of branding and storytelling in selling carbon credits. Additionally, some noted a preference among companies offsetting their emissions for locally produced carbon credits. Finally, the theme *Ecosystem Integration and Social Impact* emphasizes the broader benefits of biochar projects. Many participants highlighted how biochar systems foster local job creation, enhance community resilience, and contribute to environmental sustainability by supporting closed-loop ecosystems.

While some codes and themes were referenced slightly more frequently than others, the relatively even distribution of these topics, across the interviews suggests a consensus on the key factors that drive the success of biochar projects.

Table 3 Grouping of Initial codes to form Themes

Theme	Initial codes forming the theme	Theme Description
Feedstock Challenges and Opportunities	- Feedstock Variability Imapact - Optimal Feedstock Pairing with Technology - High-Moisture Feedstock Limitations - Seasonal Availability of Agricultural Waste - Local Biomass Sourcing	This theme addresses the complexities of sourcing, transporting, and preparing biomass for biochar production. It emphasizes how feedstock type, availability, and local sourcing directly affect operational feasibility and costs.
Financial Viability and Revenue Streams	- Diversifying Revenue Streams - Premium Pricing for High-Quality Biochar	This theme examines strategies for ensuring financial sustainability, including diversifying revenue streams through multiple income sources and achieving premium pricing for high-quality biochar products.
Technological and Operational Efficiency	- Contractual Agreements - Decentralized Biochar Systems - Local Ecosystem Integration	This theme addresses the importance of establishing clear contractual agreements, adopting decentralized biochar systems for localized production, and integrating these systems into existing local ecosystems for improved efficiency.
Biochar Application and Impact	- Local Application of Biohcar - Premium Pricing for High-Quality Biochar - Biochar Matching Customer Needs	This theme explores the application of biochar emphasizing locality, focus on high-quality biochar for achieving higher market prices, and on matching the quality of biochar to meet customer needs for application.
Market Growth and Awareness	- Local Carbon Credits - Storytelling	This theme highlights the demand for locally produced carbon credits by companies offsetting their emissions and emphasizes the use of storytelling to increase the value of carbon credits to stakeholders and buyers.
Ecosystem Integration and Social Impact	- Local Ecosystem Integration - Stakeholder Collaboration	This theme focuses on the role of stakeholder collaboration and the integration of biochar systems into local ecosystems to maximize social and environmental benefits.

Note: This table presents the broader themes identified through thematic analysis, each comprising multiple initial codes. It includes a brief description of each theme. The summary highlights key insights and patterns in biochar systems, providing a concise overview of the main trends and challenges supported by interviewee perspectives.

The frequently discussed topics *Branding and Storytelling*, *Contractual Agreements*, *Local Biomass Sourcing* and *Local Ecosystem Integration*, which were not addressed in the deductive analysis, are examined in greater detail below.

5.2.1 The Locality of Biochar Operations

The locality of biochar operations derived from the frequently present codes *Local Biomass Sourcing* and *Local Ecosystem Integration*, emerged as an important consideration for developing financially viable biochar systems. Several interviewees agreed that proximity to biomass sources and biochar application sites reduces logistical costs and emissions.

Nearly all interviewees highlighted locality as a crucial factor in creating financially viable biochar systems that also maximize environmental sustainability. Interviewee 3 stressed that planning a biochar system should begin with assessing the locally available feedstock, the type of biochar it can produce and its potential local applications, and whether there is local demand for byproducts like heat. They emphasized that these considerations—proximity of feedstock, applications, and byproduct utilization—are essential for determining the optimal location for biochar production. This was echoed by Interviewee 4 that stated "the more local it (biochar operations) is, the better it is" in terms of financial viability and environmental impact. Similarly, Interviewee 10 described an optimal biochar ecosystem as one where biomass is close, district heating grids can absorb surplus energy, and there are nearby applications for biochar, such as agriculture or material production.

While locality was considered important in all stages of the biochar value chain, feedstock procurement was highlighted as the most important. Interviewee 5 explained that the heavy logistics involved in biochar production, with approximately four tons of biomass yielding one ton of biochar, makes reducing transportation distances important. Interviewee 6 echoed this, emphasizing that transportation of raw feedstock is costly, thus proximity to both feedstock sources and application sites is optimal. However, Interviewee 5 also noted that while proximity is important, the availability of biomass should not be compromised for distance alone.

Overall, locality plays a crucial role in enhancing the financial viability and environmental sustainability of biochar systems, with proximity to feedstock, application sites, and byproduct utilization emerging as critical factors for reducing costs, minimizing emissions, and optimizing overall system efficiency.

5.2.2 Contractual agreements

Contractual Agreements emerged as a central code in the interviews for developing financially viable biochar systems under the Technological and Operational Efficiency theme. Many interviewees discussed that biochar systems, characterized by their case-specific nature and inherent risks due to limited industry data and standards, require robust contractual frameworks to ensure long-term viability. The results highlighted the necessity for comprehensive agreements across the value chain to address operational challenges, stabilize inputs and outputs, and align production with market demands. Contractual agreements were mainly discussed by the interviewees in the context of feedstock, machinery and offtake agreements.

The importance of formal contractual agreements with feedstock suppliers and customers was discussed by several interviewees as the reliability of feedstock supply is a cornerstone of biochar system stability. Interviewee 5 noted that sourcing from a diversified network of suppliers and formalizing these relationships through contracts can mitigate risks associated with feedstock scarcity (prevailing especially in northern hemisphere) and seasonal variability. For example, contractual agreements can guarantee year-round supply, ensuring uninterrupted operations even in the face of fluctuations in biomass availability. Overall, interviewees consistently stressed that long-term feedstock agreements are essential to avoiding costly disruptions of the pyrolysis process.

Similarly, interviewees stated that agreements help mitigate risks associated demand uncertainty, another common challenge in the biochar industry. Establishing long-term purchase agreements with customers wherever possible was mentioned by interviewee 8 as a way to help stabilize revenue streams and reduce market volatility. Moreover, the use of contractual agreements in increasing machine reliability emerged as a critical theme in interviews. Interviewee 3 emphasized that high-capital investments demand continuous operation and high utilization based on economics of scale, making downtime due to mechanical failure a significant financial risk. Service agreements with equipment providers can ensure timely maintenance and access to replacement parts, as highlighted by Interviewee 5, reducing the likelihood of operational interruptions and safeguarding production capacity.

Lastly, offtake agreements were discussed by the interviewees as means for biochar producers to tailor their operations to buyers' specific needs, ensuring both economic and operational alignment. Interviewee 8 noted that such agreements provide predictability in demand and pricing, which is crucial for securing investment and planning production. These contracts can also facilitate market entry by guaranteeing a consistent revenue stream for biochar, carbon credits, or heat.

5.2.3 Branding and storytelling

Branding and Storytelling developed into an important topic in the interviews for financially viable biochar systems under the theme Market Growth and Awareness. Our findings uncover the growing importance of storytelling and branding in the marketability of biochar-derived carbon credits. According to our research results, buyers are increasingly seeking credits that go beyond simple carbon removal, valuing those that offer verifiable environmental and social co-benefits. Themes such as regional dynamics, buyer preferences, the importance of co-benefits, and the role of storytelling in enhancing marketability were consistently discussed across many interviews.

The carbon credit market presents both a significant opportunity and a set of unique challenges for biochar projects, as emphasized by multiple interviewees. While carbon credits represent a potential revenue stream, the market’s volatility and lack of regulation were frequently highlighted as critical barriers. Interviewee 1 described the current state of the carbon credit market as a “Wild West,” characterized by rapid, often speculative transactions that can undermine trust and transparency. Many biochar project developers sell credits even before they are officially issued, adding layers of complexity and risk, which may deter potential investors or buyers.

The preferences and expectations of carbon credit buyers also emerged as an important theme. According to Interviewee 8, buyers are increasingly interested in credits that offer additional co-benefits beyond carbon removal. For biochar, these co-benefits might include the production of renewable energy, soil enhancement, or reduced greenhouse gas emissions from agriculture. Interviewee 9 also emphasized the importance of differentiating carbon credits based on their origin and production process, noting that as buyer awareness grows, there will likely be an increasing demand for credits that include verifiable co-benefits and are part of transparent, well-documented value chains. They highlighted that this shift aligns with broader market trends favoring high-quality credits that reflect buyers' corporate values and sustainability goals, offering a competitive advantage to biochar projects that can clearly showcase their added environmental and social impacts.

Interviewee 6 emphasized the importance of transparent Measurement, Reporting, and Verification (MRV) systems in ensuring the credible documentation and verification of these co-benefits. As the market matures, robust MRV practices are expected to become a baseline requirement, driving up the quality and potentially the value of biochar-derived carbon credits. Moreover, effective storytelling plays a crucial role in highlighting these co-benefits. As Interviewee 4 noted, a compelling narrative around biochar’s positive impacts can attract buyers willing to pay a premium for credits that reflect their organizational values. This sentiment was echoed by Interviewee 10, who emphasized that selling carbon credits profitably relies on two key factors: demonstrating a strong end use for the biochar that leverages its co-benefits and crafting a compelling narrative to effectively communicate these advantages.

Moreover, interviewees also highlighted the role of branding in differentiating carbon credits based on their origin and production process. Interviewee 9 noted a growing preference for locally produced credits: “We have clients interested in only buying from the Nordic countries, for example.” This trend aligns with the desire for transparent and well-documented value chains, which can enhance the credibility and appeal of biochar projects. However, as Interviewee 9 pointed out, even local credits require strong branding: “From a climate perspective, it shouldn’t matter where the carbon sink comes from... but carbon credits are a branding tool. That’s why you need a story around your carbon credit.”

However, some interviewees pointed out that the shift from traditional narratives centered on picturesque, small-scale projects in developing countries to more industrial settings present challenges. As Interviewee 9 observed, “An industrial plant at a municipal waste company in Sweden isn’t as attractive to sell as a story.” However, with effective storytelling, even these projects can be made appealing, potentially increasing the perceived value of their carbon credits. This strategic narrative development enables producers to pitch higher prices for their credits, emphasizing the broader social and environmental contributions of biochar systems. In summary, robust contractual frameworks were considered important for addressing the unique challenges of biochar systems, ensuring stability in feedstock supply, mitigating market and demand uncertainties, and safeguarding operational continuity. In summary, leveraging biochar’s co-benefits through effective storytelling and strategic branding was considered a key to enhancing the marketability and value of carbon credits.

5.3 Principles for the Financial Viability of Biochar Systems

From our deductive and inductive analysis research findings a set of principles for developing or advancing the financial and environmental sustainability of biochar systems has been developed. These principles emphasize adaptability, strategic collaboration, and alignment with the local context, acknowledging the diverse challenges and opportunities inherent to the biochar sector. The principles were primarily derived from the six hypotheses, although hypotheses could only partially be confirmed leading to adjustments when formulating the corresponding principle. In addition, from the three novel themes which emerged in the results, three additional principles were formulated. An overview of the set of principles and the corresponding hypothesis is presented in Table 4.

Table 4 Overview of Hypotheses and Principles

Set of Hypotheses	**Set of Principles**
H1: Source feedstock from low-interest waste streams to reduce costs and enhance sustainability by introducing circularity into the system	P1: Optimize feedstock choice by balancing cost, sustainability and application needs
H2: Target stakeholders with shared sustainability values to foster a strong ecosystem	P2: Foster sustainability alignment without excluding broader partnerships
H3: Design biochar systems to align emission reduction with cost savings and revenue opportunities	P3: Design biochar systems to align emission reduction with cost savings and revenue opportunities
H4: Develop an ecosystem where assets and services are shared among multiple stakeholders	P4: Explore options for sharing assets and services to reduce costs and improve utilization
H5: Educate stakeholders on biochar technology and its benefits to increase awareness, and drive adoption	P5: Educate stakeholders on biochar technology and its benefits to increase awareness, and drive adoption
H6: Leverage partnerships with customers to develop biochar into high-value products	P6: Align biochar characteristics with customer needs to ensure and increase willingness to pay
H7: Diversify revenue streams by internalizing all benefits of biochar and its by-products	P7: Monetize applicable benefits of biochar production to diversify revenue streams
New principle based on recurring themes in the inductive analysis of research results	P8: Locate biochar systems to optimize proximity to available feedstock, and market demand for application sites and byproduct utilization
	P9: Utilize strategic contractual agreements for risk mitigation and reliability in biochar systems
	P10: Leverage storytelling and branding to drive the value of biochar carbon credits

Note: This table summarizes the principles developed from the deductive and inductive analysis of research findings, emphasizing strategies to enhance the financial and environmental sustainability of biochar systems. The principles are primarily derived from six hypotheses, with adjustments made where hypotheses were only partially confirmed. Additionally, three principles were formulated based on novel themes that emerged during the analysis.

Principle 1: Optimize feedstock choice by balancing cost, sustainability and application needs

A financially and environmentally viable biochar system should prioritize the use of low-cost waste streams to reduce costs and enhance sustainability. At the same time, producers should consider proximity, carbon content, and reliability of the feedstock to ensure optimal performance and market acceptance. Taking a flexible, hybrid approach that utilizes waste feedstocks for general applications and deploys high-value biochar for premium markets can maximize both financial and environmental benefits.

Principle 2: Foster sustainability alignment without excluding broader partnerships

There are reasons for biochar systems to strive to engage stakeholders who share sustainability values, enabling cohesive and resilient ecosystems which mitigate tensions between profit and planet. However, they also need to adapt to the practical realities of early-stage markets by considering a wider pool of partners, recognizing that collaboration based on other priorities – such as economic reliability, operational capacity, and scalability – can be more critical for ecosystem development and growth.

Principle 3: Design biochar systems to align emission reduction with cost savings and revenue opportunities

To achieve both financial and environmental sustainability, biochar systems must focus on reducing emissions while cutting cost or increasing carbon credit revenue opportunities through feedstock choices, optimizing energy-efficient designs, and ensuring durable biochar application. This principle focuses on the relationship between emission reduction and financial performance which in many cases is mutually beneficial. By adopting flexible configurations that accommodate market and logistical constraints, biochar projects can effectively balance emission reduction objectives with the need for practical and economically viable solutions.

Principle 4: Explore options for sharing assets and services to reduce costs and improve utilization

Based on the challenges associated with high capital expenditures and underutilized equipment in the biochar industry, shared resources and services could provide a targeted solution in specific scenarios. Pooling resources may help reduce financial barriers for small-scale or new entrants, improving accessibility to critical infrastructure and machinery. However, the viability of these arrangements depends on project-specific factors such as size and available resources. While this approach can increase operational efficiency and adaptability for some biochar systems, its overall effectiveness is likely limited to projects with aligned conditions and clear boundaries for collaboration.

Principle 5: Educate stakeholders on biochar technology and its benefits to increase awareness, and drive adoption.

Stakeholder education is essential to overcome the widespread lack of awareness and understanding of biochar technology and its applications. Building knowledge through targeted education campaigns can address misconceptions, increase stakeholder confidence, and create local demand. Efforts should focus on communicating biochar's benefits, such as its role in carbon credit systems and environmental impact, while tailoring messaging to different stakeholder groups, including customers, suppliers, and local communities.

Principle 6: Align biochar characteristics with customer needs to ensure and increase willingness-to-pay

Close partnerships with customers are crucial, their primary focus being on aligning biochar quality with specific customer needs. This finding highlights the immediate importance of quality customization as a strategy for achieving premium biochar pricing and building strong customer relationships. Developing biochar into high-value products may become more critical in the future, particularly as production volumes increase and markets for biochar diversify.

Principle 7: Monetize applicable benefits of biochar production to diversify revenue streams.

Diversifying revenue streams by capitalizing on the most viable benefits and byproducts of biochar production can be critical for financial viability. While biochar and carbon credits are key revenue drivers, leveraging byproducts such as heat and energy depends on local infrastructure and market demand. Strategic planning should prioritize outputs with the greatest financial and operational feasibility, focusing on local opportunities for heat and energy utilization where possible. Other byproducts, like wood vinegar, may be deprioritized unless market conditions improve.

Principle 8: Locate biochar systems to optimize proximity to available feedstock, and market demand for application sites and byproduct utilization.

To ensure financial viability and maximize environmental impact, biochar systems should be deeply integrated into the local ecosystem. This principle emphasizes aligning biochar production, byproduct utilization, and end-application with the specific characteristics of the local context. By strategically co-locating production facilities near feedstock sources, energy consumers (e.g., district heating systems), and biochar users (e.g., agricultural or industrial applications), producers can minimize transportation costs and emissions while creating circular, localized economies. This principle complements the broader sustainability and financial principles while adding a focused lens on leveraging locality as a competitive advantage and an environmental imperative. It avoids overlap by extending beyond mere logistical considerations to emphasize strategic integration and the co-creation of localized biochar value chains.

Principle 9: Utilize Strategic Contractual Agreements for Risk Mitigation and Reliability in Biochar Systems

Integrating contractual elements into a cohesive framework mitigates the risks associated with the nascency of pyrolysis output markets and the variability of project conditions. Interviewee 1 emphasized that contracts provide clarity and reduce the uncertainties tied to feedstock supply, operational continuity, and market demand.

Principle 10: Leverage Storytelling and Branding to Enhance the Value of Biochar Carbon Credits

The principle emerging from the findings is that effective storytelling and strategic branding are critical for enhancing the marketability and value of biochar-derived carbon credits. As the carbon credit market evolves, buyers increasingly prioritize credits that demonstrate clear environmental and social co-benefits, such as soil enhancement, renewable energy production, or reduced agricultural emissions. These preferences align with broader market trends toward high-quality, transparent, and well-documented credits that reflect corporate sustainability goals. Storytelling not only builds trust and transparency but also allows biochar producers to align their offerings with buyer values, attracting premium pricing.

Implementing these principles enhances both financial viability and environmental sustainability. The more principles implemented in the design of a biochar system the higher the probability of achieving financial viability and the higher the ecological impact, accordingly principles are mutually beneficial. Although it is essential to recognize that these principles are not hierarchically structured and do not follow a prioritization schema. Each principle offers varying degrees of financial and ecological impact, reflecting the multifaceted and case-specific nature of biochar systems. Finally, these principles are highly case-specific and must be tailored to the unique conditions of each biochar project. Not all principles will be applicable universally, and their prioritization depends on regional, logistical, and market factors. Accordingly, project designers need to assess each principle and their respective impact on the individual biochar system.

In conclusion, while the integration of these principles provides a robust pathway toward financial and environmental sustainability, their application requires flexibility, adaptability, and a context-driven approach. Biochar producers must assess their unique circumstances to tailor solutions that balance ecological benefits with economic realities, ensuring long-term success in an evolving market landscape.

5.4 Contradictory Insights on Biochar Businesses

Aside from Branding and Storytelling and Contractual Agreements, further topics emerged through the inductive analysis that the evidence was less clear on. Most notably, our participants had opposing views on the ideal biochar system when it came to the degrees of centralization and integration of the value chain. Due to a lack of sufficient evidence, these topics will not be developed into principles for financial viability in this paper. However, they present intriguing subjects for further research and will be discussed in this section.

5.4.1 Centralized vs Decentralized Systems

A debate emerged between centralized and decentralized biochar production systems, highlighting trade-offs that impact financial viability and sustainability, offering a valuable area for future research.

Centralized systems achieve economies of scale, streamlined production, and meet growing carbon removal demand but can face environmental challenges due to high feedstock requirements, unsustainable local impacts, or large transportation costs, undermining climate benefits. Interviewee 9 advocated for decentralized systems, which are adaptable to local conditions, reduce transportation costs, and minimize carbon footprints. Decentralized systems also enhance market appeal and traceability, as noted by several interviewees. While decentralized systems offer benefits in sustainability and marketability, they face economic challenges such as higher per-unit costs, scaling difficulties, and inconsistent feedstock, affecting financial viability.

The tension between centralized and decentralized systems impacts economic and environmental performance, but research is needed to identify the best fit for specific conditions. Interviewee 1 suggested that smaller decentralized systems may be preferable in regions like the global south, presenting opportunities for future research.

5.4.2 Internalization vs Externalization of (Co-Benefits)

During our research, a debate emerged on the internalization versus externalization of the co-benefits associated with biochar production. Some experts and stakeholders advocated for internalizing these benefits to enhance system viability, including long-term soil health improvement, the environmental impact of replacing fossil fuels, or using sustainable construction materials. However, internalization often requires vertical integration, which may not be feasible for all stakeholders. Some interviewees highlighted value chain integration as advantageous for building an effective biochar ecosystem. Interviewee 5 mentioned that projects perform better when leveraging an existing value chain, such as in-house biomass or on-site biochar applications.

Interviewee 8 noted that customers increasingly prefer biochar projects with clear traceability across the entire value chain, suggesting that integration could enhance appeal to buyers.

Others argued that internalization is not essential and suggested capturing co-benefits through market mechanisms. For example, local markets might recognize and reward biochar's environmental advantages, allowing producers to charge a premium for its sustainable attributes or its role in renewable energy production. This perspective emphasizes external collaboration and strategic pricing to capitalize on co-benefits without full operational integration. While internalizing co-benefits might reduce monetization costs, it risks oversimplifying the challenges of improving financial viability. Many co-benefits, like reputational gains or long-term environmental impacts, may not yield immediate financial returns. This tension highlights the need for future research into frameworks that balance short-term profitability with long-term sustainability.

6 Cascais Case Study

This chapter presents a case study conducted in partnership with the Municipality of Cascais, aiming to establish a financially sustainable biochar system with a positive environmental impact. It applies the principles and guidelines developed earlier in the thesis, providing a framework for constructing financially viable biochar projects. The case study explores how these principles can be translated into actionable steps, evaluating their effectiveness in achieving both financial and environmental goals. Through an in-depth examination of project design, stakeholder engagement, and operational integration, this chapter offers insights into the practical implementation of biochar systems. The findings test the feasibility of these guidelines and highlight potential adjustments for broader adoption.

The Municipality of Cascais has shown a strong commitment to environmental innovation and sustainable development, making it an ideal partner for testing biochar strategies. Cascais actively engages in sustainability initiatives through its environmental programs, focusing on energy efficiency, renewable energy adoption, and environmental education (Câmara Municipal de Cascais, n.d.). With a goal of achieving net-zero emissions by 2050, Cascais is working to reduce greenhouse gas emissions in municipal activities and align with Portugal’s national targets (Renewable Institute, n.d.). The municipality also participates in international sustainability networks, such as ICLEI – Local Governments for Sustainability, reinforcing its dedication to ambitious climate action (ICLEI Europe, n.d.). This progressive and collaborative approach positions Cascais as an exemplary partner for implementing biochar strategies that advance both environmental and financial sustainability.

The biochar project with Cascais is grounded in an established collaborative relationship, initiated during the previous semester. A workshop was held, bringing together key municipal stakeholders whose roles intersected with potential biochar applications. Representatives from departments like circular economy and land division participated, selected for their relevance to areas that could benefit from a biochar initiative.

The workshop introduced biochar as a technology to support Cascais' environmental goals, focusing on waste reduction, soil enrichment, and carbon sequestration. Participants engaged in brainstorming exercises, generating initial buy-in and motivating stakeholders to consider biochar for Cascais' sustainability initiatives. The project then moved into a detailed exploratory phase, involving interviews with municipal contacts to identify needs, challenges, and opportunities for implementing a biochar system. These interviews helped shape the project's design, ensuring alignment with municipal objectives.

The project aimed to develop an optimal biochar strategy for Cascais that balances sustainability with financial viability. We worked closely with stakeholders (see Appendix D) to align objectives and streamline processes and conducted feasibility calculations to assess the economic potential of proposed biochar applications. This approach ensures the strategy is both sustainable and economically sound.

6.1 Cascais Biochar Strategy

Cascais' biochar strategy integrates multiple stakeholders to produce biochar, capturing carbon, enhancing soil health, and generating revenue, while aligning with sustainability goals. Figure 3 illustrates the finalized setup for Cascais biochar strategy. The process begins with sourcing wood from Cascais' forests pinpointed at Quinta do Pisão, the resource stems specifically from invasive species removal and wildfire prevention efforts. These materials align with pyrolysis requirements, offering high carbon content ideal for carbon capture and soil enrichment. Long-term contracts with forestry stakeholders are recommended to ensure stability in feedstock availability and cost efficiency.

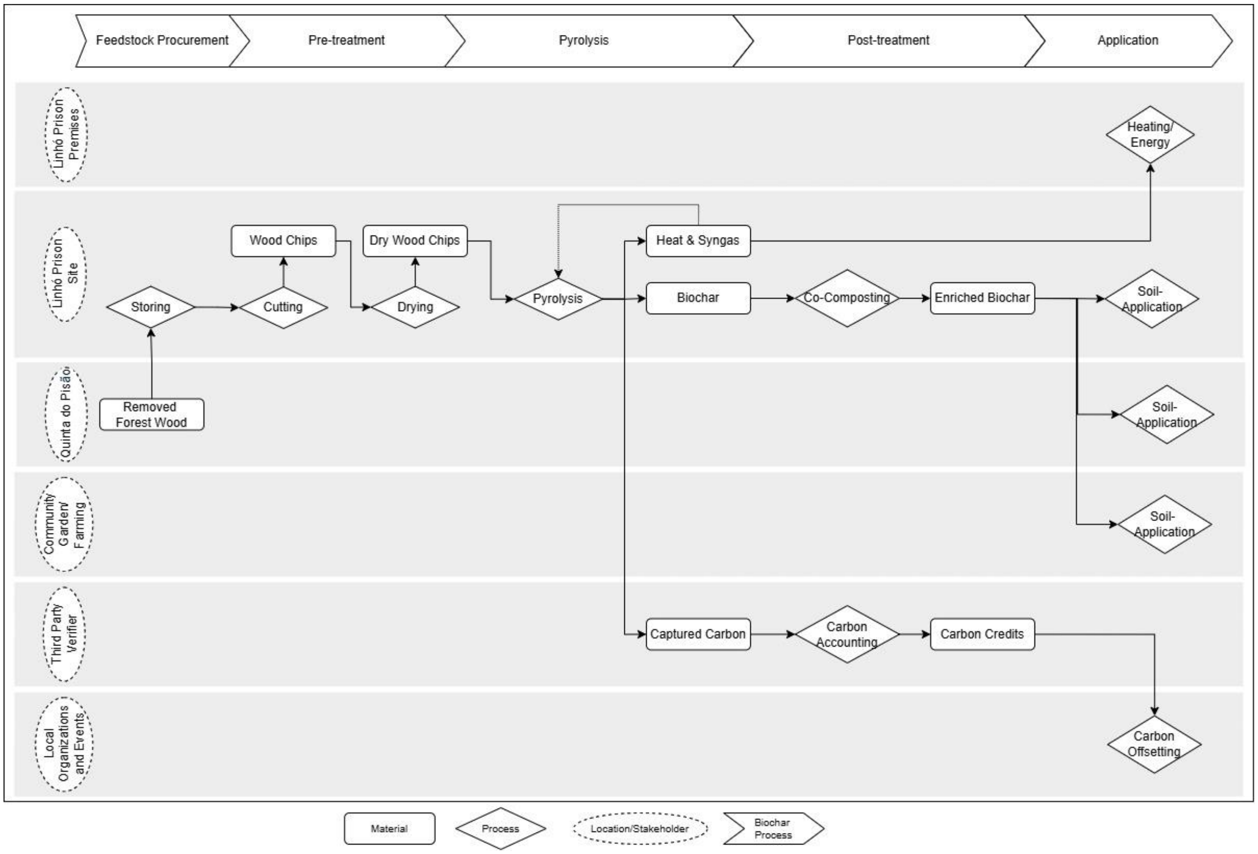


Figure 3: Visualization of Cascais´ Biochar System

This wood will be transported and stored at the foreseen production facility, the Prisonal Establishment of Linhó, located strategically in the north of Cascais. At the production site the feedstock will be stored, to minimize decomposition and facilitate year-round production. Biomass will be shredded into woodchips and pre-heated to subsequently be converted into Biochar and Heat. Biochar will primarily be used to enhance soil health in Cascais' agricultural and landscaping practices. The municipality's green spaces department will use biochar for tree planting, improving survival rates and soil quality. The agricultural department plans to integrate biochar into sustainable farming, revitalizing vineyards and crop areas. To maximize its effectiveness, biochar will be pre-charged with nutrients and mixed with soil and organic materials. Local prisons may support these pre-treatment processes. This integration ensures biochar's benefits to soil structure, water retention, and microbial activity, contributing to long-term agricultural sustainability. Excess heat from the pyrolysis process will be directed to the Linhó Prison Facility, subsidizing its heating needs. Though the heat output does not fully meet the facility's demand, it represents a practical reuse of energy that supports the project's sustainability objectives. Finally, the captured carbon will be verified by a third party and converted into carbon credits provided to the municipality for sale, catering the existing demand from local businesses and events seeking to offset their emissions, enhancing the project's financial appeal. A premium price for carbon credits is recommended, justified by storytelling that capitalizes on the project's local impact on sustainable agricultural practices, green energy and local carbon capture.

In the following sections, we will delve into the details of each stage in this setup, providing an in-depth explanation of the decision-making processes that guided our choices and shaped the project framework.

6.1.1 Feedstock

To assess Cascais' potential for biochar production, we explored a range of possible feedstock sources and their feasibility. Initially, we considered organic waste collected by the municipality from residents, sewage sludge from Águas do Atlántico's water treatment, industrial by-products from local food and water production, agricultural residues, and forestry waste.

However, EU regulations (DIRECTIVE 2008/98/EC & Directive 2010/75/EU) limit thermal treatment options for materials classified as waste, including pyrolysis, as these processes do not support recycling targets required for waste handlers. We did find that bulk waste from municipal waste handlers is not under these specific restrictions, allowing some alternative sources, like wood furniture after sorting and removal of impurities. This source could yield an estimated 5-10 thousand tons annually from all municipalities served, presenting a sufficient source although likely accompanied with significant efforts to purify and prepare feedstock. However, due to the extension of the mandate of waste handlers (Decree-Law no. 102-D/2020, of December 10), Tratolixo is planning to setup a recycling process for respective bulk waste from 2026 onwards. Thus, not matching the criteria of securing long-term feedstock supply.

Our investigation of agricultural and industrial waste indicated limited availability, as Cascais has minimal industry and farming activity, confirmed after discussion with the municipality’s commercial supervisor. Similarly, sewage sludge, while feasible for thermal treatment due to low competing demand, was determined to be unsuitable as it has minimal carbon content, thus failing to meet the primary objective of carbon capture.

Following these assessments, we engaged with Cascais’ forestry department, given that two-thirds of the municipality is forested. Maintenance of these forests, including wildfire protection and removal of invasive species, is estimated to generate ~560 tons of wood cuttings annually sufficient to support large-scale biochar production. Its recommended to establish a rotational plan that splits the to be maintained area into thirds – allowing for annual rotation, focused efforts and recovery of plots. Historically, these materials were sold to the contracted forestry company. The forestry waste aligns well with pyrolysis requirements for biochar production and the intended use to promote soil health (Domingues et al. 2017). Though feedstock comes at a cost, some invasive species removal represents a direct cost to the municipality, while other wood value exceeds removal cost. In the prevailing setting the cutting companies cost of service was offset through the wood yielded. Since the wood as a resource will be used for the biochar production Cascais needs to account for the full removal cost, per ton we estimated a removal price of ~43€ per ton (accumulating to ~24.215€ per annum), excluding transportation expenses.

Moreover, wood offers high carbon content, which would enhance both carbon capture and credit issuance, adding value to the biochar initiative. A long-term contract with a third party and/ or the forestry department could secure feedstock supply and further decrease removal cost, although the seasonal nature of woodcutting, typically performed in spring, necessitates storage at the production site to enable year-round operations. The wood needs to be stored in the form of tree trunks to prevent any accelerated decomposition. Building a storage facility of ~250m² solely consisting of racks and roofing is estimated to amount to 27.675€ investment.

Feedstock transportation is conducted via a third-party, this setup entails estimates feedstock transportation cost of 4,00€ per kilometer traveled using a standard semi-truck with a flatbed or log trailer able to load 30tons per travel, estimated to amount to solely 820€ per annum due to the proximity of feedstock source and production site. The project holds the option to further reduce transportation costs through internal synergies as Cascais operates a suitable vehicle fleet.

6.1.2 Machinery, Operations, and Locality

For Cascais' biochar production system, we evaluated various machinery options, including kon-tiki kilns, custom industrial plants, off-the-shelf solutions, and retrofitted systems. Kon-tiki kilns were eliminated early in the process due to their low efficiency in carbon capture, higher greenhouse gas emissions, fire risk, and limited capacity making them unsuitable for the scale of biomass available in Cascais. Instead, we focused on selecting an industrial-scale solution capable of handling significant biomass volumes while maximizing carbon capture. Additionally, criteria for machinery included the ability to recover syngas to utilize heat as an output improving the system's financial viability. This necessitated sophisticated technology that can prevent methane leakage during syngas capture and use.

Consultations with industry experts consistently emphasized the importance of continuous operation—ideally 24/7, or approximately 320 days per year with minimal downtime—to ensure that capital expenditures are justified, and economies of scale can take place. This feedback directed us toward established, reliable machine manufacturers with proven performance records over custom-built or retrofitted options. Additionally, to minimize operational interruptions, we recommend securing a service agreement with the machine supplier or a qualified third party, as demonstrated by other successful biochar producers, to ensure quick maintenance response times and reduce the risk of costly downtime.

Considering these criteria, we selected an industrial plant with appropriate capacity (450 tons of dried feedstock per annum) to process the annual estimated wood feedstock after drying from Cascais forests, with a high level of automation allowing for partially autonomous operation, reducing labor needs and overall costs. Machinery and equipment expenditure include the Machine from Qualterra priced at ~282.000€ (See Appendix E for machine images and specifications), ~113.000€ for an industrial shredder, ~23.000€ for a feedstock drying module, with additional ~25.000€ for equipment installation and 5% factored in for contingency to decrease risk and account for unforeseeable incidents.

In order to operate machine and biochar production we foresee one FTE with an annual salary of ~25.000€ that oversees operational processes and safeguards production. While machinery allows for autonomous operations, best practices showcased digital monitoring and a person in charge on standby.

Moreover plant's location and thus production is crucial to maximizing value creation by minimizing the costs and emissions associated with transporting feedstock and outputs, as well as supplying hard-to-transport outputs such as heat. We prioritized a site in close proximity to the feedstock source and key application areas for both biochar and heat. This would reduce logistical costs, lower emissions, and enhance the project's profitability.

In addition to transportation considerations, the site must accommodate sufficient storage for excess biomass, pyrolysis equipment, and biochar, as well as provide space for compost production, aligning with the Cascais agricultural department's plans to establish a composting facility. Shared property and machinery opportunities for pre- and post-processing between facilities could present further cost-efficiency.

Finally, the selected location must avoid disruption to Cascais residents, including minimizing noise and visual impact. Through stakeholder consultations, the Linhó Prison Facility emerged as an ideal candidate, offering sufficient space with ~52 hectares for storage, machinery, and temporary structures, while meeting key logistical requirements. Its proximity to the feedstock source, and centered position allows for optimized transportation towards the various biochar application sites, and a large demand for heat, given the prison's 800 inmates, makes it a strategically advantageous choice for this biochar initiative. Transportation length without the application of biochar across the municipality amounts to ~22km, with additional ~30km in average estimated for Biochar to reach its final application destination (See Appendix F for a visualization of transportation routes, and the location of the feedstock source and production facility). The provision of sufficient space at the Linhó Prison Facility, approximately 250m², is priced at an annual rent of ~44.000€.

6.1.3 Output and Product Usage

This section explores the various outputs of the biochar production process, including biochar itself, carbon credits, and energy, detailing their potential uses and economic implications within Cascais biochar system. Wood-tar, Wood-vinegar and bio-oil have been disregarded due to low quantities and insignificant economic value. While biochar, carbon credits and heat have been identified to be valuable in Cascais local setting. Each output contributes uniquely to achieving environmental, social, and financial goals, from enhancing soil health and supporting carbon sequestration to providing renewable energy for local facilities.

Biochar

As previously discussed, biochar can be used in a variety of cases from agriculture, construction, and metallurgy to name a few. Due to the absence of major industries located in Cascais, agricultural and landscaping uses emerged as the most impactful, addressing both sustainability goals and soil revitalization needs. The municipality's Green Spaces Department plans to plant 1,000 new trees annually in existing green spaces, incorporating biochar into the planting process can significantly improve planting survival rates and soil health. It is recommended to use in 5-10% biochar of the soil volume, translating to ~2,5 kgs per tree planting, amounting to 2,5 tons deployed annually.

The Cascais' Terras Department which operates 40 hectares of vineyards, orchards, crop areas, and horticulture, also expressed strong interest in biochar for its commitment to sustainable, biologically friendly agriculture. Per hectare it is recommended to use 5-10 tons of Biochar equal to a demand of 200-400 tons of biochar, clearly exceeding out production capacity of 112,5 tons (110 tons after supporting tree plantings), however these applications are not annual, instead they are depending on the crop cultivated and the soil condition, respectively renewal or supplemental application should be done every 1-5 years. Therefore, the remaining 110 tons of annual biochar produced matches the application potential within the Terras Department's operations. A rotational strategy should be put in place by the department, detailing how biochar will be applied in the long-term allowing for the usage of biochar as a sustainable soil amendment.

Incorporating biochar into Cascais agricultural practices will promote soil health, water retention, nutrient availability, resilience against drought stress, soil structure, microbial activity, and ultimately affect crop yields and tree survival rates. This added value aligns with the department's goals and justifies an internal biochar price of 350€ per ton. In collaboration with the departments, we estimate a combined annual application demand of the total biochar production, generating a projected internal revenue of 40.000€ thousand EUR.

To unleash its full potential best practices should be pursuit when incorporating into local soils and plantings. Most importantly, biochar should be pre-charged with nutrients (e.g., compost, manure, or fertilizer) before application. Uncharged biochar can temporarily tie up nutrients in the soil, which is the reverse and unintended effect. A collaboration with local prisons could potentially involve inmates in biochar and compost mixing, as well as packaging processes, adding a social rehabilitation dimension to the biochar initiative and potentially a potential fourth revenue stream in form of nutrient-rich substrates for local gardeners. Moreover, biochar should be mixed biochar thoroughly with the soil incorporated in to prevent root desiccation and uneven distribution, to further improve the soil biochar should ideally be mixed with organic materials to enhance microbial activity and further improve soil health.

Carbon Credits

The Cascais biochar project aims to capture carbon and generate verified carbon credits for local utilization. To achieve this, the captured carbon must undergo third-party verification, ensuring that all associated emissions, such as those from transportation and potential carbon leakages, are accurately accounted for.

This service ensures that our captured carbon can be accurately translated into verified carbon credits. Based on an estimated input of feedstock we capture 306 tons of carbon through the conversion of biomass to biochar. However, during the production process emissions are emitted which need to be subtracted from the carbon sequestrated, our calculations project a net capture of 281 tons of carbon.

Given the complexity of the verification process and the requirement for officially recognized carbon credits, an external service provider is recommended, such as Puro.Earth, to provide an accounting methodology and guide through the necessary steps. Once verified, these carbon credits offer two potential pathways for revenue. They can be sold through voluntary carbon market providers, such as Puro.Earth’s own marketplace, or they can be directly sold to organizations seeking to offset emissions. Given that Cascais has already received inquiries from local businesses interested in offsetting emissions related to their production or special events, we see local sales as a preferable option allowing to monetize the locality and storytelling.

Cost to account for carbon captured and ultimately revenue through Puro.Earth include the initial verification process which involves preparing a Lifecycle Assessment or Environmental Product

Declaration and undergoing an audit by independent third-party assessors, this one-off cost is estimated to amount to ~12.300€. Puro's Registry allows for selling CORCs via direct agreements, which ensures integrity and prevents double-counting. Transaction fees for CORC Issuance and Retirement depend on contract terms and registry use, for both combined we assume a fee of 5€ per CORC. Additionally, we foresee the expansion of Cascais' environmental departments responsibility, which will distribute and sell respective carbon credits, this is estimated to cost 1/3 FTE equivalent to ~10.000€ per annum.

It's recommended to sell the carbon credits for 369€, including 23% VAT, per ton sequestrated, reflecting a premium price for supporting sustainable agricultural practices, green energy, and local carbon capturing. Under these circumstances carbon credits revenue would amount to annual revenue of ~104.000€. This approach not only meets an existing demand but also strengthens the project's storytelling appeal by ensuring that the credits support local sustainability goals.

Energy

Despite the aim to utilize the heat and syngas produced during the biochar production process, the feedstock mass does not allow for respective technology sophistication (instead, minimal energy needs to be induced to kickstart the process representing a cost of >1,500€ per annum). During the production of biochar, the machinery allows for heat recovery in the form of syngas. The heat output will be redirected to subsidize the biochar production itself, pre-heating biomass to improve efficiency and reduce operational costs.

The remaining 70% of the heat can be channeled to the nearby Linhó Prison Facility, which houses around 800 inmates, thereby supporting their hot water needs (and potentially heating). Based on estimations, the facility's energy demand is estimated at approximately 2,000 MWh of heat annually. However, the energy output of the pyrolysis process is significantly below this demand, at ~570 MWh annually, and can only subsidize the prison's heating demand. It should also be noted that the ongoing heat output from the biochar production may not align perfectly with the prison’s heat usage, which may experience peak times throughout the day.

This energy transfer not only optimizes resources and provides a revenue stream but also contributes to the sustainability and self-sufficiency of local infrastructure. We recommend selling the energy at a prorated fee based on the prison's energy consumption at the annual average market price of 67€ per MWh, which can amount to an annual energy revenue of ~27,000€.

6.1.4 Capital Requirements & Subsidization

The biochar project requires an initial funding of ~460.000€ driven by capital expenditures for the pyrolysis plant, equipment for pre-heating, building a storage facility, installation, carbon credit certification, and contingency. To support this investment, the project qualifies for a 15% non-reimbursable grant under Portugal's Green Transition Initiative, amounting to ~€70,000. This program, funded entirely by national resources, aims to accelerate the shift to a sustainable economy by prioritizing renewable energy, carbon management, and other green technologies. While the project is profitable without subsidies, the grant alleviates the financial performance of the project. This funding mechanism not only aligns with Portugal's climate objectives but also ensures that innovative ventures that inherit a greater risk become competitive with traditional investment opportunities and can create impact.

6.2 Cascais Impact Assessment

This chapter evaluates the financial, environmental, and social impacts of the proposed biochar strategy for Cascais, building on the principles developed throughout this thesis. First, we assess the financial performance of the system using a detailed techno-economic analysis (TEA), identifying key cost and revenue drivers as well as profitability metrics. Following this, we analyze the broader environmental and social outcomes, exploring the strategy's contributions to carbon sequestration, ecosystem improvements, and community benefits. Finally, the practical implementation of the principles in the Cascais case is reflected upon, highlighting key insights, trade-offs, and lessons learned.

6.2.1 Techno-Economic Analysis

In this subchapter, we detail the approach taken for the techno-economic analysis (TEA) of the biochar system outlined in the previous section. The goal of the TEA is to evaluate the financial profitability of the system over a 20-year project lifetime. To achieve this, we employed a bottom-up modeling approach, integrating key financial metrics, assumptions, and detailed cost-revenue structures. Subsequently allowing for cost, revenue, profitability and sensitivity analysis.

To assess financial performance, we selected three widely accepted metrics: Net Present Value, Internal Rate of Return (IRR), and Payback Period. NPV measures the total value of cash flows over the project's lifetime, discounted to the present day. A positive NPV indicates that the project generates value above the cost of capital. IRR represents the discount rate at which the NPV equals zero. IRR is useful for comparing the project's returns to alternative investments. The payback period calculates the time required to recoup the initial investment from the project's cash flows. This metric provides a straightforward assessment of risk and liquidity.

General assumptions include a 20-year lifetime of the project related to the life expectancy and competitiveness of machinery and equipment, a discount rate of 4% reflecting a social discount rate, aligning with recommendations for public projects with environmental and social benefits(Broughel 2020). The 4% rate reflects EU and World Bank guidelines for long-term investments and is close to Portuguese 20-year bond yields (3%) as of late 2023(Trading Economics 2024). A 2% inflation rate was applied throughout cost and revenues, based on long-term EU inflation targets and recent trends(European Central Bank 2022). Additionally, the model includes VAT of 23% for the majority of expenses and revenues, while some fall under exemptions applying a reduced rate of 13%. Income tax is not considered in this TEA, as the proposed biochar project owned and operated by the municipality directly supports the municipality's public service mission by addressing key environmental, social, and economic objectives that benefit the local community. This bottom-up approach allowed us to estimate costs and revenues with high granularity by breaking them into distinct categories. Further details on costs and revenues can be found in 6.1. Biochar Strategy.

For simplicity and incorporating market externalities, the following figures in this subchapter reflect the inclusion of the grant if not stated otherwise. Moving forward, we conducted a detailed analysis of cost and revenue components to identify primary drivers. This includes examining CAPEX, OPEX and cost categories to overall costs and the contribution of each revenue stream to total income.

Expenses

Figure 4 shows a breakdown of the CAPEX and OPEX of Cascais' planned biochar strategy.

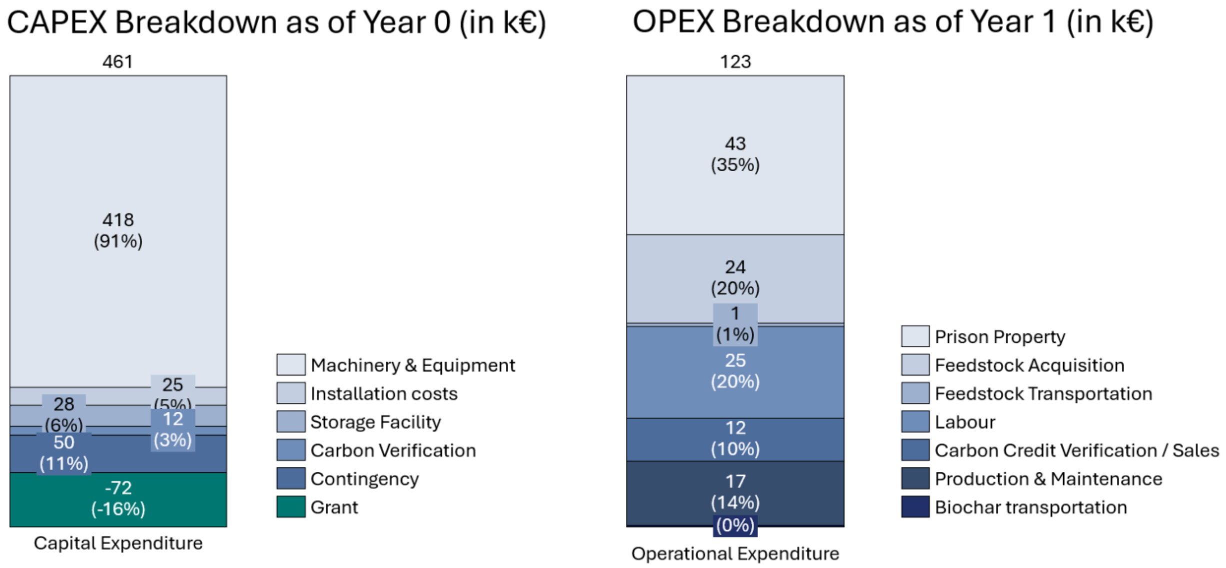


Figure 4 Cascais Case CAPEX & OPEX Breakdown

The CAPEX in Year 0 for the project amounts to €461,000, distributed across several categories. Machinery and equipment dominate the initial capital investment, representing 91% of the total costs. This includes expenditures for the pyrolysis processing unit, industrial shredder, pre-drying module, and ancillary operational equipment. These allocations highlight the capital-intensive nature of establishing biochar facilities, where specialized technology is necessary to optimize biomass conversion into biochar and recover valuable by-products. Additionally, the incorporation of a grant and contingency fund underscores the importance of financial support and risk mitigation strategies. The inclusion of a grant and contingency fund ensures both financial support and risk mitigation. The emphasis on equipment aligns with findings in the literature, which also identify pyrolysis technology as the largest cost driver of capital investments. Studies report that setting up a pyrolysis facility requires between $300,000 and $2 million for small- to medium-scale operations (Biochar Zero 2024).

The Year 1 OPEX for the project is €123,000, distributed across several categories, presenting a stark contrast to insights from the literature, where feedstock acquisition, transportation, and storage often comprised 50-70% of costs, while fixed costs were a smaller proportion. This discrepancy arises from several factors. Primarily, economies of scale in larger projects allow fixed costs to be distributed across greater volumes, leading to a higher proportion of variable costs like feedstock acquisition compared to our small-scale project. Additionally, storage requirements are excluded from OPEX, as the strategy involves building a dedicated storage facility. Lastly, by optimizing the choice of feedstock and the proximity of system components, this project achieves very low feedstock acquisition and transportation costs. These economies of scale differences also explain the disproportionate representation of operational cost categories in our project: property rent accounts for 35%, labor for 20%, and production and maintenance for 14%.

Revenues

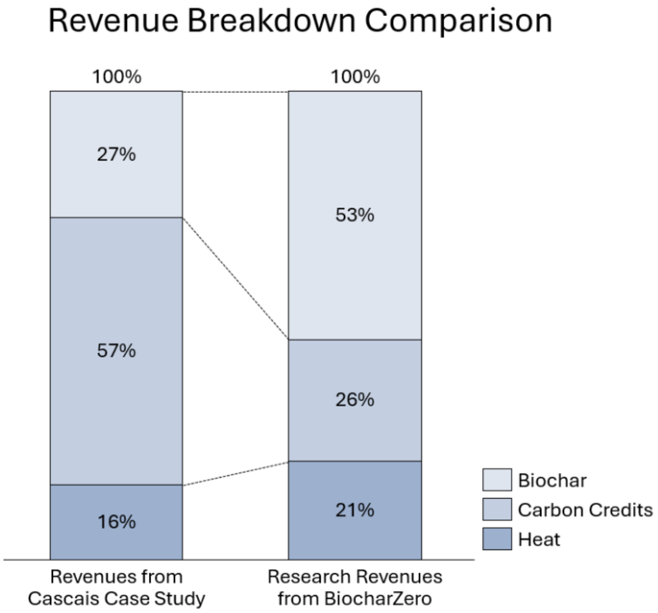


Figure 5 Revenue Breakdown Comparison: Cascais Case vs BiocharZero Research Findings

As shown in Figure 5, the literature shows a median revenue split of 53-26-21 between biochar, carbon credit, and energy income, while this project, with a split of 27-57-16, has a notably higher focus on carbon credits(Biochar Zero 2024). The primary reason for this is that the biochar, a key output, is underrepresented in the revenue profile as it is sold internally without markup. If sold at market rates for similar products, the revenue composition would appear more conventional compared to the internally accounted price of €300. Additionally, supplying heat to the Linhó Prison contributes a modest 16% of total revenue. While small, this income stream is crucial for profitability. Although excess heat could be converted into electricity for sale to the grid, our analysis shows that the scale of operations does not justify the significant investment required for the necessary equipment.

Cashflows & Profitability

Following the analysis of cost and revenue drivers, the project's viability is analyzed by investigating levelized profitability and cashflows.

Putting all costs and revenues together and leveling them out over the timeline of the project and the volume of biochar produced, there are costs of 1.530€, and revenues of 1.849€ per ton of biochar. This yields a profit margin of 319€ per ton, equivalent to 17%. (See Appendix G for a breakdown of the levelized cost of biochar per ton).

Once the initial investments are completed in year 0 (2025), the system generates steady positive cash flows with a 2% annual growth, reflecting inflation (see Appendix H for cash flow projections). Discounting these cash flows over the project timeline results in an NPV of €303,000. The investment has an IRR of 5.81%, with cumulative cash flows indicating the project breaks even between years 8 and 9. Importantly, even without the recently issued government grant for climate projects, the project remains profitable, highlighting its intrinsic financial viability, view Table 5 for a comparison of the two scenarios.

Table 5 Cascais Case Key Economic Indicators

	NPV	**IRR**	**Payback-Period**
Without Grant	269.000 €	5,23 %	10 years
With Grant	303.000 €	5,81 %	9 years

Sensitivity Analysis

Finally, we performed a sensitivity analysis to understand the impact of key variables, namely the feedstock acquisition cost and quantity of dry feedstock, as well as the selling prices of biochar, carbon credits, and heat, on the overall NPV. These variables were chosen for the sensitivity analysis as, opposed to the main cost factors such as land or labour, they are more volatile and more likely to change depending on external factors.

Table 6 Cascais Case Sensitivity Analysis

Variable	Unit	Elasticity	% Change for NPV of 0€	Value change for NPV of 0€
Feedstock Acquisition Cost	€ per ton	-1,3	78%	33.5
Dry Feedstock Quantity	Tons per year	5,7	-18%	-79.6
Biochar Price	€ per ton	2,1	-48%	-167.3
CO_2 Price	€ per ton	5,5	-18%	-67.0
Energy Price	€ per MWh	1,4	-69%	-47.1

For each key variable, we calculated the projected impact on the project´s NPV given a percentage change of 1%. In Table 6, you can see these as elasticity figures. Furthermore, we calculated by how much the variables would have to change, in relative and absolute values, to make the project break even.

The system's financial viability is highly sensitive to the annual quantity of dry feedstock processed. A reduction of approximately 79.5 tons, from 450 to 370.5 tons, would render the project unprofitable. This aligns with insights from the literature and expert interviews, which highlighted the importance of high utilization rates and a steady feedstock flow to justify the substantial capital expenditure for equipment. Since the feedstock stream from invasive species is annual and predictable, Cascais can anticipate shortages and source alternative feedstocks in advance, minimizing disruption. Therefore, the sensitivity to feedstock volumes poses minimal risk to operations.

With an elasticity of 5.5, the financial viability of the system is also quite sensitive to the price of carbon credits. This can be attributed to its outsized contribution to the total revenue (57%). The sensitivity to carbon credit sales presents both an opportunity, Cascais being able to greatly increase their revenue by commanding higher carbon credit prices, and a risk, as unbeneficial changes in the carbon market may squeeze the profit margin.

The biochar price has an elasticity of 2.1 but is unlikely to change frequently as it is accounted for internally. Nevertheless, if Cascais were to sell their biochar to third parties, this would be an important opportunity of further income.

Finally, with elasticities of 1.4 and -1.3 respectively, fluctuations of the energy prices and feedstock acquisition costs can also substantially influence the NPV of the project but are not as critical to observe for improving financial performance and mitigating risks as the carbon credit sales.

6.2.2 Assessment of Project Impacts

After analyzing the financial structure in the previous chapter, this section focuses on evaluating the impact generated by the proposed strategy. To achieve this, we apply the widely recognized Logical Framework Approach (LogFrame), which differentiates between outputs, outcomes, and impacts (Couillard, Garon, and Riznic 2009). Specifically, we categorize outputs into distinct areas, namely economic, environmental, and social, providing a structured analysis of the strategy's immediate results, medium-term effects, and long-term changes. Finally, potential negative externalities of the biochar system will be investigated.

Economic Impact

The economic outputs of the biochar strategy were analyzed in detail in the techno-economic analysis and will not be discussed in much detail in this part, as it should focus on the outcomes and impact. The outputs generated by the strategy include a cumulative profit of €692,000 and a profit margin of 17% over the project's lifetime, when discounted presenting an of IRR 5,81%. Further economic outputs that were not included within the scope of the TEA may include reduced costs of tree plantings due to lower mortality rates, and savings from the displacement of agricultural products that biochar is substituting. Furthermore, municipalities can expect reputational gains from social and environmental projects which are difficult to quantify but tend to positively impact economic activity (Delgado-García, de Quevedo-Puente, and Blanco-Mazagatos 2018). In terms of outcomes, the principles implied in the strategy demonstrate improved financial performance with a positive cash flow projection within ten years. The long-term impact of the economic component lies in contributing to local economic growth, supporting Portugal's Green Transition Initiative by fostering green innovations, and reducing reliance on traditional waste management approaches.

Environmental Impact

The environmental outputs of the strategy are central to its objectives. The biochar production process generates 112.5 tons of biochar annually, which is used to enhance tree mortality rates, improve soil health, and further supports subsequent carbon sequestration in agricultural and landscaping applications. Additionally, the system captures and verifies 281 tons of carbon annually for carbon credits and recovers approximately 570 MWh of heat each year, which is reused during production or redirected to the Linhó Prison Facility.

These outputs lead to meaningful outcomes, including enhanced soil health and water retention in Cascais' community gardens, vineyards, and agricultural land. The project contributes significantly to carbon sequestration, offsetting the annual carbon footprint of 431 households. By utilizing forestry waste, the project mitigates wildfire risks and reduces greenhouse gas emissions that would otherwise arise from decomposing organic materials. The choice of invasive species as feedstock has further environmental benefits, protecting the local ecosystem and species native to Portugal. Healthier soil ecosystems in biochar-treated areas promote biodiversity (Li et al. 2018), while improved water retention reduces the need for irrigation, further supporting sustainable agricultural practices (Kabir, Kim, and Kwon 2023; Biederman and Harpole 2013). Finally, there are potential indirect environmental benefits as the biochar and heat can displace less sustainable agricultural products or fossil fuel energy that may currently be in use.

The long-term environmental impacts are profound. The strategy significantly contributes to Cascais' net-zero emissions target by 2050, with biochar ensuring long-term carbon sequestration. Areas where biochar is applied experience better plant growth, increased vegetation cover, and improved crop yields, enhancing ecosystem services such as pollination and climate regulation. These improvements increase resilience to climate change, enabling soils to withstand droughts and extreme weather events (Blanco-Canqui 2021). Additionally, the rehabilitation of degraded lands and urban green spaces turns previously underutilized areas into productive ecosystems, reducing the reliance on synthetic fertilizers and their associated emissions (El-Naggar et al. 2019).

Social Impact

While social impact was not the primary focus of this strategy, some notable benefits are emerging. Outputs include using biochar by citizens in community gardens and the integration of the Linhó Prison Facility as a production site, leveraging its infrastructure to support the biochar operation.

These activities lead to several outcomes. Community awareness and participation in sustainability initiatives are expected to increase, driven by Cascais' green programs and educational outreach about biochar's role in tackling climate change. Additionally, the potential involvement of inmates at the Linhó Prison Facility through the potential involvement of inmates in biochar and composting operations offers a unique opportunity for providing skills and experiences that may contribute to their rehabilitation and reintegration into society.

The strategy's broader social impact includes strengthened community cohesion around shared environmental goals, fostering a culture of sustainability. In summary, the proposed biochar strategy demonstrates significant economic, environmental, and social benefits, contributing to sustainability goals while fostering innovation. Its holistic impact provides a replicable model for other municipalities seeking to balance financial viability with environmental stewardship.

Negative Externalities

The Cascais biochar project, while projected to deliver the significant environmental, economic, and social benefits mentioned above, carries inherent potential of producing unintended negative externalities. Being aware of these risks and managing them is essential to prevent larger issues from arising, and ensure that the projects creates net value in all areas.

First of all, concerning environmental issues, constructing the production facilities at Linhó prison may require the use of green spaces, potentially leading to habitat loss and reduced biodiversity in the local area. Additionally, the opportunity cost associated with the wood cuttings required for biochar production must be carefully considered. Wood that could otherwise serve as a resource for other industries, constrains local wood supplies and leads to increased competition among stakeholders, possibly driving unsustainable harvesting practices. Mitigating this risk involves ensuring sustainable sourcing practices and exploring alternative biomass inputs.

The implementation of our strategy may also carry social externalities. The use of prison labor for the operations is suggested in our strategy, offering rehabilitation opportunities and skill-building. While this represents a great social opportunity, it needs to be managed carefully to ensure ethical conduct, including fair compensation and voluntariness. Finally, the project's operations, though designed to take place in more sparsely populated areas, may disrupt Cascais residents. The increase in transportation and noise from production activities risks reducing their quality of life and could lead to community opposition. Addressing and managing these externalities is crucial to increasing the projects acceptance and improving its environmental and social impact.

6.3 Cascais Results and Discussion

The implementation of the principles into the Cascais biochar strategy exemplified how a financially viable and environmentally sustainable system can be conceptualized. This section evaluates how the principles were practically applied, focusing on their contributions to financial performance while maintaining positive environmental impact and the challenges of adapting them to a real-world context. The Insights and Learnings chapter reflects on the broader implications of these implementations and limitations, offering a nuanced understanding of how these guidelines inform strategic decisions.

6.3.1 Evaluating the Practical Implementation of Principles in Cascais

This chapter reflects on how the principles developed in this thesis were applied to the Cascais biochar strategy, analyzing their effectiveness in achieving financial viability and environmental sustainability. Each principle is evaluated to determine its contribution to the strategy, identifying successes, challenges, and areas for improvement. Furthermore, this reflection explores the extent to which these principles enhanced the financial performance of the system, providing a nuanced understanding of their practical implementation.

P1: Optimize feedstock choice by balancing cost, sustainability and application needs

The selection of forestry waste as the primary feedstock strongly aligns with this principle. Sourced from invasive species removal and wildfire prevention efforts, forestry waste provides a cost-effective biomass at ~43€ per ton and supports sustainability through forest maintenance practices and its high-carbon content. The stability and carbon content of hardwoods like acacia and eucalyptus ensure high-quality biochar for agricultural use, while pine, though slightly lower in performance, still meets the necessary requirements for Cascais' applications. However, the seasonal availability of forestry waste requires storage solutions to ensure a consistent year-round supply, introducing logistical challenges and costs for building a storage facility.

This principle guides the choice of feedstock by minimizing input costs, maximizing carbon revenue through high-carbon content, and ensuring alignment with target applications, justifying the biochar users' willingness to pay. However, excluding alternative feedstocks, such as agricultural residues, limits flexibility and resilience in the supply chain. Exploring complementary feedstock options with similar environmental and quality benefits enhances adaptability while maintaining a balance between cost and sustainability. Incorporating alternative feedstocks increases production capacity, leading to larger operations and better cost distribution, further improving the system's financial sustainability.

P2: Foster sustainability alignment without excluding broader partnerships

The Cascais strategy focuses primarily on internal stakeholders, aligning operations with municipal sustainability goals. This internal alignment fosters cohesion, reduces tensions, and streamlines decision-making, ensuring operational efficiency. For example, the Green Spaces Department and Terras directly contribute to the project’s design and biochar application in municipal initiatives.

However, this inward focus limits the inclusion of broader partnerships, which could enhance scalability and financial opportunities. While collaborations with external sustainability-focused businesses or regional stakeholders are not prioritized, their involvement could provide additional resources, expertise, and market access to support the system’s growth.

This principle helps ensure smooth collaboration within the municipal ecosystem and reduces project risks. However, its limited application to external partnerships suggests missed opportunities for greater economic and ecological impact. Expanding collaboration in future iterations improves scalability, market reach, and financial performance.

P3: Design biochar systems to align emission reduction with cost savings and revenue opportunities

The Cascais strategy exemplifies the principle by focusing on local solutions to reduce emissions and costs while balancing practical trade-offs for system viability. By sourcing feedstock from nearby forests and conducting pyrolysis at Linhó Prison, the project minimizes transportation-related emissions and costs, enhancing both cost structure and environmental impact. The choice of high-carbon feedstock is key to reducing emissions and maximizing carbon sequestration. Durable biochar application further supports carbon capture monetization by ensuring long-term carbon storage, increasing revenue from carbon credits. Although storing feedstock incurs additional costs, storage prevents decomposition, maximizing carbon credit revenue and outweighs incurred storage costs.

The project's smaller scale poses challenges in equipment selection, with limited options that fit its budget and feedstock volume. The chosen pyrolysis equipment meets basic requirements but lacks advanced features, like internal heat conversion units displacing the need of external energy, which would further optimize emissions reductions and reduce external energy dependence.

The Cascais case shows that cost reduction and carbon credit revenue opportunities align with emission-reducing initiatives, however, achieving greater environmental impact may require higher costs in certain areas. Investments in storage and advanced pyrolysis technologies enhance carbon credit revenue potential, but a detailed analysis should be conducted if increase in revenue exceeds increase in cost, enabling improved long-term sustainability and financial performance.

P4: Explore options for sharing assets and services to reduce costs and improve utilization

The Cascais strategy initially explores sharing assets and services to reduce costs and improve operational efficiency, including the possibility of utilizing preprocessing equipment at Tratolixo, the local waste management company. However, the project's volume exceeds what Tratolixo can support, making this collaboration unfeasible. This highlights a critical insight: the size of a biochar project significantly influences the feasibility of shared asset arrangements. While sharing assets can reduce upfront costs and improve resource utilization, larger projects require dedicated infrastructure or bespoke solutions, making such collaborations more challenging.

Although asset sharing is not feasible for Cascais, this principle remains relevant for smaller or medium-scale projects, where collaborative arrangements are more likely to align with operational needs. For larger projects, the focus may need to shift to maximizing the efficiency of dedicated assets while exploring alternative cost-reduction and resource optimization methods. These findings emphasize the importance of tailoring strategies to project scale and context to ensure both financial and operational viability.

P5: Educate stakeholders on biochar technology and its benefits to increase awareness, and drive adoption

Educating stakeholders about biochar technology and its benefits is crucial for adoption and project success in the current market environment, where awareness for biochar represents a significant hurdle. In the Cascais strategy, workshops and interviews introduce municipal stakeholders, local businesses, and community members to biochar’s potential for waste management, soil improvement, and carbon sequestration. These efforts align biochar with municipal goals, demonstrate its sustainability value through carbon credits, and generate local demand for the pyrolysis outputs.

While the impact of education on financial viability is indirect, it is significant. Education increases understanding and trust, making the project feasible. Municipal stakeholders are more willing to allocate resources and support biochar integration into public initiatives, which indirectly supports financial viability by fostering buy-in and creating future revenue opportunities.

Education alone doesn’t directly increase profitability but is critical for project development and securing stakeholder engagement. Future projects should prioritize tailored educational efforts to build confidence and lay the groundwork for economic success.

P6: Align biochar characteristics with customer needs to ensure and increase willingness to pay

The Cascais strategy tailors biochar production to meet the specific needs of municipal applications, such as enhancing soil in green spaces and community agricultural projects. Expert consultation confirms that the selected woody feedstocks are optimal for producing high-quality biochar with stability, porosity, and high carbon content, which align well with these applications. The flexibility of forest soils allows for repeated applications, increasing biochar's value in this context.

By aligning biochar characteristics with user needs, this principle supports financial performance by justifying and potentially creating demand. However, because the biochar is used internally in municipal projects rather than sold externally, the increased willingness to pay for its tailored characteristics cannot be monetized, highlighting a key limitation for organizations that use outputs themselves.

Future testing and adjustments in processing techniques will be crucial to maximize biochar's fit to customer needs. Additionally, exploring external markets and monetization opportunities for tailored biochar applications further enhances the financial sustainability of similar projects.

P7: Monetize applicable benefits of biochar production to diversify revenue streams

The principle of diversifying revenue streams aims to enhance financial viability by leveraging multiple outputs from biochar production. The Cascais strategy integrates biochar, carbon credits, and heat into the system’s value streams. Biochar is used internally for municipal green spaces and agricultural projects, carbon credits are sold to local businesses for offsets, and heat generated during pyrolysis is used at the Linhó Prison Facility for heating and hot water.

This approach subsidizes production costs, serves key stakeholders, and supports financial viability. For example, using biochar internally supports urban tree planting and soil improvement, reducing external costs. Similarly, using excess heat at the prison generates revenue or offsets land use costs. However, internal use limits the possibility of premium pricing for biochar and heat on external markets. Additionally, only a share of the heat is utilized at the Linhó Prison due to the lack of central heating or industrial plants in the area capable of using the remaining heat. Converting the unused heat into electricity could have been a potential solution, but the low efficiency and high capex of such modules did not justify their purchase. This highlights a trade-off between fully utilizing a byproduct such as heat, optimizing the biochar system’s economics. In contrast, carbon credits can be sold for premium pricing, significantly contributing to profitability. Minor by-products, like wood tar and wood vinegar, are excluded due to their low economic value, narrowing diversification opportunities.

The principle only partially advances financial viability. Expanding external sales of biochar and carbon credits to regional businesses or other municipalities generates additional revenue. While the principle is effectively implemented, future strategies could better balance internal use with external market opportunities.

P8: Locate biochar systems to optimize proximity to available feedstock, and market demand for application sites and byproduct utilization

The principle of strategically locating biochar systems to optimize proximity to feedstock, application sites, and byproduct utilization is key to maximizing financial and environmental benefits. However, in the Cascais strategy, this is not fully implemented. The decision to partner with Cascais is driven by shared values of innovation and sustainability rather than optimal location. While Cascais' selection brings strong stakeholder alignment and municipal support, it also limits scalability due to feedstock availability being restricted to local wood from invasive species removal.

This experience highlights the financial importance of location. While locality supports stakeholder goals and logistical efficiency, it can limit resource availability and scalability. A more flexible approach to location selection, prioritizing diverse feedstock sources and broader markets, enhances financial sustainability. Future projects should consider how location decisions balance resource availability and market potential.

P9: Utilize strategic contractual agreements for risk mitigation and reliability in biochar systems

The Cascais biochar strategy internalizes key processes such as feedstock sourcing and biochar application, providing greater control over critical elements and minimizing uncertainties around feedstock availability and biochar offtake, reflecting a privileged position of a municipality inheriting critical steps in the value chain. However, to improve clarity on responsibilities, it is recommended to establish agreements between departments and municipal entities outlining the scope of practice to ensure ongoing operations.

The limited use of external contractual agreements constrains opportunities for long-term collaborations with external buyers or suppliers. While internalization helps stabilize operations, it reduces flexibility to adapt to broader market demands. For example, the lack of offtake agreements for carbon credits or additional feedstock partnerships limits scalability and capacity to meet growing demand. Strategic contractual agreements enhance financial viability by providing revenue and supply chain predictability. Long-term carbon credit agreements with local businesses or partnerships for additional feedstock secure steady income and improve operational efficiency. Service agreements with machinery providers mitigate risks related to equipment downtime, ensuring smooth operations.

Although the Cascais strategy's internalized design limits the application of this principle, incorporating more contractual agreements strengthens the project's resilience and scalability, supporting both financial and environmental goals.

P10: Leverage storytelling and branding to drive the value of biochar carbon credits

The Cascais biochar strategy effectively integrates storytelling and branding to enhance the value of its carbon credits. By emphasizing local benefits like carbon sequestration, renewable energy generation, and soil enhancement, the project aligns with Cascais' sustainability goals. This strong narrative appeals to local businesses seeking to offset emissions and strengthens community buy-in by highlighting the municipality's environmental and social contributions.

A key aspect of the storytelling is the collaboration with the Linhó Prison Facility, which adds a social dimension by combining environmental impact with social responsibility. Inmate involvement in biochar production or packaging activities emphasizes rehabilitation and skill-building, showcasing both climate action and community upliftment.

The system's locality strengthens the narrative, showcasing carbon credits derived from local forestry waste, processed and applied within Cascais. This circular approach appeals to businesses that value transparency and local sustainability efforts. As one interviewee notes, "carbon credits are as much a branding tool as they are a climate tool." Cascais effectively leverages this insight, making its credits more appealing and likely to command a premium. This approach enhances financial viability by increasing stakeholder buy-in, willingness to invest, and willingness to pay for carbon credits.

The Cascais strategy demonstrates the value of balancing financial viability with environmental sustainability. While most principles are well-implemented, challenges emphasize the need for adaptability and context-driven solutions. Expanding partnerships, validating biochar applications, and exploring new revenue streams enhance long-term success.

6.3.2 Insights and Learnings from Implementing the Cascais Biochar Strategy

The implementation of the Cascais biochar strategy provided valuable insights into how the developed principles in this thesis function in a fully conceptualized strategy. Deriving from the inherent context-specific nature and interconnectedness of biochar system components, we found that not all principles could be implemented equally and that synergies and tradeoffs existed between the principles. Nonetheless, they were successful in informing context-specific strategic decisions, enabling Cascais to achieve financial viability while maintaining environmental sustainability in the current market environment.

Firstly, the degree to which the principles for financial viability can and should be integrated varies greatly, depending on the specific context of the potential biochar system. The context of setting up a financially, environmentally, and socially beneficial biochar system in Cascais municipality offered unique constraints and opportunities, which had to be managed. While the evaluation of how each principle could be implemented is detailed in the previous chapter, it can be said that the inherent challenges of reconciling theoretical optimization with practical, context-driven constraints were demonstrated.

Despite the constraints of applying all principles, the strategy demonstrated strong interconnections among the different guidelines, with mutually reinforcing relationships. For instance, restricted feedstock options (P1) directly influenced revenue potential (P7) and emissions goals (P3). Feedstock choice (P1) is also tied to location (P8), as proximity to resources influences scalability and costs. Broader partnerships (P2) depend on formalized contractual agreements (P9) to ensure reliability and long-term collaboration. Emission reduction (P3) and revenue diversification (P7) are closely linked through carbon credits, requiring optimized operations for maximum financial and environmental benefits. Meanwhile, education (P5) and storytelling (P10) work synergistically to engage stakeholders, and the emphasis on locality (P8) not only reduced emissions but also enhanced storytelling (P10) by showcasing the system's regional focus and circularity fostering demand for carbon credits and municipal support for the project.

Contrarily, the Cascais biochar strategy illustrates several trade-offs within the set of principles, highlighting the challenges of balancing competing priorities. A key example is the tension between locality (P8) and scalability. While sourcing feedstock, preprocessing, and production locally minimizes transportation emissions and strengthens the narrative of circularity and local impact, it also restricts feedstock availability (P1) limiting economies of scale and market expansion. This localized approach fosters community buy-in and aligns with sustainability goals but limits the potential for larger-scale operations and external partnerships. Similarly, the emphasis on the internal use of biochar (P6) to meet municipal needs prevents monetization opportunities on external markets, reducing revenue diversification. Additionally, the focus on emission reduction (P3) sometimes conflicts with the financial objectives as investment in advanced technologies might exceed subsequent revenue opportunities. The challenge lies in balancing these competing principles.

The experience of implementing the principles in Cascais highlighted the importance of interpreting them as dynamic guidelines rather than static rules. Practical constraints and contextual factors often require adapting the principles to balance feasibility with long-term economic and sustainable impact, while rigid adherence to theoretical ideals can risk undermining the project's financial viability. Moreover, the interdependencies of the principles underscored the value of prioritizing between project objectives and valuing the respective principles accordingly. Ultimately, they were a crucial tool that helped to guide our decision-making and navigate the intricacies inherent in biochar systems, shaping a financially viable system design and strategy in the specific context of Cascais municipality.

7 Conclusion & Limitations

This chapter summarizes the key findings of the thesis, focusing on how biochar systems can achieve financial viability while maintaining their environmental impact. It highlights the developed principles, and their application in the Cascais case study, and reflects on the research limitations. Finally, it outlines directions for future research to further validate and refine these insights in diverse contexts.

7.1 Conclusion

This thesis set out to address the question: "How can biochar systems achieve financial viability in the current market setting while maintaining their environmental impact?" In doing so, it sought to bridge the gap between biochar's potential to mitigate climate change and the economic realities that limit its adoption. The literature underscores that while biochar presents a highly promising solution for climate change mitigation, achieving financial viability in the current market context remains a multifaceted challenge. Through an extensive review of the market enablers and barriers, as well as cost- and revenue drivers on a system level, we obtained initial hypotheses for achieving the financial viability of biochar systems. These were refined into comprehensive principles to reflect the intricate findings generated by our subsequent expert interviews.

The principles developed from secondary and primary research methods to answer our research question serve as a flexible and context-driven framework for achieving financial viability while maintaining environmental sustainability in biochar systems. Their application requires a nuanced understanding of the synergies and trade-offs that exist between system components within biochar projects. The more principles incorporated into a system’s design, the greater the likelihood of achieving both financial and environmental goals. However, the principles are neither hierarchically structured nor universally applicable; they must be tailored to the unique conditions of each project and serve as adaptable guidelines rather than rigid directives.

Finally, this set of principles was applied to the case study of Cascais municipality, resulting in a concrete strategy that is financially viable and contributes towards Cascais´ environmental and social objectives. The Cascais case study demonstrates that the financial viability of biochar systems, which has been a key hurdle to the widespread adoption of BCR, can be achieved by using this set of principles as a tool to inform strategic decision-making and navigate the intricacies of biochar systems. By exploring these pathways towards profitability, we hope to establish the attractiveness of BCR for increased investment and contribute to the promising technology fulfilling its potential of playing a major role in mitigating the profound impact of climate change on global ecosystems, human health, and economic stability.

7.2 Limitations and Future Research

The results discussed above, derived from the literature review, expert interviews, and Cascais case study, are accompanied by several limitations which will be acknowledged in this section.

First of all, it must be said that the early development stage of the biochar market presents some limitations to our research. Due to the rapid developments of scientific research on biochar technology and climate change, as well as changing regulatory environments, the literature review sections could turn out to be time-sensitive. Further challenges arise from the limited availability and inconsistent quality of financial and environmental performance data, as market participants are limited, and many do not publicly disclose operational details. This lack of data affects the precision of the techno-economic analysis and introduces uncertainty, especially in these volatile and rapidly evolving markets. Similarly, the environmental and social impacts of a biochar system within the Cascais Case Study could not be reliably quantified within the scope of this thesis, meaning they are based on secondary data and require further investigation pre- and post-implementation.

While expert interviews enrich the study, they cannot fully capture the diverse perspectives of all stakeholders, particularly niche application end-users and policymakers, which limits the comprehensive understanding of ecosystem dynamics. Additionally, while we attempted to interview experts based across the globe, the sample may be regionally skewed towards Europe due to better accessibility.

Further, the case study with Cascais is missing a baseline scenario to compare against the proposed strategy. This absence makes it challenging to evaluate the extent to which the included principles enhance the financial viability of the biochar system. Without a reference point, the analysis cannot fully quantify the incremental improvements or measure the effectiveness of the proposed approach. It must also be noted that, while the results of our techno-economic analysis indicate that the application of our principles led to a profitable system design in the Cascais case, this will not universally be the case. While these insights offer a strong foundation for enhancing financial performance and the likelihood of reaching financial viability, their practical application and impact vary depending on specific local conditions, market maturity, and technological advancements. Further empirical testing and real-world implementation are required to validate and refine these principles in diverse contexts, ensuring their relevance and effectiveness across varying operational scenarios.

8 References

Alsaawi, Ali. 2014. "A Critical Review of Qualitative Interviews." European Journal of Business and Social Sciences 3 (4). https://doi.org/10.2139/ssrn.2819536.

Beerling, David J., Euripides P. Kantzas, Mark R. Lomas, Peter Wade, Rafael M. Eufrasio, Phil Renforth, Binoy Sarkar, et al. 2020. "Potential for Large-Scale CO2 Removal via Enhanced Rock Weathering with Croplands." Nature 583 (7815): 242–48. https://doi.org/10.1038/s41586-020-2448-9.

Biederman, Lori A., and W. Stanley Harpole. 2013. "Biochar and Its Effects on Plant Productivity and Nutrient Cycling: A Meta-analysis." GCB Bioenergy 5 (2): 202–14. https://doi.org/10.1111/gcbb.12037.

Biochar International. 2024. "RFP: 2024 Global Biochar Industry Market Research Report." Biochar International. Accessed September 16, 2024. https://biochar-international.org/news/rfp-2024-global-biochar-industry-market-research-report/.

Biochar International. n.d. "Biochar Production and By-Products." Accessed October 20, 2024. https://biochar.international/the-biochar-opportunity/biochar-production-and-by-products/.

Biochar Zero. 2024. Project Developer Guide: Key Aspects for Successful Biochar Projects Based on Industry Insights from Europe in 2024. Accessed November 2, 2024. https://biochar-zero.com/free-biochar-project-developer-guide/.

"BioFlux Biochar Consulting Services." n.d. Accessed September 10, 2024. https://www.bioflux.earth/biochar-consulting.

Blanco-Canqui, Humberto. 2021. "Does Biochar Improve All Soil Ecosystem Services?" GCB Bioenergy 13 (2): 291–304. https://doi.org/10.1111/gcbb.12783.

Blaufelder, Christopher, Cindy Levy, Peter Mannion, and Dickon Pinner. 2021. "A Blueprint for Scaling Voluntary Carbon Markets to Meet the Climate Challenge."

Broughel, James. 2020. "The Social Discount Rate: A Primer for Policymakers." Mercatus Center.

Bydén, William, and Daniel Fridlund. 2020. Carbon Negative Heat and Power with Biochar Production: An Economic Analysis of a Combined Pyrolysis and CHP Plant. Stockholm: Swedish Bioenergy Association. Accessed December 16, 2024. https://exampleurl.com.

Byrne, Tamzin. 2024. “Additionality, Leakage and Permanence.” Cambridge Centre for Carbon Credits (4C). https://4c.cst.cam.ac.uk/about/additionality-leakage-and-permanence.

Calvin, Katherine, Dipak Dasgupta, Gerhard Krinner, Aditi Mukherji, Peter W. Thorne, Christopher Trisos, José Romero, et al. 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by Paola Arias, Mercedes Bustamante.

CDR.fyi. "2023 Year in Review." CDR.fyi Blog. Published January 3, 2024. https://www.cdr.fyi/blog/2023-year-in-review.

Ismail Elgizouli, Gregory Flato, Mark Howden, Carlos Méndez-Vallejo, Joy Jacqueline Pereira, et al. Geneva: IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647.

Campbell, Robert M., Nathaniel M. Anderson, Daren E. Daugaard, and Helen T. Naughton. 2018. “Financial Viability of Biofuel and Biochar Production from Forest Biomass in the Face of Market Price Volatility and Uncertainty.” Applied Energy 230 (November): 330–43. https://doi.org/10.1016/j.apenergy.2018.08.085.

Campion, Lily, Mahbuba Bekchanova, Roxane Malina, and Tommy Kuppens. 2023. “The Costs and Benefits of Biochar Production and Use: A Systematic Review.” Journal of Cleaner Production 408: 137138. https://doi.org/10.1016/j.jclepro.2023.137138.

Clare, Abbie, Simon Shackley, Stephen Joseph, James Hammond, Genxing Pan, and Adam Bloom. 2015. “Competing Uses for China's Straw: The Economic and Carbon Abatement Potential of Biochar.” GCB Bioenergy 7 (6): 1272–1282. https://doi.org/10.1111/gcbb.12220.

Couillard, Jean, Serge Garon, and Jovica Riznic. 2009. “The Logical Framework Approach-Millennium.” Project Management Journal 40 (4): 31–44. https://doi.org/10.1002/pmj.20117.

Crombie, Kyle, Ondřej Mašek, Andrew Cross, and Saran Sohi. 2015. “Biochar: Synergies and Trade-Offs Between Soil-Enhancing Properties and Carbon Sequestration Potential.” GCB Bioenergy 7 (5): 1161–1175. https://doi.org/10.1111/gcbb.12213.

Delaney, Matt, and Janet Hawkes. 2005. Carbon Markets Investment Criteria for Biochar Projects. West Coast Regional Carbon Sequestration Partnership (WestCARB). https://biochar-international.org/wp-content/uploads/2018/04/WestCARB-Biochar-Report-Final.pdf.

Delgado-García, Juan B., Esther de Quevedo-Puente, and Virginia Blanco-Mazagatos. 2018. “The Impact of City Reputation on City Performance.” Regional Studies 52 (8): 1098–1110. https://doi.org/10.1080/00343404.2017.1364358.

Domingues, Rimena R., Paulo F. Trugilho, Carlos A. Silva, Isabel Cristina N.A. De Melo, Leónidas C.A. Melo, Zuy M. Magriotis, and Miguel A. Sánchez-Monedero. 2017. "Properties of Biochar Derived from Wood and High-Nutrient Biomasses with the Aim of Agronomic and Environmental Benefits." PLoS ONE 12 (5). https://doi.org/10.1371/journal.pone.0176884.

El-Naggar, Ali, Sang Soo Lee, Jörg Rinklebe, Muhammad Farooq, Hocheol Song, Ajit K. Sarmah, Andrew R. Zimmerman, Mahtab Ahmad, Sabry M. Shaheen, and Yong Sik Ok. 2019. "Biochar Application to Low Fertility Soils: A Review of Current Status, and Future Prospects." Geoderma 337 (March):536–54. https://doi.org/10.1016/j.geoderma.2018.09.034.

European Central Bank. 2022. "EU Monetary Policy." European Central Bank. Accessed November 29, 2022. https://www.ecb.europa.eu/ecb/orga/tasks/monpol/html/index.en.html.

Faragò, M., A. Damgaard, I. Logar, and M. Rygaard. 2022. "Life Cycle Assessment and Cost-Benefit Analysis of Technologies in Water Resource Recovery Facilities: The Case of Sludge Pyrolysis." Environmental Science & Technology. https://doi.org/10.1021/acs.est.2c06083.

Fawzy, S., A. I. Osman, N. Mehta, D. Moran, H. Ala'a, and D. W. Rooney. 2022. "Atmospheric Carbon Removal via Industrial Biochar Systems: A Techno-Economic-Environmental Study." Journal of Cleaner Production 371: 133660. https://doi.org/10.1016/j.jclepro.2022.133660.

Fawzy, Samer, Ahmed I. Osman, John Doran, and David W. Rooney. 2020. "Strategies for Mitigation of Climate Change: A Review." Environmental Chemistry Letters. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s10311-020-01059-w.

Field, John L., Catherine M. Keske, Gregory L. Birch, Michael W. DeFoort, and M. Francesca Cotrufo. 2013. "Distributed Biochar and Bioenergy Coproduction: A Regionally Specific Case Study of Environmental Benefits and Economic Impacts." GCB Bioenergy 5 (2): 177–191. https://doi.org/10.1111/j.1757-1707.2012.01187.x.

Filiberto, David M., and John L. Gaunt. 2013. "Practicality of Biochar Additions to Enhance Soil and Crop Productivity." Agriculture 3 (4): 715–725. https://doi.org/10.3390/agriculture3040715.

Garcia, Bruno, Octávio Alves, Bruna Rijo, Gonçalo Lourinho, and Catarina Nobre. 2022. "Biochar: Production, Applications, and Market Prospects in Portugal." Environments 9 (8): 95. https://doi.org/10.3390/environments9080095.

Gray, Myles, Lauren Boritzke Smith, and Wendy Lu Maxwell-Barton. 2024. Global Biochar Market Report 2023. Accessed December 16, 2024. https://145249425.hs-sites-eu1.com/2023-global-biochar-market-report.

Granatstein, David, Chad Kruger, Harold Collins, Manuel Garcia-Perez, and Jonathan Yoder. 2009. “Use of Biochar from the Pyrolysis of Waste Organic Material as a Soil Amendment.”

Grand View Research. 2023. “Biochar Market Size, Share & Trends Analysis Report by Technology, by Application, by Region, and Segment Forecasts, 2023–2030.” Grand View Research. Accessed December 16, 2024. https://www.grandviewresearch.com/industry-analysis/biochar-market.

Horbach, Jens. 2008. “Determinants of Environmental Innovation—New Evidence from German Panel Data Sources.” Research Policy 37 (1): 163–173. https://doi.org/10.1016/j.respol.2007.08.006.

Hossain, M. K., V. Strezov, K. Chan, A. Ziółkowski, and P. Nelson. 2011. “Influence of Pyrolysis Temperature on Production and Nutrient Properties of Wastewater Sludge Biochar.” *Journal of Environmental Management* 92 (1): 223–28. https://doi.org/10.1016/j.jenvman.2010.09.008.

Ibarrola, Rodrigo, Simon Shackley, and James Hammond. 2012. “Pyrolysis Biochar Systems for Recovering Biodegradable Materials: A Life Cycle Carbon Assessment.” Waste Management 32 (5): 859–868. https://doi.org/10.1016/j.wasman.2012.01.021.

International Biochar Initiative. 2024. “International Biochar Initiative.” Https://Biochar-International.Org/about-Biochar/How-to-Make-Biochar/Biochar-Feedstocks/. February 29, 2024.

International Biochar Initiative. 2015. State of the Biochar Industry 2015. Accessed September 20, 2024. https://biochar-international.org/state-of-the-biochar-industry-2015/.

IPCC. 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, E. Huntley, and J. Malley. Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/9781009157926.

Jellali, S., B. Khiari, M. Usman, H. Hamdi, Y. Charabi, and M. Jeguirim. 2021. “Sludge-Derived Biochars: A Review on the Influence of Synthesis Conditions on Pollutants Removal Efficiency.” Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2021.111068.

Kabir, Ehsanul, Ki Hyun Kim, and Eilhann E. Kwon. 2023. “Biochar as a Tool for the Improvement of Soil and Environment.” Frontiers in Environmental Science. Frontiers Media SA. https://doi.org/10.3389/fenvs.2023.1324533.

Kamarudin, Nur Salsabila, Farrah Aini Dahalan, Masitah Hasan, Ong Soon An, Nor Azizah Parmin, Naimah Ibrahim, Myzairah Hamdzah, Nor Azimah Mohd Zain, Khalida Muda, and Edza Aria Wikurendra. 2022. “Biochar: A Review of Its History, Characteristics, Factors That Influence Its Yield, Methods of Production, Application in Wastewater Treatment and Recent Development.” Biointerface Research in Applied Chemistry 12 (6): 7914–7926. https://doi.org/10.33263/BRIAC126.79147926.

Kapoor, K. K., Y. K. Dwivedi, and M. D. Williams. 2014. “Rogers’ Innovation Adoption Attributes: A Systematic Review and Synthesis of Existing Research.” Information Systems Management 31 (1): 74–91. https://doi.org/10.1080/10580530.2014.854103.

Kung, Chih-Chun, Fanbin Kong, and Yongrok Choi. 2015. “Pyrolysis and Biochar Potential Using Crop Residues and Agricultural Wastes in China.” Ecological Indicators 51: 139–145. https://doi.org/10.1016/j.ecolind.2014.06.043.

Kung, Chih-Chun, Bruce A. McCarl, and Xiaoyong Cao. 2013. “Economics of Pyrolysis-Based Energy Production and Biochar Utilization: A Case Study in Taiwan.” Energy Policy 60: 317–323. https://doi.org/10.1016/j.enpol.2013.05.034.

Köves, Mátyás, Viktor Madár, Marianna Ringer, and Tamás Kocsis. 2024. “Overview of Traditional and Contemporary Industrial Production Technologies for Biochar along with Quality Standardization Methods.” Land 13 (9): 1388. https://doi.org/10.3390/land13091388.

Latawiec, Agnieszka E., Jan B. Królczyk, Mariusz Kuboń, Katarzyna Szwedziak, Anna Drosik, Emilia Polańczyk, and Bernardo B. Strassburg. 2017. “Willingness to Adopt Biochar in Agriculture: The Producer’s Perspective.” Sustainability 9 (4): 655. https://doi.org/10.3390/su9040655.

Lefebvre, David, Adam Williams, Jeroen Meersmans, Guy J. Kirk, Saran Sohi, Pierpaolo Goglio, and Pete Smith. 2020. “Modelling the Potential for Soil Carbon Sequestration Using Biochar from Sugarcane Residues in Brazil.” Scientific Reports 10 (1): 19479. https://doi.org/10.1038/s41598-020-76474-4.

Lefebvre, David, Samer Fawzy, Camila A. Aquije, Ahmed I. Osman, Kathleen T. Draper, and Thomas A. Trabold. 2023. “Biomass Residue to Carbon Dioxide Removal: Quantifying the Global Impact of Biochar.” Biochar 5 (1). https://doi.org/10.1007/s42773-023-00258-2.

Lehmann, Johannes, Annette Cowie, Caroline A. Masiello, et al. 2021. “Biochar in Climate Change Mitigation.” Nature Geoscience 14 (11): 883–892. https://doi.org/10.1038/s41561-021-00852-8.

Lehmann, Johannes, and Stephen Joseph, eds. 2015. Biochar for Environmental Management: Science, Technology and Implementation. 2nd ed. Abingdon, UK: Routledge.

Li, Yongfu, Shuaidong Hu, Junhui Chen, Karin Müller, Yongchun Li, Weijun Fu, Ziwen Lin, and Hailong Wang. 2018. “Effects of Biochar Application in Forest Ecosystems on Soil Properties and Greenhouse Gas Emissions: A Review.” Journal of Soils and Sediments. Springer Verlag. https://doi.org/10.1007/s11368-017-1906-y.

Mašek, Ondřej, Robert C. Brown, and Shweta Bakshi. 2024. “Biochar Production Technology.” In Biochar for Environmental Management, 85–110. 3rd ed. Abingdon, UK: Routledge.

Mohammed, Ssemwanga, Nakiguli Fatumah, Kigozi Abasi, Max Olupot, Morris Egesa, Theresa Rubhara, Aleksandra Augustyniak, et al. 2024. “Co-Designing Sustainable Biochar Business Models with Sub-Saharan African Communities for Inclusive Socio-Economic Transformation.” Scientific Reports 14 (1). https://doi.org/10.1038/s41598-024-66120-y.

Möllersten, Karl, and Rizwan Naqvi. 2022. Technology Readiness Assessment, Costs, and Limitations of Five Shortlisted NETs.

Nolan, Connor, Cecilia A. Van Paasschen, and Christopher B. Field. 2024. “Additionality, Baselines, and the Proper Accounting for Land-Based Climate Change Mitigation Efforts.” Oxford Open Climate Change 4 (1). https://doi.org/10.1093/oxfclm/kgae012.

Pandit, Naba Raj, Jan Mulder, Sarah E. Hale, Vegard Martinsen, Hans-Peter Schmidt, and Gerard Cornelissen. 2018. “Biochar Improves Maize Growth by Alleviation of Nutrient Stress in a Moderately Acidic Low-Input Nepalese Soil.” Science of the Total Environment 625: 1380–1389. https://doi.org/10.1016/j.scitotenv.2018.01.022.

Perrone, Monica, Chiara Mazzocchi, Giorgia Conti, Alberto Taverna, and Edoardo Vigano. 2023. “Exploring Biochar Technology Adoption in a Circular Economy Perspective: A Technology Acceptance Model Approach.” Journal of Circular Economy Research 4 (2): 45–60.

Pierson, Derek, Nathan Anderson, Jason Brewen, Noah Clark, Michael C. Hardy, David McCollum, and James Tirocke. 2024. “Beyond the Basics: A Perspective on Barriers and Opportunities for Scaling up Biochar Production from Forest Slash.” Biochar 6 (1): 1. https://doi.org/10.1007/s42773-023-00290-2.

Pourhashem, Ghasideh, Shih Yu Hung, Kenneth B. Medlock, and Caroline A. Masiello. 2019. “Policy Support for Biochar: Review and Recommendations.” GCB Bioenergy 11 (2): 364–80. https://doi.org/10.1111/gcbb.12582.

Powis, Carter M., Stephen M. Smith, Jan C. Minx, and Thomas Gasser. 2023. “Quantifying Global Carbon Dioxide Removal Deployment.” Environmental Research Letters 18 (2). https://doi.org/10.1088/1748-9326/acb450.

Price, Catherine, John Morris, and Carol Morris. 2024. “Biochar Carbon Markets: A Mitigation Deterrence Threat.” Environmental Science and Policy 154 (April). https://doi.org/10.1016/j.envsci.2024.103704.

Quispe, J. I., L. C. Bautista, O. Mašek, and A. Bogush. 2022. “Use of Biochar-Based Column Filtration Systems for Greywater Treatment: A Systematic Literature Review.” Journal of Water Process Engineering 49: 102908. https://doi.org/10.1016/j.jwpe.2022.102908.

Raj, A., Ashutosh Yadav, S. Arya, Ranjna Sirohi, Sunil Kumar, Abhay Rawat, R. Thakur, D. Patel, L. Bahadur, and Ashok Pandey. 2021. “Preparation, Characterization and Agri Applications of Biochar Produced by Pyrolysis of Sewage Sludge at Different Temperatures.” The Science of the Total Environment 795: 148722. https://doi.org/10.1016/j.scitotenv.2021.148722.

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A., & Tavoni, M. (2019). “An Inter-Model Assessment of the Role of Direct Air Capture in Deep Mitigation Pathways.” *Nature Communications* 10: 327. https://doi.org/10.1038/s41467-019-10842-5

Roberts, Kelli G., Brent A. Gloy, Stephen Joseph, Norman R. Scott, and Johannes Lehmann. 2010. “Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential.” Environmental Science & Technology 44 (2): 827–833. https://doi.org/10.1021/es902266r.

Salma, Alaa, Lydia Fryda, and Hayet Djelal. 2024. “Biochar: A Key Player in Carbon Credits and Climate Mitigation.” Resources 13 (2): 31. https://doi.org/10.3390/resources13020031.

Salo, Esko, Kathrin Weber, Marleena Hagner, and Annukka Näyhä. 2024. “Nordic Perspectives on the Emerging Biochar Business.” Journal of Cleaner Production 475 (October): 143660. https://doi.org/10.1016/j.jclepro.2024.143660.

Sessions, John, David Smith, Kristin M. Trippe, Jeremy S. Fried, John D. Bailey, Joshua H. Petitmermet, William Hollamon, Claire L. Phillips, and John D. Campbell. 2019. “Can Biochar Link Forest Restoration with Commercial Agriculture?” Biomass and Bioenergy 123: 175–185. https://doi.org/10.1016/j.biombioe.2019.01.024.

Schmidt, Hans Peter, Nikolas Hagemann, Kathleen Draper, and Claudia Kammann. 2019. “The Use of Biochar in Animal Feeding.” PeerJ 7. https://doi.org/10.7717/peerj.7373.

Schmidt, Hans-Peter, Claudia Kammann, and Nikolas Hagemann. 2020. “EBC-Guidelines for the Certification of Biochar-Based Carbon Sinks, Version 2.1 from 1st February 2021.” European Biochar Foundation. https://www.european-biochar.org.

Shrestha, Ram K., Pierre A. Jacinthe, Rattan Lal, Klaus Lorenz, Madan P. Singh, Sergey M. Demyan, and Lindsey E. Lindsey. 2023. “Biochar as a Negative Emission Technology: A Synthesis of Field Research on Greenhouse Gas Emissions.” Journal of Environmental Quality 52 (4): 769–798. https://doi.org/10.1002/jeq2.20411.

Shackley, Simon, Abbie Clare, Stephen Joseph, Bruce A. McCarl, and Hans-Peter Schmidt. 2015. “Economic Evaluation of Biochar Systems: Current Evidence and Challenges.” Lambiotte. Accessed September 4, 2024. https://www.lambiotte.com.

Shackley, Simon, James Hammond, John Gaunt, and Rodrigo Ibarrola. 2011. “The Feasibility and Costs of Biochar Deployment in the UK.” Carbon Management 2 (3): 335–356.

Smith, Pete. 2016. “Soil Carbon Sequestration and Biochar as Negative Emission Technologies.” Global Change Biology 22 (3): 1315–24. https://doi.org/10.1111/gcb.13178.

Spokas, K. A., K. B. Cantrell, J. M. Novak, D. W. Archer, J. A. Ippolito, H. P. Collins, and K. A. Nichols. 2012. “Biochar: A Synthesis of Its Agronomic Impact Beyond Carbon Sequestration.” Journal of Environmental Quality 41 (4): 973–989. https://doi.org/10.2134/jeq2011.0069.

Srinivasan, P., A. Sarmah, R. Smernik, Oisik Das, M. Farid, and Wei Gao. 2015. “A Feasibility Study of Agricultural and Sewage Biomass as Biochar, Bioenergy and Biocomposite Feedstock.” *The Science of the Total Environment* 512-513: 495–505. https://doi.org/10.1016/j.scitotenv.2015.01.068.

Thengane, Sonal K., Kevin Kung, Josiah Hunt, Haris R. Gilani, C. Jim Lim, Shahabaddine Sokhansanj, and Daniel L. Sanchez. 2021. “Market Prospects for Biochar Production and Application in California.” Biofuels, Bioproducts and Biorefining 15 (6): 1802–19. https://doi.org/10.1002/bbb.2280.

Thies, Janice E., and Matthias C. Rillig. 2009. “Characteristics of Biochar: Biological Properties.” In Biochar for Environmental Management, edited by Johannes Lehmann and Stephen Joseph, 1st ed., 117–138. https://doi.org/10.4324/9781849770552-13.

Thomas, Sean C. 2021. “Post-Processing of Biochars to Enhance Plant Growth Responses: A Review and Meta-Analysis.” Biochar 3 (4): 345–361. https://doi.org/10.1007/s42773-021-00115-0.

Trading Economics. 2024. “Portugal 10-Year Government Bond Yield.” Accessed December 1, 2024. https://tradingeconomics.com/portugal/government-bond-yield.

Woolf, Dominic, James E. Amonette, F. Alayne Street-Perrott, Johannes Lehmann, and Stephen Joseph. 2010. “Sustainable Biochar to Mitigate Global Climate Change.” Nature Communications 1 (5). https://doi.org/10.1038/ncomms1053.

Xia, Longlong, Wenhao Chen, Bufan Lu, Shanshan Wang, Lishan Xiao, Beibei Liu, Hongqiang Yang, et al. 2023. “Climate Mitigation Potential of Sustainable Biochar Production in China.” Renewable and Sustainable Energy Reviews 175 (April). https://doi.org/10.1016/j.rser.2023.113145.

Yaashikaa, P. R., P. Senthil Kumar, Sunita Varjani, and A. Saravanan. 2020. “A Critical Review on the Biochar Production Techniques, Characterization, Stability and Applications for Circular Bioeconomy.” Biotechnology Reports 28. https://doi.org/10.1016/j.btre.2020.e00570.

Zhang, Yuying, Mingjing He, Lei Wang, Jianhua Yan, Bin Ma, Xiaohong Zhu, Yong Sik Ok, Viktor Mechtcherine, and Daniel C. W. Tsang. 2022. “Biochar as Construction Materials for Achieving Carbon Neutrality.” Biochar 4 (1): 20. https://doi.org/10.1007/s42773-022-00182-x.

Zilberman, David, David Laird, Christopher Rainey, Jung Song, and Gus Kahn. 2023. “Biochar Supply-Chain and Challenges to Commercialization.” *GCB Bioenergy* 15 (1): 7–23. https://doi.org/10.1111/gcbb.13002.

9 Appendix

9.1 Appendix A. Interview protocol and questions

1. **Introduction:**
   - Participants are introduced to the research and its purpose.
   - Background information about the interviewee is requested.
2. **Biochar System Details:**
   - Inquiry about their current involvement in biochar-related projects.
   - Questions about specific challenges and solutions in biochar systems.
3. **Carbon Credits and Market Insights:**
   - Their approach to generating, selling, or managing carbon credits.
   - Market trends, opportunities, and challenges in the carbon credit ecosystem.
4. **Operational and Technical Aspects:**
   - Details on feedstock types, plant setups, and scaling operations.
   - Discussion on financial sustainability and regional viability.
5. **Future Vision and Challenges:**
   - Their perspective on the future of biochar systems.
   - Regulatory or market barriers faced.

9.2 Appendix B. Example transcript

Note: The remaining interview transcripts are not included in this document but can be provided upon request from the group members.

Interview 1:

Interview on Biochar and Carbon Credits

Date: October 24, 2024, 7:05 AM

Dedde Gombert (0:21):

Okay, great. Thank you for your time today. So, we're currently working on a project that we started during our Master's in Innovation and Entrepreneurship. We set up a start-up focusing on projects here in Lisbon. Right now, I'm working on my thesis about how to make biochar systems financially viable, because that seems to be a challenge in the industry. At the same time, we're working on a use case for the local municipality here, exploring how to implement biochar systems. We're looking at what's needed to get such a system in place. It's still a very early-stage project. Maybe you could give an introduction to your work and how it´s related to biochar?

Interviewee 1 (2:26):

Yes, of course. We originally started as consultants under the ---. Since then, we've rebranded as ---. In the beginning, we provided consultancy services to companies in the Netherlands and Switzerland that wanted to set up pyrolysis installations to produce high-quality biochar and generate carbon credits. Over time, we realized that we could have a bigger impact by developing projects ourselves.

During that time, we learned that there is huge pressure on biomass in the northern parts of the world—every gram is utilized. We then decided to focus on a more decentralized solution for producing biochar. Now, we work with farmers in small villages, especially in India and Ghana. We train them on how to convert agricultural waste into biochar. We provide them with the necessary technology and partially finance the projects ourselves. About 60% of the carbon credit revenue goes back to the farmers, and they are allowed to keep the biochar for use as a soil enhancer.

We now have two projects in India, a third one is about to be certified, and a fourth is underway. Additionally, we have a large project in Ghana where we're expanding with at least two more projects this year. We're also exploring other opportunities, like in South Africa and South America, but those are still in the early stages.

Dedde Gombert (4:47):

That all sounds fantastic! I saw that you’re even in the top 10 on CDR.fyi. That’s really impressive.

Interviewee 1 (5:03):

Yes, we’re now in the top rankings, which is really great.

Dedde Gombert (5:08):

Indeed. That’s quite an achievement. A while ago, I was working on a data analysis and saw that you scored highly there. That’s why I really wanted to talk to you.

Interviewee 1 (5:20):

Nice to hear. Yes, we’re noticing that the biochar and carbon credit markets are developing rapidly, and more and more companies are becoming financially stable in this space.

Dedde Gombert (5:49):

How would you describe an optimal ecosystem for biochar production? Are environmental factors the most important, or are there other key considerations?

Interviewee 1 (6:10):

It depends on the scale at which you're operating. We produce biochar in a decentralized way, working with many small farmers, using relatively simple technologies. This allows us to scale up quickly without needing large investments. However, in some cases, the energy produced during pyrolysis goes to waste, as in a village in Ghana there’s no energy demand like there is in a European city. With centralized installations, you typically focus on three value streams: electricity, biochar, and carbon credits.

Dedde Gombert (6:56):

I see. So, your approach is very different from that of centralized biochar producers.

Interviewee 1 (7:38):

Exactly. In the Netherlands, we also tried setting up a centralized installation, but biomass is too expensive here. Dutch farmers are still hesitant to use biochar because they’re used to synthetic fertilizers. As someone once said, “Fertilizer is the heroin of the soil.” It’s harmful, but we’ve been using it since the 19th century. In other parts of the world, like California, biochar is more successfully applied because there’s an abundance of biomass from thinning forests to prevent wildfires.

Dedde Gombert (10:35):

Interesting! So, finding a location with an excess of biomass and an energy need is crucial for a successful biochar project?

Interviewee 1 (10:52):

Yes, exactly. Biomass is too expensive in the Netherlands to make biochar financially viable, but in other regions, it works very well.

Dedde Gombert (16:08):

I had another question about carbon credits. I've heard that some companies sell credits before they are actually realized. Do you do that as well?

Interviewee 1 (16:20):

No, we don't. We generate the credits first and sell them afterward. That's quite unique in this sector, as many companies do sell credits upfront.

Dedde Gombert (16:52):

That makes more sense. Do you think that selling credits before they're realized could cause problems in the market?

Interviewee 1 (17:02)

It could definitely become an issue, especially if projects fail to deliver what they promise. Fortunately, the percentage of undelivered credits is still relatively low, but it could become a problem in the future.

Dedde Gombert (18:02):

It was also mentioned that if big players like Microsoft were to drop out, the entire carbon credit market could collapse. What's your take on that?

Interviewee 1 (18:27)

Microsoft is indeed a major player, but if they were to drop out, it wouldn't mean the whole market collapses. Microsoft has bought many credits from companies that won't deliver until 2028. If they were to stop, it would definitely impact the market, but it wouldn't completely fall apart.

Dedde Gombert (19:14):

And how about the price of biochar? Is it stable?

Interviewee 1 (19:38):

The price of biochar varies greatly, depending on the availability of biomass and other factors. We sell biochar for about 100 euros per ton, but some companies charge much more, sometimes as high as 300 euros per ton, depending on the quality and location.

Dedde Gombert (20:08):

Interesting. So, the price is quite volatile depending on different factors?

Interviewee 1 (20:16):

Yes, the price fluctuates a lot. It depends on where you are and what someone is willing to pay. In the Netherlands, for example, we could sell it for 400 euros per ton, but that wouldn’t be profitable if we had to import the biochar from Ghana or India.

Dedde Gombert (24:50):

How do you find new farmers for your projects? Is it through word of mouth, or do you have people on the ground?

Interviewee 1 (25:21):

We mostly work with local partners who help us find new farmers. We regularly receive inquiries via our website, but we currently don’t have the capacity to take on all those requests. We have to be selective because we can’t sell enough credits to meet the demand.

Dedde Gombert (26:17):

Understandable. It sounds like a challenging but valuable approach. And when you develop new installations, how is that financed?

Interviewee 1 (26:34):

We finance them ourselves. The farmers often can’t invest upfront, so we make sure the installations are in place. Each village gets an installation, and they are shared within the community.

Dedde Gombert (27:35):

That sounds like a large investment. But it seems to work well in these communities.

Interviewee 1 (27:47):

Yes, it’s a big investment, but we’re seeing it have an impact. We’re working with around 8,000 villages at the moment, and eventually, all of them will have an installation. That’s our goal.

Dedde Gombert (28:20):

That’s impressive! Thanks for sharing these insights into your work and for your time today. It was really interesting to hear how your projects are progressing.

Interviewee 1 (28:44):

You’re welcome! I’m glad I could help. Best of luck with your project, and feel free to reach out if you have any more questions.

Dedde Gombert (29:05):

Group Part

Thank you so much. Have a great day and enjoy the rest of your week.

Interviewee 1 (29:48):

Thanks! You too. Take care.

9.3 Appendix C. Full Table of Initial Codes of Thematic Analysis

Initial code	N of participants contributing	N of transcript excerpts assigned	Sample quote (interview)
Feedstock Variability Impact	4	5	"the quality of biochar that comes out of wooden biomass, this is by far better than any other feedstock " (4)
Optimal Feedstock Pairing with Technology	5	7	"all those processes are highly dependent upon what feedstock you're using. You can't switch feedstocks." (14)
High-Moisture Feedstock Limitations	2	3	"any biomass that's relatively dry, less than 20 or 30% moisture, that is particles less than 10 millimeters, something like that, maybe less than 20 millimeters will be fine." (7)
Seasonal Availability of Agricultural Waste	3	4	"agricultural waste from the seasonal time, it will add to your supply chain, but you also need another type of biomass that you will be able to keep all year round." (17)
Local Biomass Sourcing	9	12	"you have to have a lot of feed stock readily available and not too far away, because you don't

			want to be transporting it by truck 100 kilometers away” (14)
Biomass Competition and Scarcity	3	4	"So you have competition. For the same feedstocks." (14)
Diversifying Revenue Streams	8	15	"every investor in the biochar common rule projects looks at the diversification of the revenue streams " (3)
Premium Pricing for High-Quality Biochar	4	7	"We were the first ones that actually were able to put out high quality, industrial grade, … we knew what the client wanted, and then we bought the kind of feedstock would then result in what the client wanted, and then he was so happy that he paid more." (8)
Biochar Matching Customer Needs	4	5	"so it's a different style of product (biochar in steel vs. agriculture application). You can manufacture it (biochar) to those requirements.” (14)
Local Ecosystem Integration	7	9	"you have to adapt the biochar Production According to the local conditions " (9)
Stakeholder Collaboration	3	4	" there's a lot of different processes, so finding good partners is key, and really helps to increase the chances of a successful project." (5)

Group Part

Local Application of Biochar	4	4	“always looking at it from a perspective of, what can I actually sell locally” (3)
Local Carbon Credits	2	2	“a lot of companies see it as a positive, that it's local, ... we have clients interested in only buying from the Nordic countries” (9)
Contractual Agreements	3	8	“Have continued access (to feedstock) for the life of the project, so it's all well and good having a contract for feedstock” (2)
Storytelling	4	7	"You have to have a compelling story to be able to sell it (CDR) and get a premium.” (8)
Decentralized Biochar Systems	5	12	"For every one centralized biochar project, there should be 100 decentralized projects " (1)

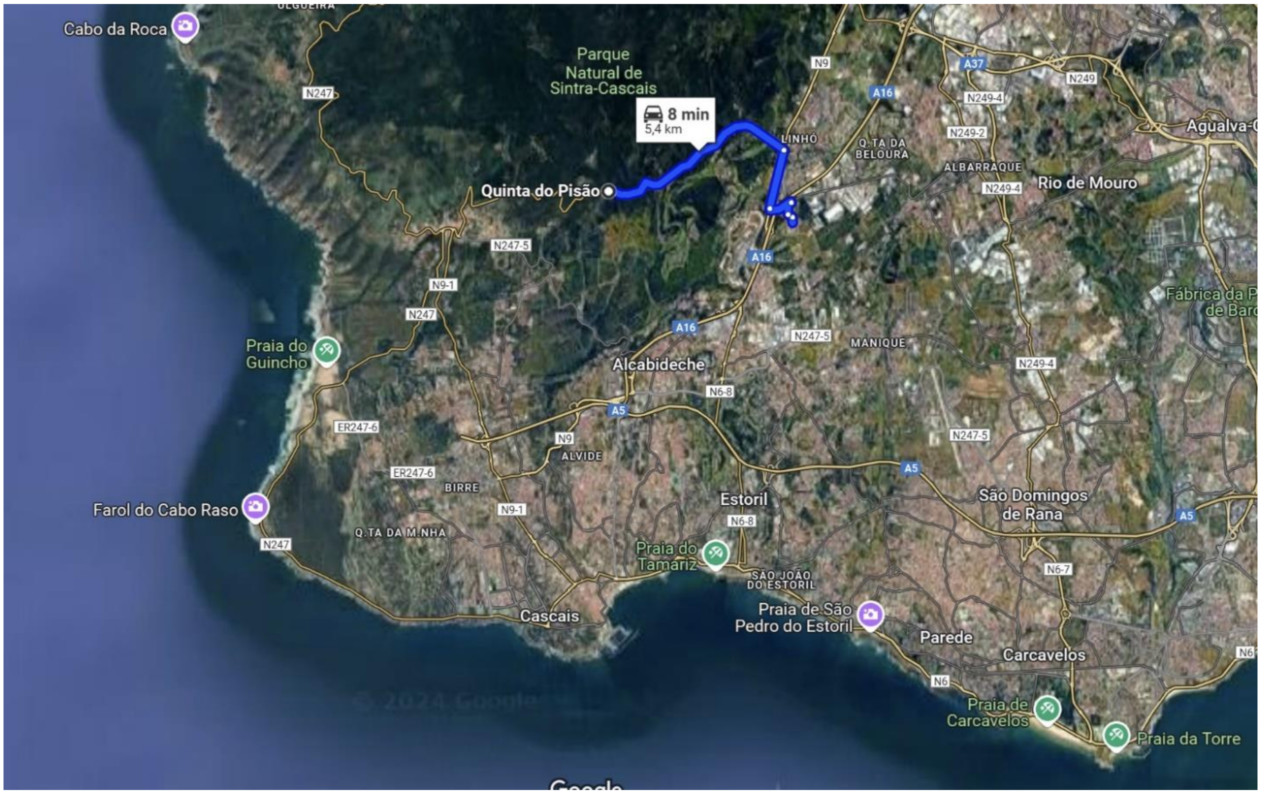
Note: This table displays the initial codes identified during the first stage of thematic analysis. For each code, it shows the number of participants who contributed relevant data, the total number of transcript excerpts assigned to that code, and an illustrative sample quote. This summary provides an overview of key themes that emerged in the interviews, indicating the frequency and distribution of each topic across the participants and providing a representative example of the perspectives shared.

9.4 Appendix D. Cascais stakeholders

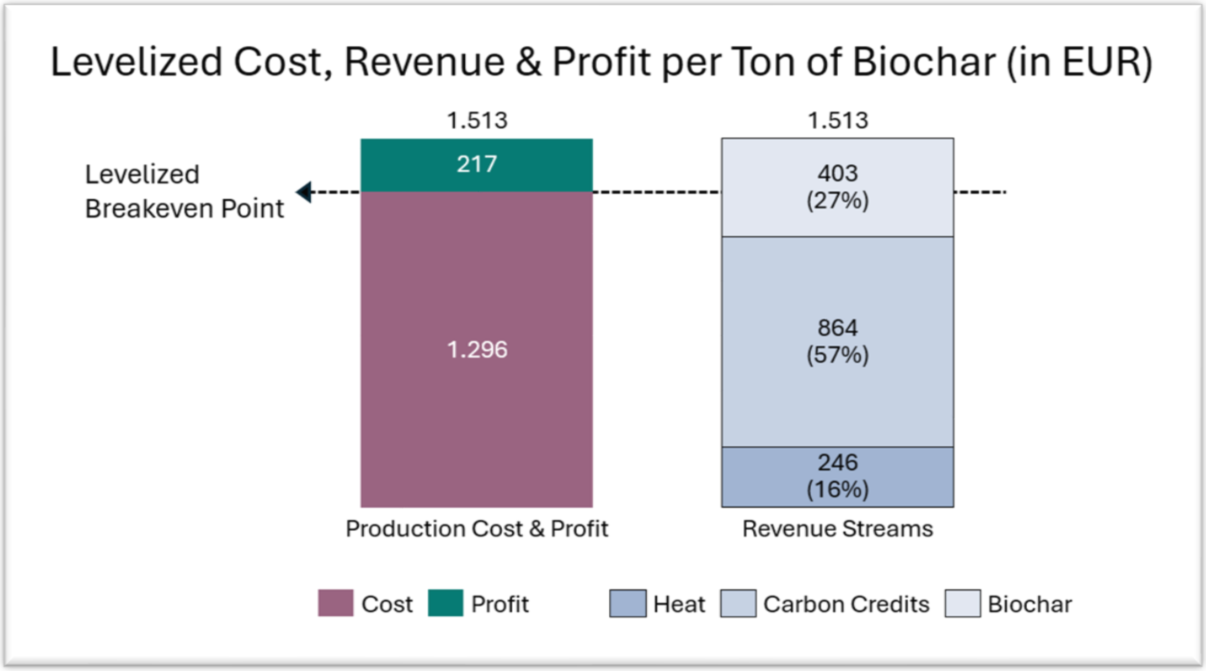
	Role	Company
Vera Melo	Head of the Future and Decision Support division	EMAC - Empresa Municipal de Ambiente de Cascais
Andre Miguel	Head of Cascais Lands Division	EMAC - Empresa Municipal de Ambiente de Cascais
Carla Macedo	Adviser to the Executive Board	EMAC - Empresa Municipal de Ambiente de Cascais
Joao Melo	Ecological Infrastructure Management Director	EMAC - Empresa Municipal de Ambiente de Cascais
Rui Jorge Cordeiro	Head of Marketing and Communication	Cascais Próxima
Estefânia Silva	General Coordinator	Associação Empresarial do Concelho de Cascais
Rui Peixoto	Head of Department of Green Spaces	EMAC - Empresa Municipal de Ambiente de Cascais
Cristiana Santos	Director at Strategic Planning Department	Tratolixo - Tratamento de Resíduos Sólidos
Diogo Coelho	Coordinator at Quinta do Pisão	EMAC - Empresa Municipal de Ambiente de Cascais

9.5 Appendix E. Biochar machine

9.6 Appendix F. Transportation Route



9.7 Appendix G. Breakdown of levelized cost of biochar per ton



9.8 Appendix H. Cashflow projections