UNIVERSITY
OF TWENTE.

Faculty of Behavioral, Management and Social Sciences

Q1 2022/23

M.Sc. Thesis – Business Administration

A platform-based design perspective on pyrolysis technology selection considering green energy, biochar production and carbon removal

Word count:	45,253
Submitted by:	Jan F. Knizia
First supervisor:	Dr. Erwin Hofman
Second supervisor:	Dr. LL.M. Leo van der Wegen
Date:	04.07.2023

Abstract: As biochar carbon removal market is gaining significance as substantial contributor to mitigating climate change it becomes increasingly important to select a technology configuration for biochar production. By taking a platform-based design approach for non-assembled products, this study aims to identify the most profitable and capable integrated manufacturing system for biochar production, green energy conversion, and CO_2 sequestration certificates. First, production platforms for biochar for soil amendment and green energy are established. Subsequently the respective product-, process- and raw-material platforms are developed. The report follows by establishing a comprehensive set of 26 criteria for evaluation of technology alternatives extracted from literature. An Analytic Hierarchy Process (AHP) analysis was performed, including extracting preferences from seven company stakeholders of a German biochar manufacturing company to determine criteria weights. Further, four technology alternatives available on the market were evaluated through the AHP model. The robustness of the model was then tested by performing a sensitivity analysis including potential scenarios for financial moderator variables. Results of the study show that stakeholders assign highest weight to the production platform for biochar for soil amendment. Results further indicate that despite having the highest initial investment, a two-step pyrolysis gasification system provides superior biochar cost, heat and electricity output, and carbon sequestration performance. The study's theoretical contribution is threefold: (1) It applies platform-based design theory for non-assembled products to biochar systems, (2) develops a production platform for biochar and (3) establishes a set of evaluating criteria for integrated pyrolysis manufacturing systems. The platform-based design perspective has valuable implications for managerial understanding of manufacturing capabilities, strategic planning, and further product and process development in biochar systems.

Keywords: biochar, platform-based design, non-assembled products, analytical hierarchy process, AHP, biochar carbon removal (BCR), pyrolysis, technology selection

Statement of authorship

I hereby declare that I am the sole author of this master thesis and that I have not used any sources other than those listed in the bibliography and identified as references. I further declare that I have not submitted this thesis to any other institution in order to obtain a degree.

Hamburg, 04.07.2023

Jan

Table of contents

Table of figures

List of tables

List of abbreviations

Abbreviation	**Definition**
AHP	Analytical hierarchy process
AIJ	Aggregation of individual judgements
AIP	Aggregation of individual priorities
APR	Ablative plate reactor
ASR	Auger and screw reactor
B2B	Business to business
BCR	Biochar carbon removal
BFB	Bubbling fluidized bed reactor
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CEC	Cation exchange capacity
CHP	Combined heat and power
CI	Consistency index
CORC	Carbon dioxide removal certificate
CR	Carbon removal
CVR	Cyclone vortex reactor
DACH	Germany, Austria, Switzerland
DCF	Discounted cash flow
DEA	Data envelopment analysis
DM	Dry matter
DS	Dry substance
EBC	European Biochar Certificate
EBI	European Biochar Industry Consortium
EP	Engineering and Procurement
ESCO	Energy service company
EU	European Union
FA	Financial analysis
FBR	Fluidized bed reactor
FSC	Forest Stewardship Council
HTT	Highest treatment temperature
IBI	International Biochar Initiative
IRR	Internal rate of return
LCA	Life cycle analysis
LHV	Lower heating value
MADM	Multi attribute decision making
MCDM	Multi criteria decision making
NET	Negative emissions technology
NPV	Net present value
OEE	Overall equipment effectiveness
OPEX	Operating expenditure
ORC	Organic Rankine Cycle
OS	Original substance
PAH	Polycyclic aromatic hydrocarbons
PBD	Platform-based design

PEFC	Program for the Endorsement of Forest Certification Schemes
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
QFD	Quality Function Deployment
RI	Random Index
ROI	Return on investment
RQ	Research question
SQ	Sub-question
SSA	Specific surface area
SUB	Subsystem
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technology Readiness Level
WHC	Water holding capacity

List of units

Unit	**Definition**
°C	Temperature in degree Celsius
min	Time in minutes
mm	Millimeter
g t^{-1} DS	Gram per ton dry substance
€/t	Euros per ton
CO2eq/kWh	Carbon dioxide equivalents per kWh
CO2eq	Carbon dioxide equivalents
w.%	Weight percent
kWh	Kilowatt hours

1 Introduction

In order to achieve the EU's ambitious climate goals by 2050 and limit global warming to the 2.0°C threshold, we know that solely reducing emissions in our everyday lives is not sufficient. Greenhouse gas emissions must be actively removed from the atmosphere. Such "engineered carbon removal" (EBC, 2012-2022) is facilitated by different technologies. One technology that already scales today is biochar (Christie-Miller & Harvey, 2022). The industry about biochar is rapidly gaining momentum with many manufacturing firms and technology suppliers entering the market (European Biochar Industry Consortium [EBI], 2023). It remains to be seen who will be able to position itself best considering the technological manufacturing baseline and market strategy. Company X is among the leading contestants in the race towards net zero. With many biochar manufacturing technologies on the rise and a great diversity of products that can be developed from biochar, selecting a technology and hence streamlining product development processes is a crucial and complex task which company X wants to approach. This chapter provides a short introduction to company X in section 1.1, the current problem in section 1.2 and the research questions and conceptual model in section 1.3.

1.1 Company background

Company X is a young cleantech startup operating in the biochar industry, leveraging biochar carbon removal (BCR) technology, a negative emissions technology (NET) (McGlashan et al., 2012). The company's goal is to reach one megaton of carbon removal by 2030. The company's core value generating manufacturing process is pyrolysis, a thermal biomass conversion process in reduced oxygen environments (Bridgwater, 2019, p. 1221). The main products that are offered to the customer based on the continuous manufacturing process are

- biochar (and derivative products),
- renewable energy products in form of electricity and heat in form of hot water, warm water and steam for industrial and public customers
- carbon dioxide removal (CDR) certificates based on the inherent CO2 sequestration potential of the biochar.

The company is currently scaling and expanding its production capacity throughout Central Europe and in this regard investigating opportunities for diversification of its product portfolio, as well as its manufacturing technology.

1.2 Problem statement

The company wants to pursue a high variety strategy in terms of its product offer to the market. In process industries, a high variety strategy involves producing a wide range of products or variations of products to meet diverse customer needs. The goal is to offer the customers a greater choice and flexibility while maintaining efficient operations and profitability. To implement a high variety strategy, manufacturers need to have efficient and flexible production processes that can accommodate the production of different product variants. A high variety strategy could be used in biochar production platforms to produce a range of biochar products that cater to different applications and markets. Biochar is a type of charcoal that is produced by heating organic material reduced oxygen environments, and it has a variety of potential uses, including soil amendment, carbon sequestration, wastewater treatment, filtration and many others. A high variety strategy for biochar production could include the following:

- Producing biochar from different feedstocks, which can affect its properties such as water retention, surface area, and porosity.

- Offering biochar products with different particle sizes, which can cater to different applications, such as soil improvement or air filtration.
- Providing biochar with different activation levels, i.e., treating biochar with chemicals or heat to increase its surface area and enhance its adsorption properties.
- developing customized biochar blends with other materials such as compost or fertilizer, to create customized products that meet specific customer needs such as organic farming or urban landscaping.

Platform-based design is an approach that can help with a high variety strategy for non-assembled products (R. Andersen, 2022; Lager, 2010, 2016). It involves designing a product family based on a common platform or architecture that can be customized to create different product variants. This approach enables manufacturers to offer a wide range of product variations while minimizing design and production costs. By using a platform-based design approach, manufacturers can reduce the complexity of their production processes, as they can use common components and manufacturing processes across different product variants. This results in greater efficiency, lower costs, and higher quality products (A.-L. Andersen et al., 2022; Lehnerd & Meyer, 2014; Samuelson & Lager, 2019).

Several pyrolysis continuous feed systems and peripheral technology modules are currently available on the market in the form of integrated manufacturing systems (H. Tan et al., 2021). The financial viability of pyrolysis systems is generally more likely when waste biomass is considered as feedstock due to its lower price; a variety of char and energy products in form of heat and electricity are sold to the market; and when the carbon sequestration potential of the biochar products is monetarized through the sale of carbon credits (Campbell et al., 2018, p. 333).

Company X wants to acquire a new integrated manufacturing system for their core manufacturing process. The main criteria for a technology to be eligible for selection are market readiness, regulatory compliance and focus on biochar production and carbon removal. The manufacturing technology should allow for satisfaction of further different parameters imposed on a plant set-up by the company’s product portfolio. An appropriate technological configuration should be able to

- *allow for optimization of biochar properties* regarding a high variety strategy,
- *maximize the energy output* for the generation of hot water, warm water, steam, or electricity,
- *maximize CO2 sequestration potential* of the biochar,
- *minimize investment costs* as well as *operational effort* for the equipment employed.

To find an exclusive technological configuration that is sustainable for all potential feedstocks and applications is a challenging task due to the variety in feedstocks, scalability and type of systems available (Garcia-Nunez et al., 2017, p. 5; Garcia-Peréz et al., 2020). Currently there is no feasible scientific basis established in the company’s processes for evaluating the different available solutions of the technology suppliers on the market considering the different products and use-cases of biochar.

In this regard, the research goal is to evaluate and select the most profitable and capable integrated manufacturing system for valorization of waste biomass into the products explained above.

The underlying assumption of this research is that company X’ business model will further diffuse in the biochar market due to the complexity and opportunities the pyrolysis technology offers for the processing of biomass (Campbell et al., 2018; Garcia-Peréz et al., 2020).

As biochar systems are highly complex involving many interrelated factors, the applicability of platform-based design for non-assembled products offers potential avenues to structure a technology selection process and derive a comprehensive set of criteria for selection of the company’s core manufacturing technology.

1.3 Research questions & conceptual model

Regarding the problem definition as well as the theory presented above, the following main research question (RQ) can be formed:

Which *pyrolysis technology alternative* is the most profitable and capable for the realization of a high variety strategy for *biochar production, green energy* and *carbon removal* taking a *platform-based design perspective for non-assembled products?*

Moreover, it is possible to derive further sub-research questions (SQ) for the work at hand:

SQ 1 Platform-based design for non-assembled products		How can platform-based design for non-assembled products help the company in structuring its approach to the selection of an integrated pyrolysis manufacturing system?
SQ 2 Production platform – Biochar for soil amendment	SQ 2.1	Who are the customers the company currently serves with biochar, what are their main needs and how do these translate to required functionalities of the biochar products for each application?
	SQ 2.2	Which subsystems are relevant for the biochar production process platform?
	SQ 2.3	How do the biochar product functionalities translate to process platform requirements?
	SQ 2.4	How do the biochar product functionalities translate to raw-material platform requirements?
SQ 3 Production platform – Green energy	SQ 3.1	Who are the customers the company currently serves with green heat, what are their main needs and how do these translate to product properties?
	SQ 3.2	Which subsystems are relevant for an energy conversion process platform?
	SQ 3.3	How do the energy product properties translate to process platform requirements?
	SQ 3.4	How do the energy product properties translate to raw material platform requirements?
SQ 4 Selection criteria		Which are the selection criteria imposed by the company's high variety strategy on potential technology alternatives?
SQ 5 Technology selection & alternatives	SQ 5.1	Which is the best selection methodology for the technology selection problem?
	SQ 5.2	Which alternatives are subject to selection and how were they chosen?
	SQ 5.3	How are the different alternatives configured?

	SQ 5.4	What are the benefits of each type of alternative?
SQ 6 Alternative selection	SQ 6.1	Which integrated manufacturing system alternative is the most profitable one satisfying all requirements of all production platforms to the highest extent?
	SQ 6.2	Which integrated manufacturing system is the best one for each production platform?

To answer the main research question and corresponding sub-research questions, the thesis is structured according to the following conceptual model as illustrated Figure 1.

First, this thesis introduces platform-based design theory to the reader. In this regard, it discusses the theory's application in conventional manufacturing industries for assembled, discrete products, and process industries for non-assembled products. The thesis considers the main benefits and disadvantages of the latter, rather young research stream, originating in the early 2000s and closes with an answer to SQ 1 in chapter 2.

Subsequently, the thesis explores the biochar system and embeds it in platform-based design theory. Departing from customer requirements retrieved through an open interview with representatives of the company's sales department to products of biochar systems it applies the concepts of product platform, process platform, and raw material platform to biochar systems and defines product families for biochar as a platform material for application to soil and green energy products. Moreover, it establishes the underlying process platform for both product families and gives a brief overview of the most important subsystems. It considers carbon sequestration certificates, based on the biochar's inherent ability to emulate the natural carbons sequestration process as derivative product of biochar production for soil amendment and closes with an answer to SQ 2 in chapter 3 and SQ 3 in chapter 4.

Due to the close coupling of product quality, raw material and manufacturing process, the thesis assigns special emphasis to the pyrolysis process and the manufacturing technology and the hitherto essential requirements of the production platforms to the manufacturing equipment. It presents a comprehensive set of criteria summarizing the requirements of the different production platforms and relevant for a selection process and closes with an answer to SQ 4 in chapter 5. This chapter further focuses on giving an overview of the different alternatives subject to investigation.

Chapter 5 further outlines different selection methods and evaluates the advantages and disadvantages for the selection problem at hand. Subsequently, the currently available and market ready technology solutions for the pyrolysis manufacturing equipment considering real market data provided by leading technology suppliers become subject to evaluation through the Analytical Hierarchy Process (AHP) method.

Using the selected method, the thesis subjects four technology alternatives to the suggested criteria and ranks them according to their fit to the developed production platforms answering SQ 6 in chapter 6.

Subsequently, the research at hand discusses the best available technological solutions for the biochar- and green energy production platforms as well as business model and suggests an ideal choice for the realization of the product families in chapter 7. It further evaluates the benefits and disadvantages of approaching biochar systems with a platform-based design perspective for non-assembled products.

Finally, the report concludes with a managerial recommendation, a theoretical and practical contribution and discusses limitations of the work suggesting avenues for further research to be conducted for biochar systems and platform-based design theory.

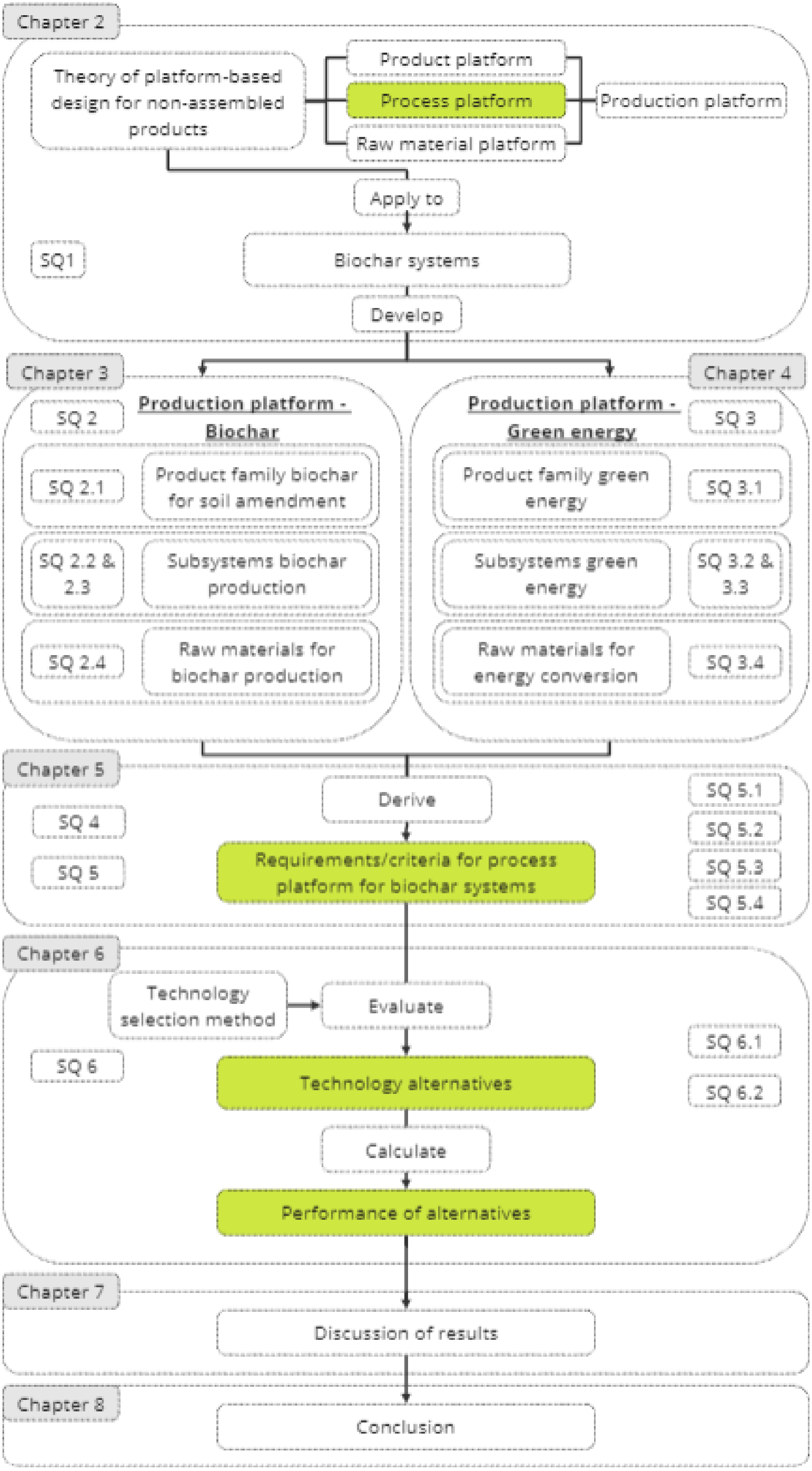


Figure 1 Conceptual model

2 Fundamentals of platform-based design in process industries

This chapter describes the fundamentals of platform-based design (PBD). It first emphasizes the development of PBD in manufacturing industries with discrete, assembled products. Subsequently it draws the comparison to PBD for process industries with non-assembled products and concludes with an answer to the sub-question SQ 1 *How can platform-based design for non-assembled products help the company in structuring its approach to the selection of an integrated manufacturing platform?*

Section 2.1 introduces the general concept of platforming and introduces product families to the reader.

Section 2.2. explains the application of platform-based design concepts in the context of assembled products in manufacturing industries.

Section 2.3 picks up the notion and transfers it to process industries and non-assembled products explaining the key differences between manufacturing industries for assembled products considering product properties, transformational manufacturing process and feedstock selection, concluding with an explanation of production platforms.

Section 2.4 summarizes the chapter providing an answer to SQ 1 *How can platform-based design for non-assembled products help the company in structuring its approach to the selection of an integrated pyrolysis manufacturing system?*

2.1 Platforming and product families

Understanding new approaches to product and systems design and development, including their implications for doing business especially is a challenge for industrial organizations. Platform concepts have been on the rise for the past decades and provide promising benefits throughout different organizational disciplines (Meyer & Dalal, 2002).

Product platforms, manufacturing platforms, process platforms and other types of platforms are common organizational concepts to exploit a firm's product portfolio, target markets and the processes for creating and delivering value. The goal is to engage in product family development practices to be able to achieve sufficient variety in product offers to the market while achieving and "maintaining economies of scale and scope within manufacturing capabilities" (R. Andersen, 2022; R. Andersen et al., 2022; Lager, 2017, p. 20; Pirmoradi et al., 2014; Samuelson & Lager, 2019; K. Ulrich, 1995).

A product family can be understood as a set of products that share common components and functions. The products only exhibit certain specifications which are deemed relevant for a certain market segment and final customer. The common, shared components of the products are usually referred to as a product platform (Lehnerd & Meyer, 2014; Pirmoradi et al., 2014; K. Ulrich, 1995).

A product platform can be defined as "the common subsystems and interfaces used within and shared across different individual products" (Meyer & Dalal, 2002). The identification and exploitation of commonalities promises potential for scalability, i.e., to achieve required price performance propositions for different market segments through combining product and process subsystems. This further increases flexibility in application of different functions throughout different market systems (Meyer & Dalal, 2002).

2.2 Assembled products

Platform-based design has its origin in the world of assembled or discrete products with the emergence of mass customization in the 1990s (R. Andersen et al., 2022; Meyer & Dalal, 2002; Pirmoradi et al., 2014).

Ulrich (1995) and Lehnerd and Meyer (2014) investigated the role of product architecture for assembled products for the manufacturing firm and define product architecture as "the scheme by which the function of the product is mapped onto physical products". "The arrangement of functional elements", "the mapping of functional elements to physical components" and the "specification of interfaces between interacting physical components" (K. Ulrich, 1995, p. 3) are key guiding themes for platform-based design of assembled products. A product architecture ultimately determines how the different elements and components of a product are structured and interact with each other (R. Andersen et al., 2022). Product architecture is an important consideration in the design and development of a product, as it can have a significant impact on the product's performance, reliability, scalability, maintainability, and other factors.

The definition of product architecture is further expanded through the concept of modularity. In the context of assembled products, a module is a pre-manufactured physical or non-physical unit that can be easily integrated into a larger system or product. Modules are often used in the manufacturing process to facilitate the assembly of complex products by breaking them down into smaller, more manageable components. They also contribute to the overall system performance through interfaces governing the interaction between components or modules. Several components can be integrated to form a module. An example would be printed circuit board modules or mechanical modules. Another benefit of designing modules composed of several components is the increase of efficiency of the assembly process as well as the reduction in complexity of complex manufacturing systems (K. Ulrich, 1995; K. T. Ulrich et al., 2020).

The function structure of a product relates to the purpose of the product and its final use rather than to its physical properties. A product can have several functional elements which can be broken down into further detailed levels of description increasing the complexity and abstract of a function of a product. The functional elements can be arranged in a so-called "function structure" (K. Ulrich, 1995, p. 420). Either standardized or company internal linguistic terms are usually used to describe the functional elements of each product (K. Ulrich, 1995, p. 3). Ulrich concluded that the design of a product architecture has important implications on six important managerial challenges, namely establishing sufficient product variety; balancing product performance for different market segments; achieving sufficient product standardization in order to increase cost efficiency and lead time performance; facilitating product change; and updating and developing the organizational structure of the firm accordingly.

2.3 Non-assembled products

Since the early 2000s a new research stream has developed aiming to investigate the philosophy of platform-based design in the context of process industries (R. Andersen et al., 2022). Although it is largely used for assembled products the theory is not directly applicable to non-assembled products. This is since inputs and outputs in process industries are not physical (machined) components but raw materials or ingredients. Compared to manufacturing industries that assemble products in a discontinuous process, non-assembled products in process industries follow a V-type divergent process flow in a continuous flow pattern (Delft & Zhao, 2021; Lager, 2017). This means that non-assembled products are often further delivered to and transformed in other downstream transformation facilities whereas assembled products might leave a manufacturing plant either readily assembled or are put together in assembly plants (Lager, 2010).

The production system required to process these materials has a significant influence on the product family that can be realized. Hence, process development and product line development need to be interlinked as the complexity of the process technology increases with each further derivative product developed (R. Andersen, 2022; Lager, 2017, p. 20; Meyer & Dalal, 2002).

Process industries are industries that involve the transformation of raw materials into finished products through a series of chemical or physical processes. Examples of process industries include the petroleum industry, the chemical industry, the pharmaceutical industry, the food and beverage industry, the pulp and paper industry, and the metals and mining industry. These industries rely on specialized equipment and processes to transform raw materials into finished products (Lager, 2010, 2017; Pirmoradi et al., 2014).

Process industries often involve the use of hazardous materials and chemicals, and as a result, they are subject to strict regulations and safety standards. They also typically require specialized training and knowledge to operate and maintain the equipment and processes used in the industry (R. Andersen et al., 2022).

Several characteristics delineate process industries and requirements to platform-based design in this regard from assembled (discrete) product platform concepts. These are expressed through (1) the properties of the input material, (2) characteristics of the underlying process for transformation of that material and the (3) desired properties of the final product (Delft & Zhao, 2021; Lager, 2010, 2017; Samuelson & Lager, 2019). Table 1 briefly summarizes the main characteristics of process industries considering these three dimensions.

Table 1 Characteristics of process industries (Delft & Zhao, 2021; Lager, 2010, 2017; Samuelson & Lager, 2019)

Feedstock materials	• The transformation process is fed with materials or ingredients instead of components. • These materials can be subject to change in the **form** of degradation imposing other significant challenges on a production system. • The properties of the input materials determine the final quality of the products.
Transformation process	• Batch processing, semi-continuous processing and continuous processing are common for the transformation process in process industries. • Usually, the process is adapted to a small number of input materials from which a myriad of final products is generated. • Raw materials can undergo various substantial changes and transform to identifiably different final products, compared to other manufacturing industries.
Properties of the final product	• In most cases final products are homogenous with inherent structures determining the product functionalities. • Final products are highly interrelated imposing challenges on strategic changes to product portfolios and production systems (Lager, 2017, p. 23).

Product platforms

Extending the notion of commonality and sustainable customization R. Andersen et al. (2022) attempted to provide a delineation of the characteristics of products from manufacturing industries for assembled products from non-assembled products. Although the differentiation provided in Table

2 might not be representative for all process industries, it manages to give a clear understanding of key differences. The authors compared the products of both types of industries considering eight different characteristics.

Table 2 Differentiation of characteristics of non-assembled and assembled products adapted from (R. Andersen et al., 2022; Lager, 2010, 2017)

Characteristic	**Manufacturing industry**	**Process industry**	**Description**
Product structure	Deep	Shallow	Non-assembled products are often comprised of few or only one subsystem.
Product constellation	Assembled structure	Blended formula	Combining raw materials instead of components is a key concept.
Number of input materials	Many	Few	Non-assembled products might be made from only one material.
Storage time	No practical limit	Often limited	Products have the potential to deteriorate, i.e., in food industries.
Material grade	Predictable	Variable	As Lager (2017) describes, input materials mostly determine the final quality of the product.
Regulatory constraints	Low	High	Products of process industries might be subject to high regulations.
Product flow	Primarily convergent	Primarily divergent	Process industry products are mostly further processed into multiple derivatives.
Balance of residual products	Not important	Important	Depending on the transformational process, process products, co- or by-products are produced in varying conditions, which is usually not an issue for assembled products.

Function-based leveraging strategies for non-assembled products

As non-assembled products in process industries do not share components or interfaces a function-based perspective on new product development is the most feasible. Final products usually exhibit well-defined functionalities. The decomposition of the different products into their different functions requested by the final customers allows for an adequate design of a product family and the according platform-based design process of manufacturing processes and the raw material basis (Lager, 2010, 2016, 2017).

A function-based leveraging strategy for product development over different market segments can be applied to further innovation and the exploitation of commonalities between customer requirements. Through such a strategy the basis for a product platform can be identified by integrating marketing and engineering strategies. Usually, these requirements are collected based on the performance requirements a product must fulfill depending on the market segment (Lager, 2016, 2017)

A product family can offer multiple functions. Depending on the product such a function could be included or omitted, covered by the entire family, only a fraction or a single product. Functional properties are part of the design requirements for products and can support the identification of a product platform for a product family. Derivative products could be classified by the degree to which they achieve these design requirements and define the product variety (Lager, 2017, pp. 26–27).

Process platforms

As already introduced in chapter 2.2, the concept of modularity is also applicable in process industries although with a higher focus on processes and their subsystems. Modularity in subsystems as well as interfaces enable a manufacturer to construct modular processes. Shared subsystems are likely to result in shared manufacturing processes among product families. Derivative products can be developed by adding or subtracting subsystems and processes. Further it can be argued, that this modularity in subsystems increases the potential to include third party process development capacity into the design of new process equipment (Lager, 2017; Meyer & Dalal, 2002).

The underlying basis for a product family is set with the manufacturing system. As Meyer and Dalal's (2002) study indicates a strong process platform has the potential to consistently support value creation processes throughout several product generation- and design cycles. In this regard, several process variations are needed to achieve the required variety in the product offer. This implies that to realize a product family, a process family is needed, which is subject to the same principles of commonality and differentiation as the product family. The process family also shares common process structures which are organized in a process platform. In order to sustain the competitive position of the organization and the relevance of product families, manufacturing technology needs to be continuously improved and updated (Lager, 2017, p. 22; Samuelsson et al., 2016).

As already stated above, the product platform and process platform are interlinked. Some authors even argue that 'the process is the product for process industries' (Mogensen et al., 2022). Accordingly, commonalities in production processes and technology configurations need to be identified. Exploiting such process families can lead to significant cost and risk reduction. Because of the close interlinkage of manufacturing process and product, investments in production technology are the foundation for product development and hence the basis for innovation. For this reason, the process technology configuration is regarded as a starting point for identification of process platforms which serve as foundation for the development of derivative production structures. The resulting family of production processes is facilitated by commonalities in production technology and process logistics (Lager, 2017, p. 27).

Production platforms for non-assembled products in most cases require complex manufacturing technology characterized by high investment costs potentially leading to lock-in to current product families and manufacturing processes (Meyer & Dalal, 2002).

Raw material platforms

Compared to other manufacturing industries non-assembled products can be a combination of raw materials which are blended and transformed to even a new "product entity" through different transformation mechanisms. The final products are usually homogeneous depending on the input material properties. The commonality between input materials used in different production platforms, i.e., a respective combination of product- and process platforms serves as foundation for the identification of raw material platforms that can be leveraged over different production systems. Logistics play a crucial role eventually necessitating raw material logistics platforms (Lager, 2017, p. 27; Samuelson & Lager, 2019).

Due to the influence of the feedstock materials on the final product the design of non-assembled products must be considered from an end-to-end perspective. If products exhibit commonalities and these can be identified and a shared logic between design aspects, functionalities, production processes and raw materials can be identified. Platform-based design can enable to exploit these commonalities (Delft & Zhao, 2021; Lager, 2017, p. 26).

As raw materials highly influence the quality and performance as well as functionality of the final products, a function-based leveraging strategy highly correlates with the availability, choice and quality of the raw materials used.

Production platforms

Samuelson and Lager (2019, p. 135) argue that due to the homogenous nature of the products manufactured, and the close coupling between customer needs, products, production processes and raw materials a "well-integrated production and design philosophy is needed".

Hence the product-, process- and raw material platforms together form the integrated production platform of an organization. Depending on the customer requirements regarding the final products' properties as well as the according market segmentation several production platforms might need to be developed. For each production platform the development of each of these platforms is implicit. Market information is needed to transform customer desires into a product platform expressing the need for and extent of product variety. This information can be broken down into product specifications and functionalities which further impose requirements on the process setups that can subsequently be organized as a process platform facilitating the generation of a product family. This translates to the raw material platform identifying the required input materials for each production platform (Lager, 2017, p. 27).

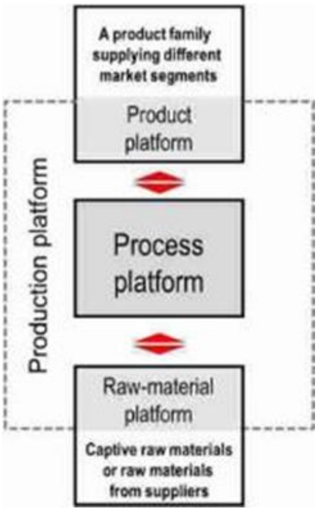


Figure 2 Framework for platform-based design of non-assembled products - Integration of product-, process-, and raw-material platforms into a production platform adapted from Lager (2017, p. 27)

Depending on the product portfolio of an industrial firm, as well as the need for a high product variety strategy, several production platforms can be developed enabling the identification of further commonalities between products, processes and raw materials (Delft & Zhao, 2021; Lager, 2017; Samuelson & Lager, 2019). As illustrated in Figure 3 these production platforms can be coupled. The higher the degree of commonality, the more likely the company will be able to achieve cost-efficiencies in product development, manufacturing system configuration and raw material sourcing, all while ensuring the pitfalls of product platforming as described above are prevented.

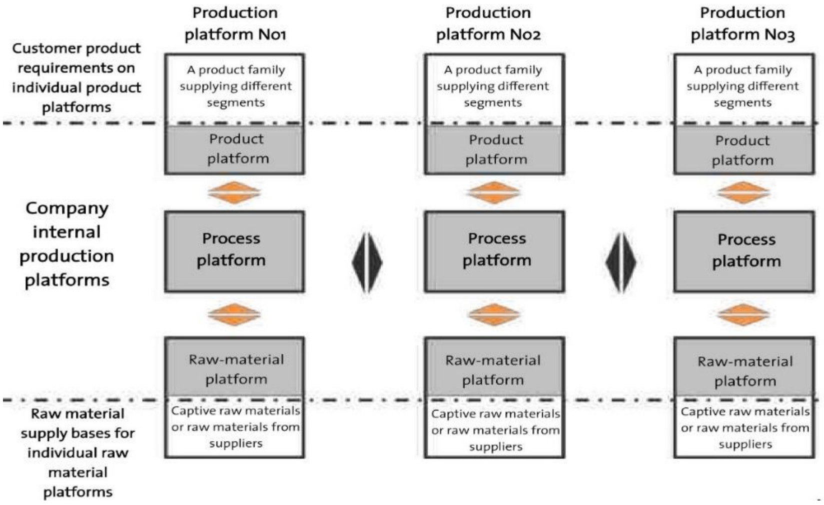


Figure 3 Framework extension through multiple production platforms (Lager, 2017; Samuelson & Lager, 2019)

2.4 Chapter summary

Giving an answer to sub-question 1 *How can platform-based design for non-assembled products help the company in structuring its approach to the selection of an integrated manufacturing platform?* this chapter summarizes the aspects of platform-based design in process industries.

Throughout the past two decades, platform-based design theory scholars transferred concepts for platform-based design for assembled products to the non-assembled products manufactured in the process industries and tested their feasibility. Final products differ in terms of their underlying raw materials, also referred to as feedstock materials or ingredients, their structure, constellation, depth, the number of input materials and process flow patterns.

The notion of the integrated production platform emerged including highly integrated product-, process- and raw material platforms which inform each other (see Figure 4).

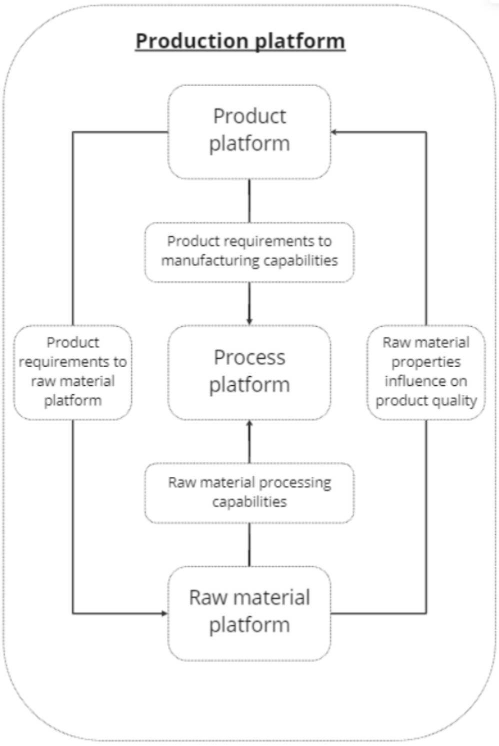


Figure 4 Interrelations of the integrated production platform in process industries adapted from Lager (2017)

As for assembled products, platform approaches are enabling to exploit commonalities of products, processes, and raw materials to generate the most adequate product offer for different market segments and to facilitate a resource efficient high variety strategy.

The notion of commonality is the main guiding theme combining all different platforms. Considering the structure of functional elements of different non-assembled products offered by a company, direct implications can be derived for the underlying process platform which includes a set of complex and interlinked subsystems of process technology with prospects for getting more extensive and complex with each further product derivative added.

As the process platform and the process equipment respectively are an integral part of product development efforts it is feasible to leverage platform-based design theory for the selection of a complex integrated manufacturing platform to realize different product families. The set of capabilities of the manufacturing platform is subject to requirements imposed by the underlying raw materials, needed for the final products as well as directly by the products themselves.

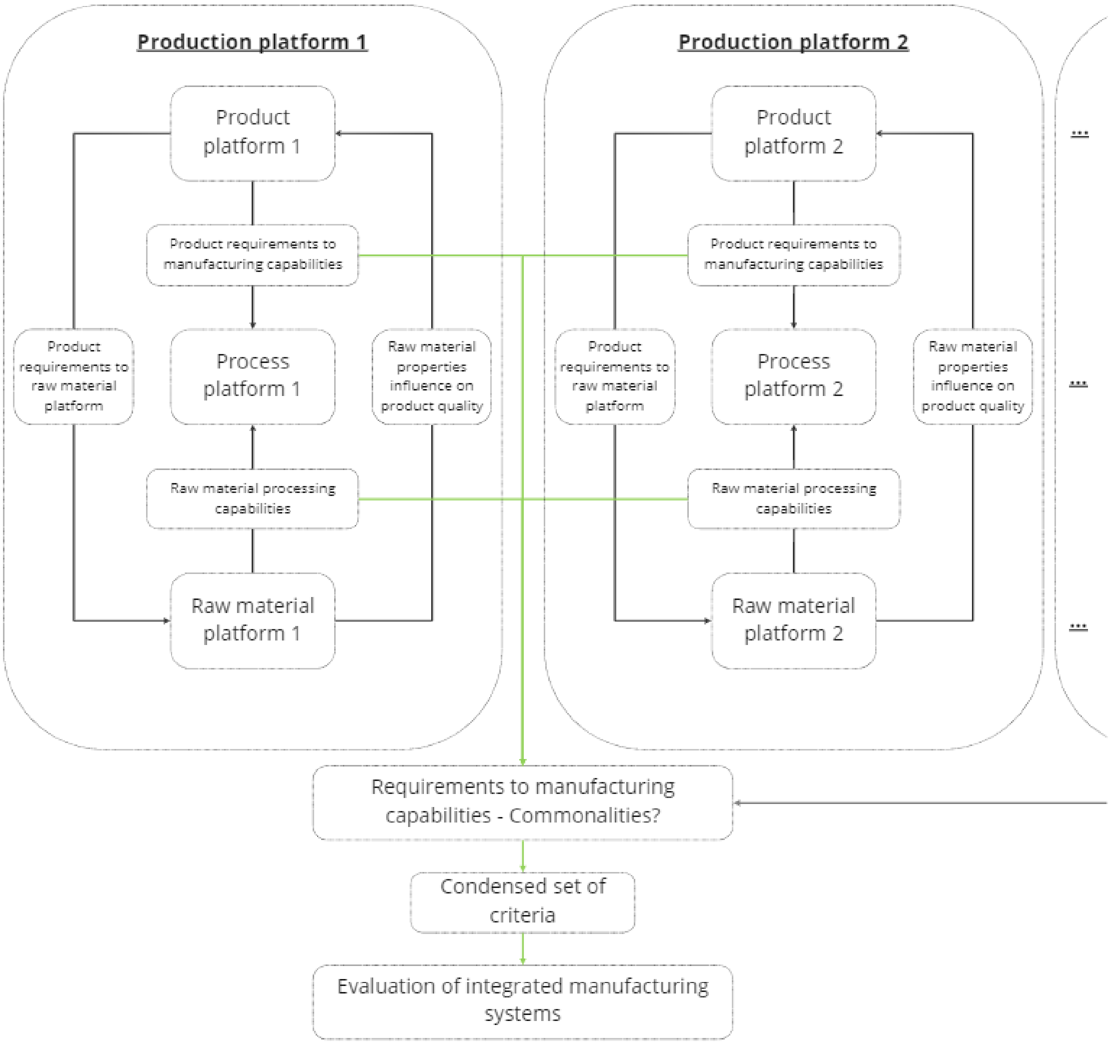


Figure 5 Interrelations of integrated production platforms and implications for process capabilities

Emphasizing the framework for platform-based design for non-assembled products introduced by Lager (2017) it becomes evident that with each further product derivative and production platform added, also adds new requirements to the process platform, i.e., its manufacturing capabilities (see Figure 5). The following sections take the company's high variety strategy for biochar products as departure point and establish relevant product families, based on the inherent properties and benefits of biochar and the underlying manufacturing process. The focus is on the manufacturing capabilities of the process platform with the ultimate goal to end up with a condensed set of criteria for a subsequent evaluation of integrated manufacturing systems available for selection.

As the biochar systems are highly complex involving many interrelated factors in a multifactor complex system, the suitability of platform-based design for non-assembled products offers potential avenues to structure a technology selection process and derive a comprehensive set of criteria for selection.

3 Production platform – Biochar

This chapter concerns the functionality of biochar as a product, its properties and the company's main customers' needs regarding the functionality of the biochar products. Section 3.1 describes biochar and its physical as well as chemical properties in order to introduce the reader to the functionalities and capabilities of the biochar product.

The chapter further ventures into the applications of biochar focusing on applications to soil and the establishment of a product family for biochar for soil amendment in section 3.2. This sub-chapter answers sub-question SQ 2.1 *Who are the customers the company currently serves with biochar, what are their main needs and how do these translate to required functionalities of the biochar products for each application?* The goal is to develop a function structure, which can be leveraged over the different customer segments.

Section 3.3 then focuses on answering sub-questions SQ 2.2 *Which subsystems are relevant for the biochar process platform?* and SQ 2.3 *How do the biochar product functionalities translate to process platform requirements?*

Section 3.4 ultimately ventures into the raw materials for biochar production and answers SQ 2.4 *How do the biochar product functionalities translate to raw-material platform requirements?*

Section 3.5 concludes with a summary of chapter 3.

3.1 What is biochar?

Biochar is a term to describe biomasses which were subjected to a thermochemical – either pyrolytic or hydrothermal – decomposition reaction leading among other things to an increase in their relative carbon content. This process is used to emulate the natural carbon sequestration process leading to the formation of fossil coal (Quicker & Weber, 2016; Weber & Quicker, 2018). The carbonaceous product can subsequently be used as a substitute for fossil based carbon additives in technical processes (Weber & Quicker, 2018, p. 240). The final solid fuel obtained is a stable, carbon rich, porous material produced at a slow heating rate and at relatively low temperature between 400-700°C (Ghodake et al., 2021; Ippolito et al., 2020).

Biochar is usually produced from a variety of biogenic feedstocks such as agricultural and forestry waste products, municipal waste, green and food waste, and many others. The utilization of these feedstock materials and their pyrolytic conversion enables to lock carbon into its recalcitrant form[1] with a durability of more than 1,000 years. This indicates the technology's potential to effectively support the mitigation of climate change as one of the few, technologically ready and available negative emissions solutions on the market (Ippolito et al., 2020).

Products and services enabled through thermochemical treatment processes provide value beyond thermal and electric energy recovery. Respective technologies must be seen as part of the concept of circular low carbon economy (Porshnov, 2022, p. 3).

---

[1] A form with high resistance against biodegradation (Knapp and Bromley-Challoner (2003).

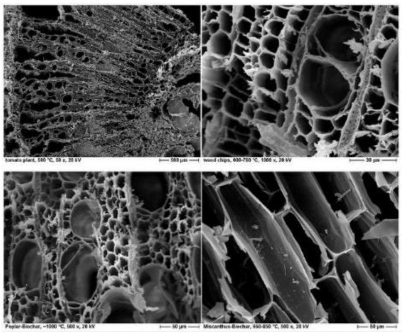


Figure 6 Biochar under the microscope (Ladygina & Rineau, 2013)

The following section presents a selection of physical and chemical properties of biochar, relevant to the final products and applications which serve to evaluate the investigated integrated pyrolysis systems presented in the empirical part of this thesis. From the physical and chemical properties of the material, an according function structure can be extrapolated which is to be leveraged over the different customer segments as according to (Lager, 2010, 2016, 2017; Samuelson & Lager, 2019). This thesis does not claim full coverage of all factors relevant to all biochar applications which are currently applied and investigated, therefore the following chapter is not exhaustive and only presents the relevant properties for soil amendment applications. For further, detailed information, the reader can refer to Lehmann and Joseph (2015) and Quicker and Weber (2016).

Applications of biochar

Biochar production from diverse organic "wastes" and byproducts of agricultural and industrial origin has become a promising study subject because of its positive benefits. A wide range of agricultural as well as industrial products are offered on an international market (Kocsis et al., 2022; Lehmann & Joseph, 2015).

Biochar has the potential to function as a platform carbon material for pollutant removal, soil remediation, CO2 capture, energy storage, as construction material, as composite material, as additive and substitute for a great variety of industrial substances and many others (see Figure 7) (EBC, 2012-2022; D. K. Gupta et al., 2020; Liu et al., 2015; Schmidt et al., 2019; Zhang et al., 2022).

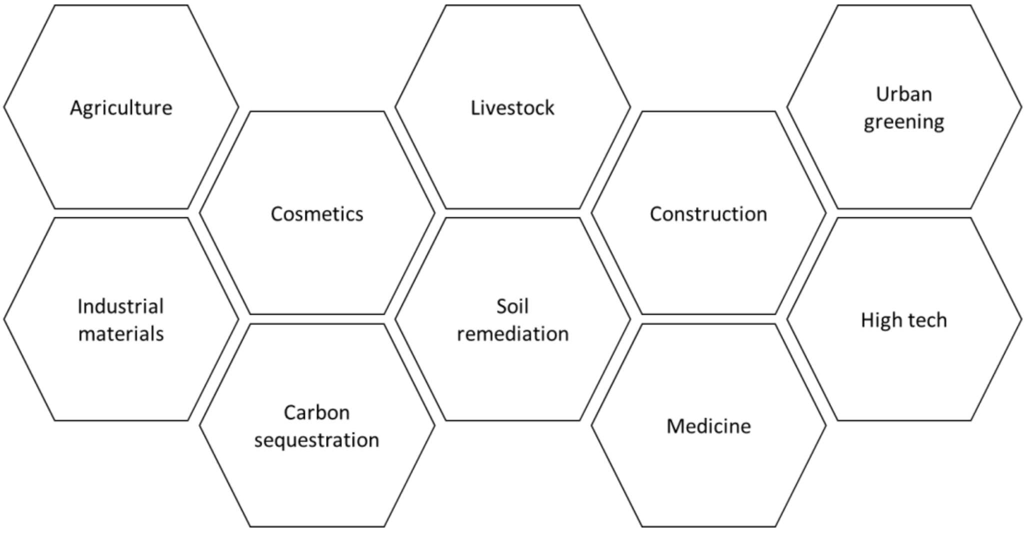


Figure 7 Application areas of biochar adapted from Zhang et al. (2022), Liu et al. (2015), Lehmann and Joseph (2015), D. K. Gupta et al. (2020)

Due to the early developmental stage of the whole biochar market, most of the biochar applications for instance industrial materials do not provide sufficient market readiness yet. This resonates with potential customers who currently do not sufficiently understand the potential benefits of biochar and resulting. Another important factor to consider is the lack of adequate standards and regulations (EBC, 2012-2022). For this reason, the following sections for further elaboration of a production platform for biochar focuses on its application to soil for purposes of soil remediation, urban blue and green infrastructure, and agricultural use. Figure 8 presents the general benefits of biochar for soil amendment.

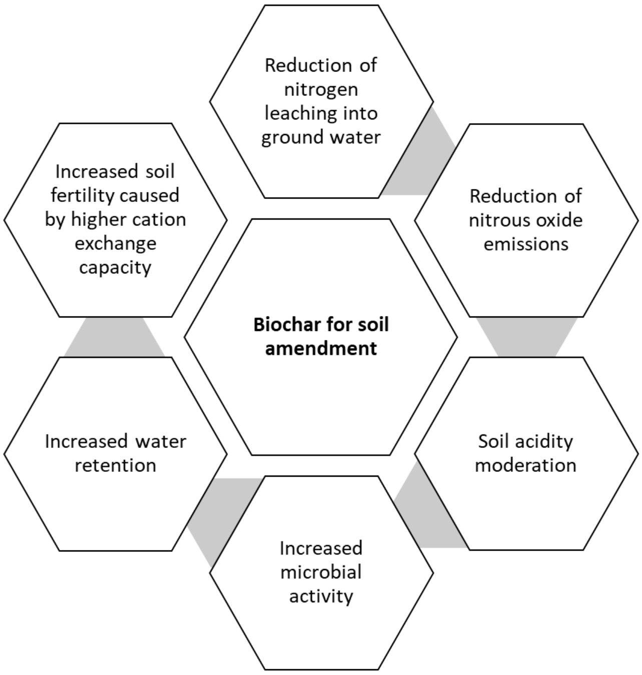


Figure 8 Biochar for soil amendment, benefits adapted from Kocsis et al. (2022) and IBI (2023)

Physical and chemical properties of biochar

Properties of the carbonized product determine its final application and vice versa. In the following, several important properties of biochar are explained. These will be of further relevance later and enable the reader to understand the relation between process conditions, pyrolysis system configuration and the benefits of the different technological solutions presented in the technology evaluation. Research differentiates between functionality, porosity and specific surface area (SSA) and particle size distribution in terms of physical and structural properties. Chemical properties are fixed carbon and volatile matter, pH-value, cation exchange capacity and ash content.

Porosity and surface area

Volatile gases being released from the feedstock during pyrolysis increase the porosity and surface area of the final product. Research differentiates micro- and macroporosity of the biochar. Micropores up to 2µm are referred to as micropores responsible for the adsorptive capacity[2] of the material which is relevant for any gaseous or liquid filter application and hence soil remediation purposes (Lehmann & Joseph, 2015, p. 95). Macropores are pores of more than 10µm and highly relevant if biochar is considered primarily as soil amendment, since these pores can provide a habitat for microorganisms, increase aeration of soil and root hair growth (Kocsis et al., 2022; Lehmann & Joseph, 2015, p. 99).

---

[2] Adsorptive capacity to the ability to absorb molecules of different media (Ladygina and Rineau (2013).

A large surface area is favorable for a variety of final applications and related to a number of other material properties such as cation exchange capacity (CEC) and water holding capacity (WHC) (Weber & Quicker, 2018, p. 252). The SSA of soils determines their WHC. Biochar is supposed to improve soil physical properties in sandy as well as clayey soils through its porosity. Moreover, a high SSA favors the development of microbial activity and populations in, resulting in overall greater fertility of the soils (Lehmann & Joseph, 2015, p. 95). SSA of several hundred square meters are common (Kocsis et al., 2022). The influence of the pyrolysis process and its parameters on this property is still largely unclear, only some studies suggest that their influence is minor. However, heating rate and treatment temperatures have an influence this can be mainly attributed to the biochemical composition of the input materials (Muzyka et al., 2023).

Particle size distribution

The particle size distribution of the carbonized product is largely influenced by the feedstock size distribution although it needs to be acknowledged that the pyrolysis conditions as well as reactor configurations subject the feedstock particles to shrinkage and attrition. Heating rate, highest treatment temperature (HTT) and pyrolysis pressure further influence the particle size distribution. A high heating rate and large feedstock particles can result in a majority of large particles due to the limited heat transfer into the core of the particles. A high HTT favors the development of small particles and an increased pyrolysis pressure can result in swelling and particle clusters due to inflicted particle fusion (Lehmann & Joseph, 2015, p. 101).

Water holding capacity (WHC)

The WHC of biochar is relevant for different applications as adsorptive material for sponge city concepts and generally to increase the WHC of soils. As further elaborated in the section about the chemical properties of biochar, the reduction of functional groups on the surface of the material increases its hydrophilicity, i.e., its ability to store water. The increased porosity of the material also supports this characteristic. However, both mechanisms have potential for complementing or counteracting their effects on water holding capacity. In most cases, the hydrophilicity of the biochar is increased compared to the feedstock material (Weber & Quicker, 2018, p. 253). While the pyrolysis treatment temperature influences the WHC, the feedstock is again the determining factor (Marshall et al., 2019).

Functionality

During carbonization the most important process is the thermal decomposition of the feedstock structure. Functional groups are detached, and oxygen and hydrogen released. A critical metric for several applications, i.e., soil amendment and remediation, is the H/C ratio. A low ratio indicates a high carbon content, less functional groups, and increased number of aromatic structures in the char. These exhibit a high thermodynamic stability, which is important for soil amendment requiring long-term stability of the carbonaceous material (Ippolito et al., 2020; Weber & Quicker, 2018, p. 247).

Fixed carbon and volatile matter

After the release of volatile compounds from feedstock material during the pyrolysis process the carbon remaining in the solid fuel is referred to as fixed carbon. For some applications, a very high carbon content of > 90% is required to replace fossil fuel carbon carriers. These are for example metallurgical applications as well as biochar produced for carbon sequestration purposes. Process temperatures of > 700°C are required to produce such high fractions. The increase of the relative carbon content is a direct result of the release and hence decrease of volatile matter in form of process gases, also referred to as devolatilization (Weber & Quicker, 2018, p. 247). Lignocellulosic biomass with a high lignin content is the best biomass regarding the yield of this metric (Weber & Quicker, 2018).

pH-value

The pH-value provides information about the alkalinity or acidity of the carbonaceous material. Especially soil amendment applications have strict requirements to the pH value of the biochar used. As functional groups are detached from the material during pyrolysis, which are acidic, the remaining solid material becomes more basic. This development is proportional to the number of functional groups released. Moreover, the relative content of ash further increases. As a matter of fact, it can be stated that an increasing pH-value is caused by increasing carbonization. The treatment temperature is the most influencing factor in this case (Weber & Quicker, 2018, p. 248).

Cation exchange capacity (CEC)

The cation exchange capacity is a general parameter for soils' ability to adsorb and release the nutrients which are needed for plant growth. It results from negative surface charges and the underlying metric is the number of exchangeable cations a material can hold. The cation exchange capacity is influenced by the surface structure of the biochar. Biochars produced at low temperatures (resulting in a high surface area) exhibit the highest cation exchange capacities. Here, enough functional groups are still present to provide negative charges. Consequently, the CEC decreases with higher treatment temperatures (Weber & Quicker, 2018, p. 249).

Ash content

The ash content of the feedstock material significantly influences the ash content of the resulting biochar. Whereas water is evaporated from the biochar, the ash remains in the final product. As an inorganic compound it determines the biochar's feasibility for a range of applications. A high ash content could for example decreases the biochar's ability for carbon sequestration (Weber & Quicker, 2018, p. 249).

3.2 Product family – Biochar for soil amendment

Whereas the previous section delved into the properties of biochar and its inherent benefits for soil amendment, this section concerns the customer needs, the product functionalities and ultimately the manufacturing capabilities of the process platform. According to the main revenue streams of the company, three main applications of biochar for soil amendment can be identified, which are mostly requested by the market. These are urban landscaping or greening, application in the agricultural context, and soil remediation (Köhler, 2022).

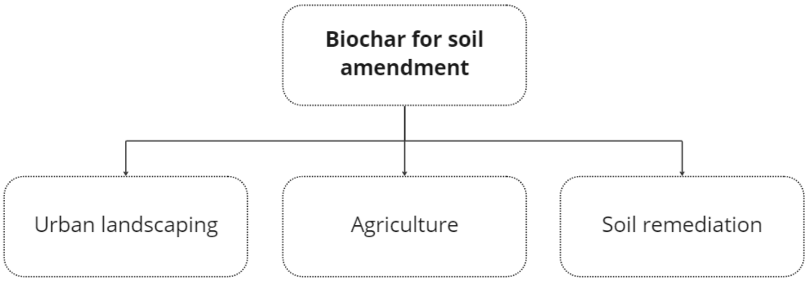


Figure 9 Market segmentation depending on final application

The relevant sub-research-question for this chapter is SQ 2.1 *Who are the customers the company currently serves with biochar, what are their main needs and how do these translate to required functionalities of the biochar products for each application?*

Agricultural applications – Main customers, their needs and product functionalities

Main customers of the company for agricultural applications of biochar include agro-industrial trading companies which have established exclusive B2B contracts for delivery. They act as B2B intermediaries leveraging a wide network of distribution and further downstream manufacturing facilities producing material blends based on biochar. The main customer needs identified by the company's sales representatives are compliance with EBC certifications, a high water holding capacity (WHC) as well as a high filtration capacity of the biochar products. Currently, the company only sells biochar made from wooden feedstock materials to these customers. Moreover, the customers request different particle sizes (Köhler, 2023).

In addition, physically or chemically enhanced biochar can improve the health and performance of agricultural soils and increase plant yields. The biochar's main appealing benefit is its ability to release nutrients stored in the carbonaceous product and reduce the need for industrial fertilizers which become subject to a lower leaching rate after incorporation of the carbonate into soil. Amending the physical structure of soils, biochar increases their WHC and provides potential for remediation through reducing the ecotoxicity of soils by immobilizing organic and inorganic contaminants. The bioavailable nutrients stored in the biochar are released and thus biochar can act as slow-release fertilizer further adding to the soil health and fertility. Greater nutrient retention is another beneficial factor. Again, the benefits of biochar application to soils depend on feedstock, pyrolysis conditions as well as particle size of the biochar and soil composition and properties (Allohverdi et al., 2021).

Urban landscaping – Main customers, their needs and product functionalities

Main customers for urban landscaping applications of biochar include municipalities with sustainability strategies including the goal of improving their blue and green infrastructure. Furthermore, great landscaping product manufacturers acting as B2B intermediaries with further downstream refining facilities contribute a vital part to the company's revenue. Additionally, blue and green infrastructure construction and project development companies are interested in the biochar's inherent benefits. The sales team of the company identifies compliance with EBC certifications, high filtration and water holding capacity, soil remediation effects as well as tailored particle sizes as fundamental customer needs (Köhler, 2023).

Approximately 85% of the annual precipitation on the impervious surfaces in cities is converted to surface runoff. This increases the frequency and intensity of floods, reduces aquatic biodiversity and deteriorates the "channel morphology in urban stream systems" (Werdin et al., 2021, p. 1). Biochar is used as an additive for urban blue and green infrastructure for the purpose of passive treatment of storm water. Its ability for filtration as well as its increased WHC depending on SSA as well as porosity and pore size distribution are main determinants for a successful application in this area. Moreover due to lower solid density resulting from the porosity of the material it can reduce the weight of substrates used for green roofs influencing the requirements imposed on the structural capacity of buildings (J. Wang et al., 2023). Biochar amendment rate as well as particle size are the main influencing parameters for this application (Werdin et al., 2021). The EBC-Urban standard is the determinant for urban applications of biochar with strict quality requirements for storm water management and filter capabilities of biochar (EBC, 2012-2022, p. 12). Special emphasis is on polyaromatic hydrocarbon trace elements which can cause cancer and are abundant in urban environments.

Soil remediation – Main customers, their needs and product functionalities

The sales representatives of the company further identify soil remediation as another relevant factor for the differentiation of market segments. Customers from the agricultural as well as urban landscaping realm, however, did not directly express the need for these functionalities of the product. Nevertheless, this product functionality is considered to play an important role in the further segmentation of customers in the future (Köhler, 2022, 2023).

The focus of biochar application purposes for soil remediation is on decontamination of soils and preventing the leaching of environmentally harmful substances such as heavy metals, water soluble metal ions, agrochemicals, antibiotics, and others. The main material property relevant to the adsorption of organic and non-organic contaminants is the CEC of the biochar. SSA and degree of hydrophilicity are responsible for the carbonaceous material to hold water. Compared to other soil remediation techniques like soil washing, leaching and extraction, biochar application does not lead to an eradication of the contaminants in soil but a stabilization and a transformation into "less soluble and less bio-accessible forms" (Guo et al., 2020, p. 8). To achieve the desired effects, it is essential to incorporate tailored biochar products at an adequate soil specific rate to the contaminated soils (Guo et al., 2020). The biochar must comply with EBC-Urban and EBC-Agro certifications (EBC, 2012-2022; Köhler, 2022, 2023).

Carbon sequestration

In recent years, different approaches have been developed for engineered carbon dioxide removal (CDR) on an industrial scale. This market is increasingly gaining attention from regulators as well as industrial companies worldwide. It is estimated that the global economy will largely rely on carbon removal technologies with an estimated market size of 1.5 – 2 billion tons of engineered carbon removal annually by 2030 (Christie-Miller & Harvey, 2022). Biochar is one of several engineered carbon sequestration options available to contribute to greenhouse gas mitigation (D. K. Gupta et al., 2020).

The process of photosynthesis converts CO2 through plant assimilation and stores it in biomass above and below the ground. Moreover, the CO2 is captured in soil organic biomass. This process is referred to as natural carbon sequestration. Soil organic carbon buildup is a very slow process taking several years or even decades. Through human interference with the biosphere and intensive tillage practices as well as soil erosion the organic soil carbon content is prone to deteriorate at a faster rate than its buildup (D. K. Gupta et al., 2020, p. 145). Biochar can sequester CO2 in the form of solid carbon in soils in soil applications emulating the natural carbon sequestration process.

The potential of biochar for carbon sequestration is promoted because of its high carbon content and stability in soil, resulting from its resistance to biotic[3] and abiotic decay[4] (D. K. Gupta et al., 2020, p. 147). While remaining fixed for an estimated period of 90 - 1,600 years, carbon matter is still subject to decomposition depending on its state as well as soil conditions. The relevant factor determining the rate of degradation is the molar ratio between hydrogen and organic carbon content of the carbonaceous material referred to as H/C_{org} ratio. This is an indicator for the presence of aromatic carbon structures in the biochar and the intensity of the pyrolysis process. A ratio of <0.7, indicating high share of aromatic structures, is generally regarded as high-quality and high stability form of biochar (Allohverdi et al., 2021). However, different standards and methodologies such as the EBC Sink

---

[3] Biotic = decomposition through living organisms

[4] Abiotic = decomposition caused by natural elements, such as water, temperature, sun etc.

Certificate and the puro.earth methodology for carbon sequestration through biochar even request even lower ratios and take a more conservative approach to the permanence of carbon sequestration of biochar in soil (EBC, 2022; puro.earth, 2022). Current findings suggest that >65% of the organic carbon stored in biochar with a H/C_{org} ratio of <0.7 remains in soil applications after 100 years (Guo et al., 2020). Therefore, the puro.earth methodology chosen for a calculation of the potential for carbon sequestration of biochar estimates a permanence of up to 100 years for soil applications (puro.earth, 2022). Depending on the biomass and pyrolysis conditions levels the H/C_{org} ratio fluctuates (EBC, 2012-2022).

The function structure of biochar

Inferring from the information presented above this section provides an answer to SQ 2.4 *How do the biochar product functionalities translate to raw-material platform requirements?*

in the form of an expanded function structure of the biochar product for all three applications.

As we can currently not estimate which of the customers and applications in the agricultural, urban landscaping and soil remediation context will determine the company's success in the long-term, the production process remains a source of innovation (Lager, 2016, 2017). Therefore, Table 3 lists more than the functions requested by the main customers. As some customers of each market segment further express the need for the carbon sequestration performance of the biochar Table 3 also includes this functionality.

Table 3 Function structure of biochar product for urban blue and green infrastructure, application to agricultural soil and soil remediation

Urban blue & green infrastructure	Agriculture	Soil remediation
• Comply with EBC-Urban certification requirements for soil • Increase water holding capacity (WHC) • Increase aeration of soil • Reduce weight of substrates • Increase plant available water • Adsorb organic and inorganic contaminants of stormwater • Sequester carbon	• Comply with EBC-Agro certification requirements for soil • Increase water holding capacity (WHC) • Increase nutrient density • Slowly release bioavailable nutrients • Reduce leaching of fertilizers • Reduce fertilizer input • Increase crop yields • Reduce ecotoxicity of soil • Sequester carbon	• Comply with EBC-Agro certification requirements for soil • Increase water holding capacity (WHC) • Reduce ecotoxicity of soil ○ Immobilize heavy metals ○ Immobilize polar gases ○ Immobilize water soluble metal ions ○ Immobilize agrochemicals, antibiotics, and poly-aromatic hydrocarbons ○ Sequester carbon

3.3 Process platform biochar for soil amendment – Subsystems & requirements

Answering sub-question 2.2 *Which subsystems are relevant for the biochar production process platform?* Figure 10 illustrates the process platform for biochar production which is composed of four general sub-systems each including different process modules and manufacturing equipment.

For the sole biochar production only two subsystems are usually required: subsystem one (SUB_1) relating to the storage of the feedstock material and subsystem two (SUB_2) covering the material transformation. The solid fuel in form of the biomass enters the manufacturing process and might move through subsystem five (SUB_5) in case the biogenic feedstock needs to be pre-processed to alter its properties for the subsequent transformation process. Subsystem five includes process modules for the control of its particle size and moisture content. After the material transformation the now carbonaceous solid fuel might be subjected to product refinement processes in subsystem six (SUB_6) (Kaltschmitt, 2019; Kaltschmitt et al., 2016; Lehmann & Joseph, 2015).

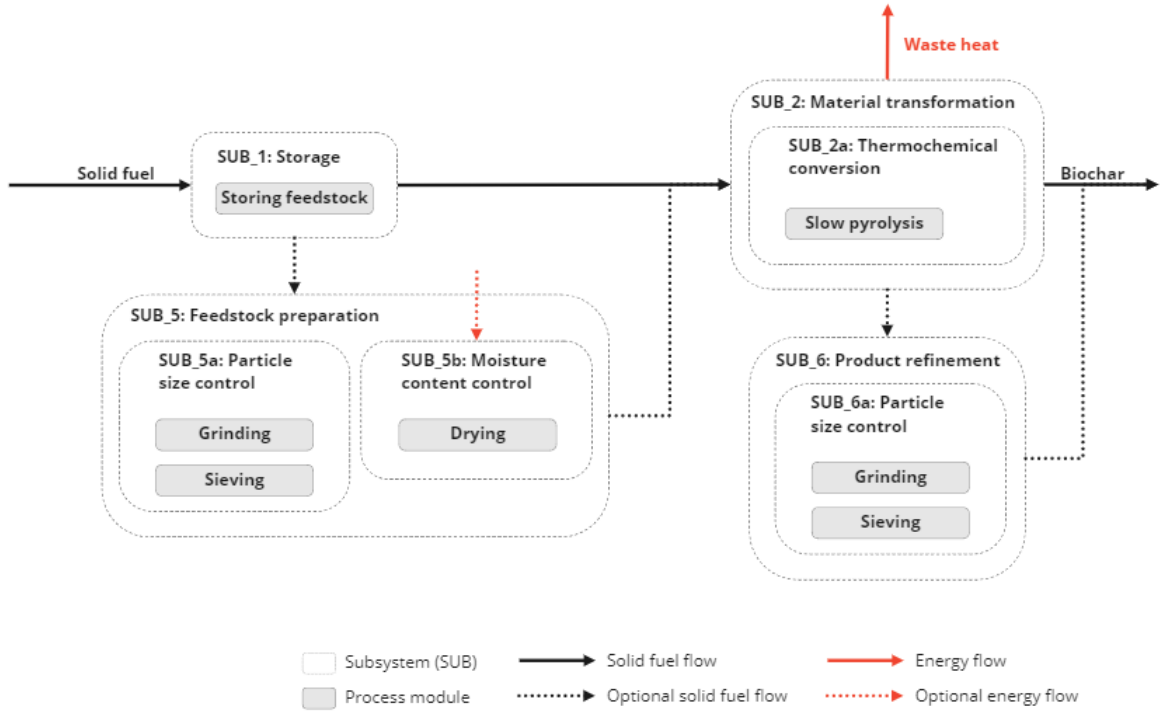


Figure 10 Process platform for biochar production adapted from Kaltschmitt et al. (2016, p. 1241), Lehmann and Joseph (2015) and Kaltschmitt et al. (2016)

Giving an answer to SQ 2.4, *How do the biochar product functionalities translate to process platform requirements?* Table 4 presents several requirements. Most of the properties of the final product depend on the raw material properties, in other words “the ingredients” according to Lager (2017).

Table 4 Biochar - Requirements to process platform

Description	Value	Unit	Remarks
Biochar conversion rate	↑	%	Since the pyrolysis process produces a gaseous, a liquid and the solid product biochar, the yield of the latter must be maximized.
Conversion rate liquid fuel	↓	%	Conversion pathways of the different pyrolysis products are competing. Any decrease in gaseous product generation may result in a higher solid fuel yield.
Conversion rate gaseous fuel	↓	%	See conversion rate liquid fuel.
Process control	↑	%	Highest treatment temperature, residence time and heating rate are the most critical parameters. Process control regarding these factors is

			critical. It should be possible to tune the treatment temperature to the best extent.
Treatment temperature range	↑	Δ°C	The biochar yield and product properties are directly influenced by the treatment temperature. It must be adapted accordingly.
Residence time rage	↑	Δmin	Residence time is one of the most influential factors on final product quality.
Input material properties possible • Particle size • Moisture content • Range of input materials • Experience with input materials	 ↑ ↑ ↑ ↑	 mm % Number Number	The bigger the particle sizes possible to be processed, the less pre-processing of the biochar is required, resulting in lower costs. Same applies to the moisture content. The equipment should be able to process a range of input materials as well as already adapted to these materials.
Low polyaromatic hydrocarbon (PAH)	↓	g t^{-1} DS	The buildup of PAH depends on employed pyrolysis technology and process control, and the separation of biochar from pyrolysis gases in the reactor and during the discharge of the material.
Cost per ton of biochar	↓	€/t	According to the market demand for lower biochar prices, to further diffuse the product in the market.

Depending on the standards to be achieved and regulations to be complied with, as well as to increase the yield of carbon credits issued on basis of the manufactured carbon material, emissions control of the manufacturing process is an essential requirement to the process platform (D. K. Gupta et al., 2020).

According to the EBC certificate, the release of non-combusted pyrolysis gases into the atmosphere is prohibited. Nationally determined emissions thresholds must be kept and the equipment needs an EBC-type certification to be able to claim the C-sink certification (EBC, 2022).

Process emissions which are documented and relevant for the product performance of carbon credits are the following according to the EBC C-Sink certificate:

Table 5 Carbon sequestration - Requirements to process platform

Description	**Value**	**Unit**	**Remarks**
CO2 equivalents emitted per unit of electricity consumed*	↓	CO2eq/kWh	-
CO2 equivalents emitted for preheating the pyrolysis*	↓	CO2eq	Some reactor configurations require fossil fuel for starting the reactor.
CO2 equivalents emitted during pyrolysis*	↓	CO2eq	Depending on the heating principle as well as system performance in terms of filtering the process streams different values are to be

			expected. The feedstock again has a significant influence on emissions, because depending on the energy content and reactor configuration additional energy input in form of fossil gas might be required to succeed with the thermochemical conversion process.
Water consumption*	↓	I	-
*All requirements are calculated based on 1t of biochar (DM)			

3.4 Raw material platform biochar for soil amendment – Requirements

Providing an answer to sub-question 2.4 “How do the biochar product functionalities translate to raw-material platform requirements?” this section presents requirements to a raw-material platform (see Table 6).

Biochar requirements to raw material platform

The final product's composition is proportional to the initial properties and concentrations of substances in the raw material (Kocsis et al., 2022). Preferably, biomass with a high lignin content is used to produce biochar. Lignin favors the yield of the solid fuel obtained from the pyrolysis process. Hemicellulose as well as cellulose thermally degrade earlier during the process. These compounds contribute to the release of condensable gases due to their lower stability (Weber & Quicker, 2018, p. 242).

According to Ghodake et al. (2021) agricultural residues, agro-industrial waste, hard-wood forestry biomass, food waste and livestock manure are feedstocks that are subject to current research with a wide basis of information about appropriate processing conditions and raw material conditions. Predominantly, agricultural lignocellulosic biomass residues like corn stover, wheat straw or rice straw, and forest residues like thinning and logging residues; aquatic biomass; cardboard waste; municipal solid waste; wastewater organic sludge as well as dedicated energy crops are used for scientific and industrial biochar production. The more homogenic the input material the more consistent the process and the quality of the final products. Lignocellulosic biomass is composed of hemicellulose, cellulose and lignin. These components have different decomposition behaviors, and their content is determined by biomass species, soil, age of the plants, growth and harvesting conditions imposing challenges on the consistency of the production process and the properties of the final products (Dhyani & Bhaskar, 2019; Soria-Verdugo, 2019).

The products and their function structure resulting from the physical and chemical properties impose several requirements on a biochar raw material platform. Critical parameters are documented in the relevant standards a biochar manufacturer is likely to pursue for developing a reputation in the biochar market. Main requirements target the contamination of soil. Depending on the certification class for biochar products and their final application the following requirements must be considered when choosing a respective input material (EBC, 2012-2022; Ghodake et al., 2021).

Table 6 Biochar - Requirements to raw material platform

Description	Value	Unit	Remarks
Utilization of biomasses	-	-	Fossil fuels must be avoided.
Separation non-biogenic / organic materials	-	-	A clean separation of non-biogenic from organic materials must be achieved in the feedstock.
No toxic contaminants	-	-	No paint residues, solvents or other toxic substances must be in the biomass.
Utilization of waste products	-	-	According to the German Biomass Strategy, preference is to be assigned to waste products (BMWK, 2022).
PEFC / FSC certification	-	-	Only forest material which is certified according to PEFC or FSC guidelines can be used.
Heavy metals content	↓	$g\ t^{-1}$ DS	The heavy metals content in feedstocks is an essential determinant for selection. The weight reduction during the pyrolysis process leads to a concentration of heavy metals in the biochar. Therefore, the lower the initial heavy metals content in the feedstock, the better.
Chlorine content	↓	w.%	A low chlorine content is another requirement for the feedstock material because of its corrosive effect on the reactor materials.

Carbon sequestration requirements to raw material platform

Depending on the feedstock different levels of carbon sequestration through biochar can be obtained. Generally, lignocellulosic biomass is preferred as raw material, since it possesses the highest organic carbon content. The biochar carbon content increases with the lignin content of the feedstock. Feedstocks with high ash content are less feasible due to the lower share of carbon. A high ash content prevents the formation of aromatic structures in the biochar and reduces its stability which is detrimental for soil carbon sequestration (D. K. Gupta et al., 2020).

Agricultural and forestry residues, agro-industrial wastes, short rotation forestry, dedicated energy crops are lignocellulosic biomasses with a high lignin and low ash content and preferred for carbon sequestration purposes. Furthermore, they are abundantly available at a low price because of their classification as waste material (Fawzy et al., 2022; Fawzy et al., 2021).

As evaluated by Guo et al. (2020), wooden residues provide the highest potential for carbon sequestration as illustrated in Figure 11. In general, the concentration of the carbon content in the final product increases with temperature due to the induced mass reduction and secondary char formation mechanisms as will be explained later in this document.

According to literature, the following general requirements can be identified for the respective biochar raw material platform from a carbon sequestration perspective (see

Table 7):

Table 7 Carbon sequestration - Requirements to raw material platform

Description	Value	Unit	Remarks
C_{org}	↑	w.%	A high organic carbon content of the feedstock is essential.
Ash	↓	w.%	A high ash content results in a low carbon content of the final product.
Lignin	↑	w.%	A high lignin content favors the conversion into carbon.
Lignocellulosic biomass	-	-	Lignocellulosic biomass is preferred due to its high lignin content.

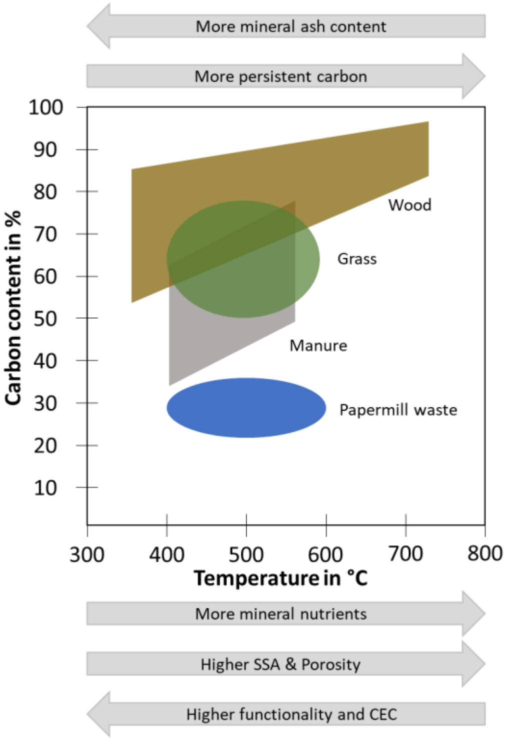


Figure 11 General change trends of biochar's total carbon content, carbon stability, mineral ash content, porosity, specific surface area, abundance of surface functional groups, and cation exchange capacity over feedstock and pyrolysis temperature adapted from Guo et al. (2020)

Since the carbon sequestration certificates are only a secondary product, derived from the inherent potential to emulate the natural carbon sequestration process, exhibiting high economic flexibility in terms of their generation, the author refrains from developing a dedicated raw material platform for this section. Carbon credits based on biochar are relatively new to the market and experienced their instigation in the beginning of 2020. Currently, a differentiation of biochar certificates regarding additionality and permanence of storage is increasingly being requested by the market. Respective standards are under review. However, since this product is in its early developmental stage the underlying data to legitimate such a differentiation is insufficient. Therefore, a general raw material platform for biochar is subjected to the requirements established in this section.

3.5 Chapter summary

Answering sub-question SQ 2.1, the company's main customers for agricultural biochar are B2B intermediaries who distribute, and manufacture biochar blends based on wooden feedstock. Compliance with EBC certifications, high water holding capacity, and filtration capacity are essential customer needs and product functionalities. The constitution of soils can be improved, increasing their WHC and providing potential for remediation.

The company's main customers for urban landscaping applications of biochar include municipalities, landscaping product manufacturers, and blue and green infrastructure construction companies. Compliance with EBC certifications, high filtration and water holding capacity, soil remediation effects, and tailored particle sizes are fundamental customer needs in this target segment. Biochar is used as an additive for urban blue and green infrastructure for the purpose of passive treatment of stormwater, and its ability for filtration and increased WHC are main determinants for a successful application.

Soil remediation is another relevant factor for a differentiation of market segments, with the focus on decontamination of soils and preventing the leaching of environmentally harmful substances. The main material property relevant to the adsorption of organic and non-organic contaminants is the CEC of the biochar.

Giving an answer to SQ 2.2 the main subsystems relevant for biochar production include storage, feedstock preparation (drying, grinding, sieving etc.), material transformation process (in this case thermochemical conversion through pyrolysis and product refinement subsystems (i.e., subsequent grinding, sieving).

While biochar conversion rate as well as throughput need to be maximized, the conversion rate to liquid fuel as well as gaseous fuel need to be minimized due to competing reaction pathways of the products. Process control must be high, indicating the best adaptability of treatment parameters such as treatment temperature as well as residence time. The buildup of polyaromatic hydrocarbons in the reactor as well as other process emissions must be reduced to increase the carbon sequestration performance of the final product. The same applies to the cost per ton of biochar answering SQ 2.3.

Answering SQ 2.4 The properties and concentrations of substances in the raw material significantly affect the composition and functionality of the final biochar product. Lignocellulosic biomass with high lignin and low ash content, no toxic contaminants, a classification as waste biomass, a low heavy metals and chlorine content is preferred as it favors the yield of solid fuel. It moreover possesses the highest organic carbon content for carbon sequestration. Agricultural and forestry residues, agro-industrial waste, and dedicated energy crops are among the preferred feedstocks due to their high lignin and low ash content, and their abundance at low cost. The contamination of soil is a critical parameter that must be considered, and relevant standards must be followed. The concentration of carbon content in the final product increases with temperature, inducing mass reduction and secondary char formation mechanisms. While carbon sequestration certificates are a secondary product, they provide high economic flexibility in terms of their generation, and respective standards are under review.

4 Production platform – Green energy

This chapter briefly introduces the reader to the need for renewable, green heat, follows with an explanation for waste heat generation of the pyrolysis process, then dives into the production platform for heat products. Sections 4.1 – 4.2 concern the customers of the company and their main needs answering SQ 3.1 *Who are the customers the company currently serves with green heat, what are their main needs and how do these translate to product properties?*

Section 4.3 then dives into the process platform for renewable heat answering SQ 3.2 *Which subsystems are relevant for an energy conversion process platform?* as well as SQ 3.3 *How do the energy product properties translate to process platform requirements?*

Section 0 concerns SQ 3.4 *How do the energy product properties translate to raw material platform requirements?*

4.1 The customers' need for green energy

Concerning SQ 3.1 Most of the industrial players and public institutions in Germany have committed to decarbonize their operations until 2030 through leveraging a myriad of renewable energy technologies such as solar, wind and hydro power (Pantaleo et al., 2014; Piterou & Coles, 2021; WCBSD, 2022).

Decarbonizing industrial heat supply represents the next big hurdle to achieve a secure and environmentally friendly energy supply. Many companies are likely to use a combination of energy sources to satisfy their industrial needs for renewable energy. The combination largely depends on market dynamics, availability of fuels and policies implemented by local governmental institutions. Also, public utilities have identified the decarbonization of their heat supply as an essential part of their strategies to become carbon neutral (Kaltschmitt et al., 2016; Pantaleo et al., 2014; Piterou & Coles, 2021; WCBSD, 2022).

One key technological solution includes "third party waste heat" as provided by the thermochemical conversion process of biomass. Being restricted by budgetary constraints and competing capital needs of different internal organizational projects, investment capital for low-carbon projects might be scarce, especially considering the current energy crisis. The market shows increased awareness for energy efficiency measures. Main hurdles for the implementation renewable energy projects are low availability of investment capital as well as limited know-how (EU-ESCO, 2021; Pantaleo et al., 2014, p. 239). In this regard, the company identified several customer needs regarding their energy supply referring to SQ 3.1 *Who are the customers the company currently serves with green heat, what are their main needs and how do these translate to product properties?*:

- Decoupling capital expenditure (CAPEX) from their decarbonization strategy. Customers aim to finance their heat supply through operating expenditure (OPEX), leading to an improvement in return on assets and capital employed by service contracts (Ziegner & Milla, 2022).
- Customers want to outsource the expertise to operate the new low carbon heat technologies. Consequently, know-how does not have to be developed in-house enabling a buying organization to increase focus on their own innovation projects (Ziegner & Milla, 2022).
- Long-term security of energy supply at competitive prices. Agreements are usually negotiated for suppliers enable to secure an thermal energy price stability over the long-term, and to realize immediate cost savings in markets in which the company as specialized thermal energy provider can leverage market conditions as well as technological know-how (Piterou & Coles, 2021; WCBSD, 2022; Ziegner & Milla, 2022).
- Customers further request high stability of the energy supply and demand base-load compliance for their district heating networks as well as their industrial processes (Ziegner & Milla, 2022).

4.2 Product family – Pyrolysis and green energy

The thermochemical conversion process of pyrolysis provides a viable and efficient approach for valorizing biogenic feedstocks, transforming them into sustainable energy in the form of heat and electricity (Mong et al., 2022). Despite its potential, pyrolysis processes generally achieve lower energy production compared to consumption due to various inefficiencies, including heat losses during the process, energy consumption of feedstock drying, the need for ex-situ preparation or modification of input materials, inefficient heating inside the reactor, and challenges in optimizing product and quality yield simultaneously (Mong et al., 2022). However, four distinct energy products can be generated through pyrolysis and peripheral modules, catering to customers' needs for reliability, cost-effectiveness, and sustainability (Li et al., 2019; Ziegner & Milla, 2022).

Pyrolysis-generated steam is a reliable, cost-effective, and sustainable energy product. Customers require a consistent and stable supply of steam without interruptions or variations in quality. Cost-effectiveness depends on the efficiency of the pyrolysis process, conversion rates, and operational costs. Pyrolysis offers a sustainable option for steam generation through integrating subsystems for product-related waste heat recovery. The success of this energy product will depend on the efficiency, cost, and environmental impact of the pyrolysis process, as well as the availability of reliable waste materials (Li et al., 2019; Ziegner & Milla, 2022).

In addition to steam, pyrolysis can generate warm water (70-90°C) and hot water (above 110°C), which can be utilized for various applications such as space heating and industrial processes. Customer needs for warm water and hot water are similar to those for steam, including reliability, cost-effectiveness, and quality. A reliable and consistent supply of warm water and hot water is crucial for customers, as any interruption in supply or variations in quality can cause significant disruptions to their operations. Additionally, customers seek warm water and hot water that are cost-effective and competitively priced compared to other available sources. Sustainability and environmental impact are also important considerations for customers, as they seek warm water and hot water that has a lower carbon footprint and lower emissions of pollutants and greenhouse gases. Pyrolysis can offer a more sustainable option for generating warm water and hot water, as it utilizes waste materials that would otherwise be discarded (Li et al., 2019).

Industrial and public customers further request the supply of renewable electricity as part of their decarbonization strategy for their energy supply. Electricity generated from pyrolysis is a reliable, cost-effective, and sustainable energy option for customers (Y. Yang et al., 2017). Reliability is crucial for consistent and stable supply, while cost-effectiveness depends on efficient conversion rates and operation costs. Sustainability considerations include lower carbon footprints and reduced emissions (Y. Yang et al., 2017). Pyrolysis utilizes waste materials that would otherwise be discarded, offering a more sustainable solution compared to fossil fuel-based sources. The success of this energy product is dependent on the efficiency of the pyrolysis process, availability of low-cost waste materials, and meeting customer demands. Depending on the pyrolysis system and reactor principle, electricity-integrated pyrolysis manufacturing systems can also supply this energy product (Y. Yang et al., 2017).

In summary, the product family for the energy component of the biochar business model comprises steam, warm water, hot water, and electricity. These products cater to customers' needs, focusing on reliability, cost-effectiveness, and sustainability. Efficient pyrolysis processes, waste material utilization, and integrated waste heat recovery systems are key factors in addressing these needs (Lehmann & Joseph, 2015; Li et al., 2019; Porshnov, 2022; Q. Yang et al., 2015). As the potential of pyrolysis-based waste processing methods becomes increasingly recognized, they can contribute to climate mitigation efforts, renewable energy grids, carbon-negative waste-to energy approaches, and the development of a circular economy (Lehmann & Joseph, 2015; Li et al., 2019; Porshnov, 2022). Harnessing the advantages of pyrolysis technology, energy producers can provide sustainable and cost-effective solutions for customers, resulting in reduced carbon footprints, minimized emissions, and optimized resource use (Guo et al., 2020; WCBSD, 2022; Y. Yang et al., 2017). Although the target customers of the company cannot yet be certainly differentiated Figure 12 provides a preliminary outline.

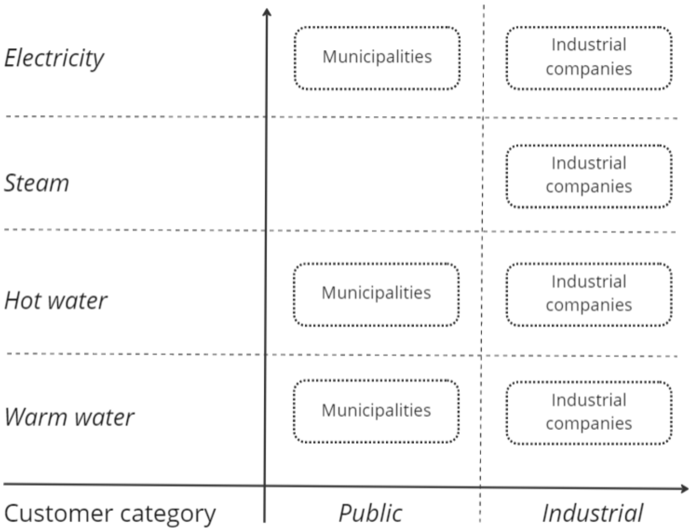


Figure 12 Service family green energy and market segmentation

4.3 Process platform – Green energy

Referring to SQ 3.2 *Which subsystems are relevant for an energy conversion process platform?"*, in case an energetical transformation of gaseous (or liquid) byproducts of the material transformation process is desired, either to sustain the material transformation process, support other subsystems (i.e., the feedstock preparation process of subsystem five (SUB_5)), or generate new energy products, subsystem three (SUB_3) responsible for the waste energy recovery is needed. Depending on the type of energy supply and the quality of the energy carrier (i.e., syngas, flue gas, exhaust gas, hot air etc.), some systems introduce subsystem four (SUB_4) as a preliminary step responsible for process stream cleaning, to increase the efficiency of the modules in subsystem three (SUB_3). Finally, subsystem seven (SUB_7) covers the emissions control of the whole system with either end of pipe solutions in form of exhaust gas filters or other process modules.

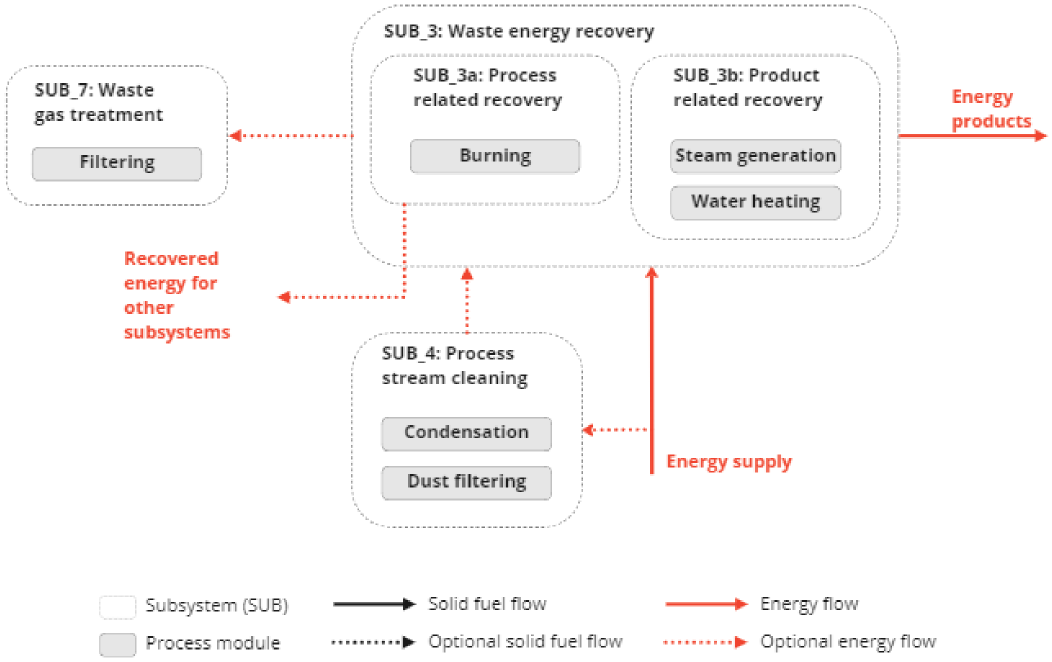


Figure 13 Process subsystems for renewable heat products own presentation adapted from Kaltschmitt (2019), Kaltschmitt et al. (2016) and Lehmann and Joseph (2015)

Answering SQ 3.3 *How do the energy product properties translate to process platform requirements?* the final energy products – steam, hot water, and warm water – impose a common set of requirements onto the process and raw material platform see

Table 8.

Table 8 Green energy - Requirements to process platform

Description	**Value**	**Unit**	**Remarks**
Energy carrier yield	↑	kW/h	The energy yield must be maximized.
Process reliability	↑	% (OEE)	Process reliability should be high, characterized by a high operating equipment efficiency (OEE).
Energy conversion efficiency	↑	%	The system should run as efficient as possible.
Conversion rate (gaseous fuel)	↑	%	Most of the biomass should be converted into gaseous fuel.

4.4 Raw material platform – Green energy

This section concerns SQ 3.4: *How do the energy product properties translate to raw material platform requirements?*

From an end-to-end perspective the product family for green energy influences the choice of input materials since these “ingredients” determine the quality and especially the yield of the final products. Essentially, only a few parameters are important for an underlying feedstock choice. The following requirements of the green energy product family are depicted in

Table 9.

Table 9 Green energy - Requirements to raw material platform

Description	**Value**	**Unit**	**Remarks**
High lower heating value (LHV)	↑	kW/kg	A high LHV of the feedstock is beneficial for a high energy yield(Y. Yang et al., 2017).
Low cost	↓	€/t	The material must be low cost (Y. Yang et al., 2017).
High availability	↑	t/a	The material must be widely available and not compete with other use cases(BMWK, 2022; Y. Yang et al., 2017).
Moisture content	↓	%	A low moisture content increases conversion efficiency and decreases cost (Ghodake et al., 2021; Ippolito et al., 2020).
Classification as waste material	-	-	According to the BMWK (2022).

4.5 Chapter summary

Answering SQ 3.1 the company's green heat products derived from waste heat serve industrial customers and public institutions in Germany committed to decarbonizing their operations through renewable energy technologies. The main needs of these customers are to decouple capital expenditure from the decarbonization strategy, outsource the expertise to operate new low carbon heat technologies, secure long-term energy supply at competitive prices, and ensure high stability of energy supply and demand base-load compliance for their district heating networks and industrial processes. The company's green energy value proposition model addresses these needs by providing service contracts and expertise to customers, while also maximizing energy yield for each system. The company offers three distinct energy products, warm and hot water, steam, and electricity with different temperature and flow requirements suitable for a variety of industrial applications. Industrial customers in different industries, including the food industry, chemical industry, and pharmaceutical industry, require varying amounts of energy in different forms.

The main subsystem relevant for the process platform is the energy recovery and conversion subsystem composed of product related energy recovery (for the final energy products) and process related energy recovery (for feedstock preparation or the thermochemical conversion process itself) which provides an answer SQ 3.2.

Answering SQ 3.3 the yield of the energy carrier, which is used for the energy product generation, process reliability, energy conversion efficiency, as well as the conversion rate of the gaseous fuel produced by the process need to be maximized.

The raw materials selected need to provide a sufficient lower heating value, must be low cost, classified as waste material, exhibit a low moisture content and be abundantly available, providing an answer to SQ 3.4.

5 Methodology & data collection

In the first part of the thesis, the theory of platform-based design for non-assembled products was applied to biochar systems. The theory's concepts support structuring products, underlying processes, and raw material selection. As stated in section 2.4 several evaluation criteria can be derived from the requirements to the integrated pyrolysis manufacturing systems established in the literature.

In this regard, evaluating and selecting the right manufacturing technology to meet operational and strategic objectives is a key competence to be developed by manufacturing companies. The purpose of technology selection is to generate strategic and operational value to the business in light of competitive dynamics and rapidly evolving market requirements, especially in new, highly innovative markets. Decisions need to be made with regard to a myriad of facets of a business (Chuang et al., 2009). The goal of technology selection is to process information regarding different potential technology alternatives and to ultimately make a choice for an investment and the adoption of a new technology respectively. This implies making trade-offs in light of a company's different strategic and operational objectives (Hamzeh & Xu, 2019).

In line of this, this chapter aims to address sub-research questions SQ 4 and SQ 5.1 – SQ 5.4 with sections 5.1-5.5 concerning the selection of an appropriate technology selection method, its principles and the arrangement of selection criteria in a decision hierarchy in section 5.3.

Section 5.6 covers SQ 5.2 *Which alternatives are subject to selection and how were they chosen?,* SQ 5.3 *How are the different alternatives configured?,* and SQ 5.4 *What are the benefits of each type of alternative?*

Section 5.7 concludes with a short summary of the findings.

5.1 Choosing a selection methodology

Concerning SQ 5.1 according to Shehabuddeen et al. (2006, p. 325), "technology selection involves choosing a technology that a firm views as most suitable based on the consideration of its technological, organizational, and business environments". Organizational complexity, dynamism of the business environment and the myriad of complex technological options support the need for a company specific technology selection method that allows for direct operational application in the field (Farooq & O'Brien, 2012; Farooq & O'Brien, 2007; Shehabuddeen et al., 2006).

To determine the most feasible manufacturing technologies satisfying the objectives of the company several multi criteria decision making (MCDM) approaches can possibly be used. Due to the nature of the business problem explained above, i.e., the fact that Company X must evaluate and select the most appropriate technology from a finite and explicit set available on the market, this literature review focuses on multi attribute decision making (MADM) as part of MCDM.

To determine the most feasible selection and evaluation method, as recommended by scholars from the University of Twente, 212 different publications from the Journal of Cleaner Production were screened for the keywords "pyrolysis AND multi-attribute decision making OR MADM". Most of these publications rely on sophisticated hybrid decision making methodologies. Only twelve of these articles concern pyrolysis technology, with two focusing on altering the properties of the final product (Xu et al., 2022; Yousef et al., 2021) one on fast pyrolysis (Rodríquez-Machín et al., 2021), two on fuzzy MCDM (Alao et al., 2022; Mousavi et al., 2022) (Alao et al., 2022; Mousavi et al., 2022), three apply life cycle analysis (LCA) (Lu & El Hanandeh, 2019; Shearian Sattari et al., 2022; Teoh & Li, 2020) (Lu & El Hanandeh, 2019; Shearian Sattari et al., 2022; Teoh & Li, 2020), one compares different MCDM approaches (Zabaniotou et al., 2018), two are techno economic assessments (Afrane et al., 2021; Diehlmann et al., 2019), and one applies the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Baranitharan et al., 2019) method. None of the publications focused on processing commercial data of leading pyrolysis technology suppliers or establishing selection criteria for integrated manufacturing systems nor do they apply a platform-based design perspective to the respective research matter.

According to Hamzeh and Xu (2019) we can differentiate between *single* and *hybrid* MADM approaches for solving a technology selection problem. Single approaches try to leverage one methodology. Most commonly used single method approaches are briefly explained in the following.

Analytical hierarchy process (AHP) is a decision-making tool that takes an Eigen value approach to the pairwise comparison of alternatives and allows to establish a numeric scale for quantitative as well as qualitative data. The process also allows for further combination with other methods as will be explained later (Vaidya & Kumar, 2006).

Data envelopment analysis (DEA) allows for the measurement of the relative efficiency of decision-making units with multiple inputs and outputs. Although it can be classified as a linear programming method, several studies have used this method for purposes of technology selection (Hamzeh & Xu, 2019).

Application of *fuzzy logic* in technology selection processes enables to handle vagueness and ambiguity regarding imprecise information available for a set of attributes (i.e., about purchasing cost, operating cost, disposal cost etc.) and most importantly human judgement. The approach uses fuzzy membership functions to account for these issues (Hamzeh & Xu, 2019; Kafuku et al., 2019; van de Kaa et al., 2014).

Concepts of *financial analysis* such as discounted cash flow (DCF), net present value (NPV) or internal rate of return (IRR) are commonly seen in technology selection studies and an integral part of the majority of problem approaches due to the importance of including an economical perspective (Hamzeh & Xu, 2019).

Finally, *mathematical programming* (also multi-objective optimization, multi-objective programming, multi-attribute optimization) is used to formulate a technology selection problem with the help of objective functions that need to be optimized. These are usually minimization or maximization problems (Hamzeh & Xu, 2019).

Since most of the technology selection problems impose an interdisciplinary challenge on industrial managers the methods applied to solve such problems also need to take an interdisciplinary approach. (Hamzeh & Xu, 2019). The final method to be selected should enable to ratings introduced by stakeholders have the ability to process quantitative as well as qualitative data (technical requirements and intangible factors like the reputation of a supplier) and help to objectify the subjective data gathered from experts. Accordingly, the technology selection methods presented above are subjected to the set of criteria:

- Deal with missing information,
- Process quantitative and qualitative data,
- Process data objectively,
- Allow for stakeholder input,
- Allow for inclusion of several factors,
- Allow for establishment of a decision hierarchy

Table 10 shows a selection of different technology selection approaches and evaluation criteria. As Table 10 suggests, either the application of the analytical hierarchy process (AHP) or fuzzy logic appear to be the most feasible alternatives as applicable method for the technology selection problem. A combination of the two methodological approaches as hybrid approach might be feasible. However, since the AHP is already deemed fuzzy while still providing sufficient operational use to the stakeholders a fuzzification of the selection problem results in a “black box” approach causing a low acceptance of the solution by the decision makers. It effectively captures key aspects of platform-based design theory for non-assembled products like biochar. It allows for the prioritization of criteria, enabling stakeholders to assign relative weights to the respective criteria. Stakeholders evaluate alternative technologies through pairwise comparisons, considering efficiency, output quality, process complexity, and feedstock requirements. Trade-off analysis is facilitated, enabling stakeholders to make informed decisions based on their preferences. Consensus building is supported by AHP, fostering inclusive discussions among stakeholders from different domains. Quantitative outputs in the form of priority weights for criteria and alternatives facilitate ranking and selection of the most suitable technology. Sensitivity analysis assesses the robustness of results. AHP's structured approach and multicriteria analysis are beneficial, but it may not capture the full complexity of platform-based design theory. For this reason, the AHP is chosen with a subsequent sensitivity analysis according to Triantaphyllou and Sánchez (1997) and a thorough investigation of the scales chosen for the different criteria.

To deal with missing data, a pitfall of the AHP, literature values or industry averages are used and applied to the respective alternatives selected in case only limited data is made available by suppliers.

Table 10 Technology selection methods and evaluation criteria

Technology selection methods	Deal with missing information	Process qualitative data	Process quantitative data	Process data objectively	Allow for stakeholder input	Allow for inclusion of several factors	Establish decision hierarchy	Source
Analytical hierarchy process (AHP)		X	X	X	X	X	X	Vaidya and Kumar (2006) Hamzeh and Xu (2019) R. W. Saaty (1987)
Data Envelopment Analysis (DEA)		X	X	X	X			Hamzeh and Xu (2019) Dutta et al. (2022) Vörösmarty and Dobos (2020)
Fuzzy Set Theory	X	X	X	X	X	X		Hamzeh and Xu (2019) Simić et al. (2017)
Financial Analysis (FA)			x	X				Hamzeh and Xu (2019)

Mathematical programming (MP)			X	X				Hamzeh and Xu (2019) Ocampo et al. (2018)
Technique for order preference by similarity to ideal solution (TOPSIS)			X	X	X	X		Hamzeh and Xu (2019) Panda and Jagadev (2018)
Preference Ranking Organization Method for Enrichment Evaluations (Promethee I/II)		X	X	X	X	X		Hamzeh and Xu (2019) Abdullah et al. (2019)
Quality Function Deployment (QFD)		X	X	X	X			Oliveira et al. (2020) Lager (2017)

5.2 Principles of the AHP

The analytical hierarchy process (AHP) allows for the systematic and sequential elicitation of individual preferences for certain choice criteria as well as their subsequent evaluation with the use of a mathematical procedure. In structured interviews or surveys, participants are asked to choose which of two criteria they believe to be more essential and by how much compared to the other criterion. The outcomes of all pairwise comparisons performed in this manner serve as the foundation for deriving the so-called principal eigenvectors or eigenfunctions using matrix algebra. Inferred from the preferences represented in the assessments of the pairwise comparisons, the weights for each of the choice criteria included in a hierarchy level make up the right eigenvector. The pairwise comparisons must be performed after developing a decision hierarchy in accordance with the AHP process approach. The decision goal, the decision criteria (at various levels) including sub criteria which are subdivisions of the criteria, and finally the alternatives from which a choice is to be made at the lowest level are included in the decision hierarchy (see Figure 14).

According to R. W. Saaty (1987) and T. L. Saaty (2008) main steps of the AHP include the following:

1. Conceptualize the decision based on a hierarchy.
2. Construct a set of pairwise comparisons.
3. Determine the consistency of the pairwise comparisons.
4. Calculate the weight vectors.
5. Calculate the principal eigenvector for each alternative.

Step 1: Conceptualize the decision based on a hierarchy.

A decision hierarchy enables the structural composition of the decision problem. Figure 14 illustrates a sample hierarchy composed of goal level with including the overall decision target, a criteria level with the main decision criteria C_j, sub-criterial level and finally alternative level including all relevant alternatives. As indicated, the hierarchy as well as selection of alternatives could potentially be extended.

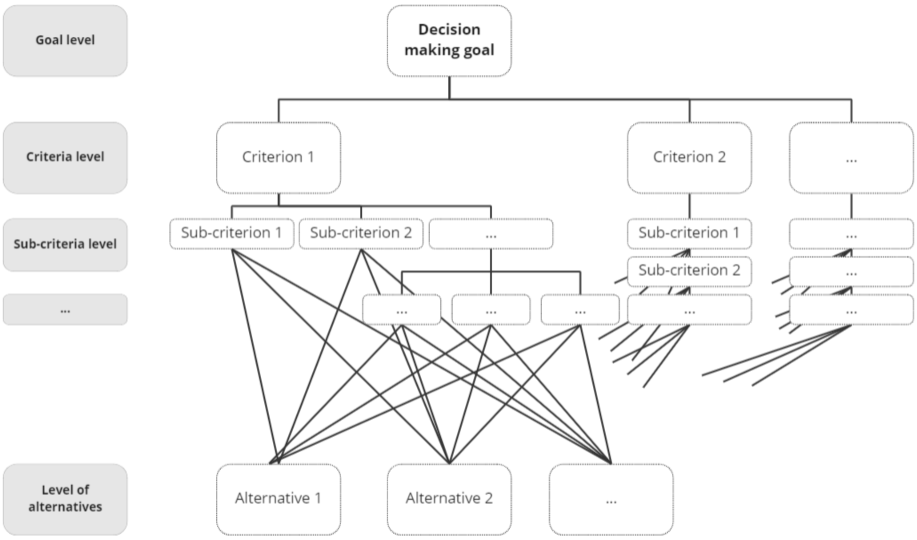


Figure 14 Example hierarchy of the AHP adapted from R. W. Saaty (1987)

On the same hierarchical level, decision criteria should be precisely specified, mutually exclusive (free of redundancy) on a hierarchical level, thorough, and comparable to one another.

A precise specification of the criteria is required to avoid irritation and conceptual distortion in the decision-making process. Furthermore, decision-makers need to comprehend the criteria easily.

The goal is to achieve a complete mapping of the decision situation. The nature of criteria can vary between, fixed achievement criteria, i.e., striving for a precisely fixed value, satisfaction criteria, i.e., striving for a minimum deviation to a target value, object maximization criteria, and object minimization criteria T. L. Saaty (1994).

Before processing the raw criteria data with the AHP, it needs to be normalized by means through setting up utility functions for the criteria which can follow different distributions. The data is normalized according to the procedure described in chapter 6.3.

Step 2: Construct a set of pairwise comparisons.

After the decision hierarchy has been established, using Saaty's fundamental scale of absolute numbers (see

Table 11), all criteria on a hierarchy level are contrasted with one another.

Using pairwise comparison matrices that depict all paired comparisons, preferences are quantified based on the specified decision structure. The pairwise comparisons show how important each criterion is in relation to the others. The related values enter numerically into the matrices and subsequent matrix calculations, even though the individual comparisons are assessed on an ordinal scale (see

Table 11). Table 12 shows a sample pairwise comparison matrix $A = a_{ij}$ with n decision criteria.

Table 11 Saaty's fundamental scale of absolute numbers (R. W. Saaty, 1987; T. L. Saaty, 1994, 2008)

Intensity of importance on an absolute scale	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement favor one activity over another
5	Essential or strong importance	Experience and judgement favor one activity over another
7	Very strong importance	An activity is strongly favored, and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	
Rationals	Ratios arising from the scale	If consistency were to be forced when obtaining n numerical values to span the matrix

Table 12 Sample pairwise comparison matrix according to R. W. Saaty (1987) and T. L. Saaty (2008)

Decision criterion	Criterion 1	Criterion 2	…	Criterion n
Criterion 1	a_{11}	a_{12}	…	a_{1n}
Criterion 2	a_{21}	a_{22}	…	a_{2n}
…	…	…	…	…
Criterion n	a_{n1}	a_{n2}	…	a_{nn}

The established pairwise comparison matrices enable to calculate the priorities for the different criteria by either raising the matrix to large powers and summing each row and dividing each sum by the total sum of all the rows or approximately by adding each row of the matrix and dividing by their total.

Since the matrices conform to principles of reflexivity ($a_{ij} = 1$ for i = j along the diagonal) and reciprocity ($a_{ij} = 1/a_{ij}$) one enters the whole number in its appropriate position and adds the reciprocal in the transpose position resulting in a total of (n*(n-1) / 2) pairwise comparisons for n decision criteria.

Step 3: Determine the of consistency of pairwise comparisons.

An essential condition for successful execution of the decision-making process is a high degree of consistency in pairwise comparisons. For each group of pairwise comparisons, a consistency measure must be calculated indicating the consistency of the ratings given by the decision makers involved in the process. This, so-called consistency ratio (CR) determines whether the individual pairwise comparisons are consistent compared with the rest of the comparisons, satisfying the transitivity criterion (i.e., If A is preferred to B and B is preferred to C, then A is preferred to C. Specifically, if A is three times as preferable as B and B is three times preferable as C, then A is nine times preferable as C) (Ji & Jiang, 2003). λ_{max}, the maximum eigenvector value of the pairwise comparison matrix is the basis for the consistency ratio. λ_{max} is always equal or greater than n for positive reciprocal matrices if the matrix is consistent. Through normalizing the maximum eigenvector to the size of the matrix Saaty derives the consistency index (CI)

$$CI = \frac{(\lambda_{max} - n)}{n - 1}$$

Subsequently, the average CI of 500 different randomized matrices is generated, resulting in the randomized index (RI). The CR is calculated by dividing the respective CI of a matrix by the RI to determine to what extent the generated pairwise comparison matrix deviates from a randomly generated pairwise comparison matrix. CR is calculated as follows:

$$CR = \frac{CI}{RI}$$

A deviation of 10%, i.e., CR ≤ 0.1 is regarded as sufficient, taking into consideration that subjective ratings conducted by humans can never be 100% consistent. A measure of less than 10% is still acceptable according to Saaty.

Step 4: Calculate the weight vectors.

With the help of the maximum eigenvalue λ_{max} the weight vectors w_i, indicating the importance of the different criteria are calculated:

$$w_i = \frac{\sum_{j=1}^{n} a_{ij} \times w_j}{\lambda_{max}} \; for \; all \; i = 1, 2, \dots, n$$

The eigenvector computation may be thought of as a straightforward average calculation, where the weights produced represent the average of all potential comparisons of the criteria with one another. The eigenvector that represents the weights for the criteria can be obtained by a variety of calculating techniques. Saaty (1994) further explains different methods.

Because several decision makers are involved in the AHP, the individual preferences of the need to be aggregated to determine a mean. Forman and Peniwati (1998) differentiate between the aggregation of individual judgements (AIJ) and the aggregation of individual priorities (AIP). The authors argue that in case the individuals function as a unit the AIJ is to be used whereas in case the individuals are considered as separate individuals the latter is the appropriate mode for aggregation. The focus of this section is on the AIJ, since in this case the decision makers have to function as unit and aggregate their judgements for the sake of the company resulting in a “synergistic aggregation of individual judgements” (Forman & Peniwati, 1998, p. 166). In such an event, the geometric means must be used to aggregate the group’s priorities. Although individual identities are lost when the hierarchy is synthesized, they are preserved for each cluster of criteria when a judgment is made. When there are too many inconsistencies in a person's collection of judgements, the group may urge them to think about modifying one or more of their conclusions. Based on the inconsistency ratio, the group may also choose to exclude a particular person's judgements from the geometric average for a cluster of criteria. Applying the geometric mean to the AHP, the cells of the pairwise comparison matrices are filled with the geometric mean of the ratings of x persons involved:

$$a_{ij} = \left(a_{ij(1)} \times a_{ij(2)} \times \dots \times a_{ij(x)}\right)^{\frac{1}{x}} \; for \; all \; i = 1, 2, \dots, n$$

To determine the overall performance measure of an alternative as an ultimate step the determined weight vectors are multiplied with the normalized vector of expression of each alternative for the criteria. Accordingly, the performance of the alternatives culminates in a single performance value or an overall “score” enabling the decision maker. The performance value (P_i) is calculated according to the following formula:

$$P_{\mathrm{i}} = \sum_{j=1}^{n} a_{ij}\, x \times W_j\ for\ all\ i = 1, 2, \dots, n$$

with W_j the weight of criterion C_j, and a_{ij} the performance measure of alternative A_i with respect to criterion C_j.

5.3 Selection criteria

Answering the sub-research-question SQ 4 *Which are the selection criteria imposed by the company's high variety strategy on potential technology alternatives?* based on the requirements established to the process platform and raw material platform, and the aspect of cost-optimization, the following selection criteria serve for evaluation of the alternatives for both production platforms. The criteria were retrieved from literature and are not exhaustive (see Table 13). These are mostly technical criteria as according to Shehabuddeen et al. (2006) and retrieved from the literature about pyrolysis technology and the resulting products. However, the company executives expressed the need for further including the suppliers' maturity in an investment decision expressed by a supplier's pursuit for innovation, reputation and experience with setting up industrial size plants (Knizia, 2023). The so-called "pressure[…]" factors as mentioned by Shehabuddeen et al. (2006), i.e., the compliance with environmental and regulatory standards is considered in a pre-liminary selection of the suppliers (see chapter 0). If suppliers do not comply, they are not taken into consideration.

While the following selection criteria consider the factors described above, it does not include internal requirements for adoption of a technology such as amount of training required as according to Shehabuddeen et al. (2006), because according data was not made available by suppliers. An overview of the selected alternatives expression for each criterion can be found in appendix C.

Table 13 Selection criteria overview

Criterion	**Biochar Production platform for soil amendment**			
LV1 Sub-criterion	Carbon Sequestration performance			
LV1 Sub-criterion	CORC factor (max)	Unit: unitless	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	The CO2 removal certificate (CORC) according to the puro.earth methodology was chosen as being representative for the carbon sequestration potential to be possibly achieved with a respective system configuration of a technology alternative. This factor considers a full LCA from a cradle to grave perspective covering raw materials extraction, raw materials logistics, conversion to biochar, biochar logistics, and biochar end use. In case an LCA was available for the respective supplier, data was calculated. Although only the conversion to biochar would be the most interesting part of the CORC, this data was not sent by the contacted suppliers although requested. Only the CORC factor could be provided.			
LV1 Sub-criterion	Biochar product performance (max)			

Description	The biochar product performance relates to the different functionalities of the final biochar product. These functionalities were selected according to the ones requested by the final customers as described in chapter 3.2.			
LV2 Sub-criterion	Water holding capacity (max)	Unit: %	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	The water holding capacity (WHC) is an essential final product functionality requested by the main customers of the company and relevant for all applications in soil. The higher the WHC, the better.			
LV2 Sub-criterion	Stability in soil (min)	Unit: unitless	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	The stability in soil is highly relevant for the biochar application in soil as well as the carbon sequestration. It is expressed with the H/C_{org} ratio, i.e., the ratio between molar hydrogen and organic carbon content (Schimmelpfennig & Glaser, 2012). The lower the ratio, the higher the stability.			
LV2 Sub-criterion	Carbon sequestration potential (max)	Unit: %	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	The inherent carbon content stored in the final carbonaceous biochar product is a proxy for the carbon sequestration potential of the biochar. The higher, the better. Although a lot of environmental factors influence the feedstock condition and hence final product properties, the input materials considered for comparison of the alternatives are wood based with a high lignin content and hence comparable carbon contents.			
LV1 Sub-criterion	Manufacturing capability (max)			
Description	The manufacturing capability of an integrated biochar manufacturing system depends on several factors. Output and conversion related factors, the overall availability of the plant, and the process conditions. Process conditions are further divided into temperature and residence time ranges possible with a respective system, which are the most influential processing parameters on final product quality (see chapters 3 and 4).			
LV2 Sub-criterion	Biochar output (max)	Unit: kg/h	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	The biochar output is connected to the feeding rate and conversion rate of the reactor. The effect of the feeding rate on the process is largely determined by the reactor configuration, especially its size (Dhyani & Bhaskar, 2019; Soria-Verdugo, 2019). The biochar output per hour indicates the speed to which extend biochar can be manufactured at the optimal process conditions for highest carbon content yield in the final carbonaceous product. Optimal			

	treatments temperatures and residence times as suggested by the respective supplier are considered for this metric.			
LV2 Sub-criterion	Biochar conversion rate (max)	Unit: %	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	The biochar conversion rate, i.e., the conversion rate to solid carbonaceous fuel is an indicator for the effectiveness of the process, i.e., whether most of the energy stored in the wooden feedstock material is converted into solid or gaseous fuel. The higher the ratio, the better.			
LV2 Sub-criterion	Plant availability (max)	Unit: %	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	Plant availability is important for biochar production as well as for the generation of green energy products and indicates the percentage of planned production time in which a machine produced.			
LV2 Sub-criterion	Process adaptability			
Description	Process adaptability describes the possibility to tailor process parameters in order to achieve the best biochar quality for the respective application. The two most influential process parameters are residence time and temperature (Allohverdi et al., 2021; Dhyani & Bhaskar, 2019; Lehmann & Joseph, 2015; Raza et al., 2021; B. Singh et al., 2014; C. Wang, 2021).			
LV3 Sub-criterion	Treatment temperature range (max)	Unit: °C	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	As treatment temperature is one of the most influential factors, a great range of different treatment temperatures possible with the respective reactor configuration allows for tailoring the final product according to the respective soil application to the best extent (see chapter 3). Reactor temperature is one of the determining process parameters largely affecting the yield of the different pyrolysis products, as already indicated above. The thermal energy available in the reactor is a function of the reactor temperature. A higher temperature can be beneficial for the solid fuel produced, as lignin decomposes over a wide temperature range. Higher temperatures favor increased thermal cracking of hydrocarbons which is beneficial for liquid and gaseous yield. However, the temperature for maximum yields is always depending on the biomass composition and other parameters (Dhyani & Bhaskar, 2019; Raza et al., 2021; Soria-Verdugo, 2019).			
LV3 Sub-criterion	Residence time range (max)	Unit: min	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	Residence time is the amount of time the biomass is subjected to the thermochemical transformation process. A great range of residence times			

	possible with the respective reactor configuration allows for tailoring the final product according to the respective soil application to the best extent. The residence time determines the yield distribution of the final products. Short residence times, favor the generation of liquid fuels. Long residence times are beneficial for solid fuels such as biochar due to the possibility for secondary char formation induced by the pyrolysis vapors. Research suggests that pyrolysis systems could be classified solely through the residence time of pyrolysis vapors. This residence time can be calibrated through the inert gas flow inside the reactor that guarantees the absence of oxygen. Increasing the inert gas flow results in a shorter residence time. Nitrogen (N) is usually used due to its inert characteristics, low cost and high availability (Dhyani & Bhaskar, 2019; Raza et al., 2021; Soria-Verdugo, 2019).			
LV2 Sub-criterion	Raw material capabilities			
Description	Depending on reactor configuration, different raw materials can be processed. A high material processing capability delivers to the company's high variety strategy about biochar products. Particle sizes, moisture content as well as experience with input materials cater to the raw material capabilities (Bridgwater, 2019; Dhyani & Bhaskar, 2019; Muzyka et al., 2023).			
LV3 Sub-criterion	Particle sizes possible (max)	Unit: mm	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	The heat reactions inside the reactor are influenced by the particle size of the feedstock. A coarser particle size promotes biochar production due to the higher temperature difference between the inner and outer layers of the particle. Additionally, the vapors forming during the process must travel longer distances through the char layer reinforcing its build-up. Small particle sizes of the input material are preferred to prevent bridge building while feeding the material into the reactor. On the other hand, excessively fine parts are suboptimal because they could be removed from the reactor through the inert gas flow used to adapt the residence time. Smaller particle sizes can result in higher gas yield and lower char and tar formation. Depending on the reactor type, different particle sizes are eligible for processing. Additionally, the economic perspective regarding feedstock preparation needs to be considered as well (Dhyani & Bhaskar, 2019; Raza et al., 2021; Soria-Verdugo, 2019). The bigger the particle sizes which can possibly be processed with a reactor configuration, the less material preparation required in terms of particle size reduction and the lower the price of the (wooden) feedstock material and the cost spent on material preparation (Werdin et al., 2021).			
LV3 Sub-criterion	Moisture content possible (max)	Unit: %	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	Depending on the heating principle and reactor configuration, different maximum moisture contents for the feedstock material are possible. The higher the maximum moisture content while still operating efficiently the			

	better. An initially lower moisture content benefits the yield of the solid product required (Demirbas, 2004).			
LV3 Sub-criterion	Experience with input materials (max)	Unit: unitless	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	Experience with input materials means the amount of different input materials a supplier has already processed at an industrial scale for commercial purposes. The criterion follows a linear distribution.			
LV3 Sub-criterion	Material processing capability (max)	Unit: low, medium, high	Scale level: ordinal	Source: determined by stakeholders
Description & operationalization	Depending on the reactor configuration, an integrated pyrolysis manufacturing system has different material processing capabilities for the process to run efficiently. Some reactors are attuned to one specific biomass whereas other others could potentially be used for a great variety of feedstocks (i.e., inorganic feedstock materials) (Uddin et al., 2018).			
LV3 Sub-criterion	Minimum lower heating value required (LHV) (min)	Unit: MJ/kg	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	The LHV, also referred to as calorific value or energy value of a fuel, is the amount of heat generated during the combustion of a specified unit of that fuel. It is measured in energy over mass of fuel or energy over volume of fuel. Depending on the reactor configuration a minimum lower heating value is required for efficient performance of the manufacturing system. The lower this heating value the better for the feedstock selection, due to opening up more possibilities (Raveendran & Ganesh, 1996).			
Criterion	**Production platform green energy**			
	Although the main products of the production platform for green energy are steam, hot water, warm water and electricity, only the heat available from the manufacturing process is the determinant for the heat products, as well as the electricity yield (Raveendran & Ganesh, 1996; Walmsley et al., 2019; Y. Yang et al., 2017).			
LV1 Sub-criterion	Heat yield (max)	Unit: kW	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	The heat yield in combination with the energy carrier is the determinant for subsequent yield of any thermal energy product, whether steam, hot water, warm water (Kaltschmitt, 2019; Raveendran & Ganesh, 1996; Y. Yang et al., 2017).			

LV1 Sub-criterion	Electricity yield (max)	Unit: kW	Scale level: metric	Source: retrieved from supplier data
Description & Operationalization	Each one of the integrated pyrolysis manufacturing systems has a different electricity yield. Some might be able to only satisfy their own demand, others might be able to deliver additional electricity to the customer.			
LV1 Sub-criterion	Product capability (max)	Unit: low, medium, high	Scale level: ordinal	Source: expert input
Description & operationalization	Depending on the energy carrier used for generation of energy products as well as the reactor configuration the capability of a system to produce green energy products is limited since the energy carrier (syngas or fluegas) might have limited usability for the generation of respective products. Fluegas for example can only be used for the generation of heat products whereas syngas can be converted into electricity and green heat products as well (E. Macchi, 2017). Low product capability = 1/3 energy products (heat, steam, electricity) Medium product capability = 2/3 energy products High product capability = 3/3 energy products			
Criterion	**Supplier maturity**			
	Especially in this novel and growing market for biochar suppliers, maturity is an essential factor for a manufacturing company who leverages technology for the production and development of the mentioned products. Experience in the market, a supplier’s pursuit for innovation and its market reputation are determining factors.			
LV1 sub-criterion	Experience in the market (max)	Unit: unitless	Scale level: metric	Source: retrieved from supplier data
Description & operationalization	Experience in the market is operationalized by the number of plants a supplier has already established on an industrial (not pilot) scale. It can be expected that with the increasing age of a supplier the marginal returns for experience per new plant constructed decrease over time. However, due to the nascent stage of the market this criterion follows a linear distribution.			
LV1 sub-criterion	Pursuit for innovation (max)	Unit: unitless	Scale level: metric	Source: retrieved from patent databases
Description & operationalization	An indicator for a supplier’s pursuit for innovation is its patent output. The higher the patent output for the core technology and products that can potentially be developed in the biochar market, the better (Pavitt, 1982; Ponta et al., 2021) This criterion also follows a linear distribution.			
LV 1 sub-criterion	Market reputation (max)	Unit: low, medium, high	Scale level: ordinal scale	Source: expert input

Description & operationalization	Market reputation is generally an abstract construct. Resulting from the impressions the different internal company experts gained from trade fairs and meetings with respective suppliers and their other customers, the market reputation is operationalized with an ordinal scale ranging from low over medium to high (Ziegner & Milla, 2022).			
Criterion	**Financial performance**			
Description	As the goal of the company is to also select the most profitable integrated pyrolysis manufacturing system financial performance is another criterion.			
LV1 Sub-criterion	Cost per unit of biochar (min)	Unit: €/t	Scale level: metric	Source: calculated
Description & operationalization	Cost per unit of biochar is calculated based on the ratio of energy yield in the form of solid fuel (i.e., biochar) and gaseous fuel (i.e., syngas or flue gas). Assessing the cost per unit allows you to see the cost of producing one unit of the product, which can be useful for evaluating the efficiency of the technology. It takes into account production costs and can help to identify areas to reduce costs. Moreover, it can help to optimize production processes and identify areas to increase efficiency.			
LV1 sub-criterion	Cost for energy			
Description	Cost for energy can be separated into the costs per unit of heat and unit of electricity.			
LV2 sub-criterion	Cost per unit of heat (max)	Unit: €/kWh	Scale level: metric	Source: calculated
Description & operationalization	Cost per unit of heat is based on the ratio between the energy yields for heat and electricity. First the costs are separated according to the ratio between solid and gaseous fuel yield. Subsequently, the costs for gaseous fuel yield are further separated based on the ratio of the heat yield and the electricity energy yield. This serves as an approximation since specific actions of the operators cannot be assigned to energy conversion rendering an action-based costing difficult and not feasible at the moment.			
LV2 sub-criterion	Cost per unit of electricity (max)	Unit: €/kWh	Scale level: metric	Source: calculated
Description & operationalization	Cost for electricity is based on the ratio between the energy yields for heat and electricity. First the costs are separated according to the ratio between solid and gaseous fuel yield. Subsequently, the costs for gaseous fuel yield are further separated based on the ratio of the heat yield and the electricity energy yield.			
LV2 sub-criterion	Initial investment (min)	Unit: €	Scale level: metric	Source: retrieved from supplier data

Description & operationalization	The amount of initial investment necessary for a respective alternative is oriented towards the number of reactors the company would consider regarding their growth plans and volumes of their distribution network for the final product of biochar. Different numbers of machines would be purchased based on their performance in terms of biochar and energy output.			
LV2 sub-criterion	Payback period (min)	Unit: a	Scale level: metric	Source: calculated
	The term payback period refers to the amount of time it takes to recover the cost of an investment. In simple words, it is the length of time an investment reaches a breakeven point. Shorter payback periods mean more attractive investments while longer payback periods might be less favorable.			
LV2 sub-criterion	Return on investment (RoI) (max)	Unit: %	Scale level: metric	Source: calculated
Description & operationalization	Return on investment (ROI) is a performance metric used to assess an investment's efficiency or profitability or to contrast the efficiency of several investments. ROI aims to quantify the amount of return on a certain investment in relation to the cost of the investment. For each alternative the internal rate of return is calculated additionally to determine the annual rate of growth the investment is expected to generate.			

5.4 AHP Decision Hierarchy

The decision hierarchy in Figure 15 adopts the criteria established in the previous section. Some of the criteria established in the sections about requirements to the process platforms and raw material platforms are omitted from this hierarchy and only indirectly represented, such as the cation exchange capacity of the supplier biochars, particle size distribution, functionality, PH value, and ash content. This facilitates conducting pairwise comparisons for the stakeholders. Furthermore, the respective data for the criteria was not made available by the suppliers.

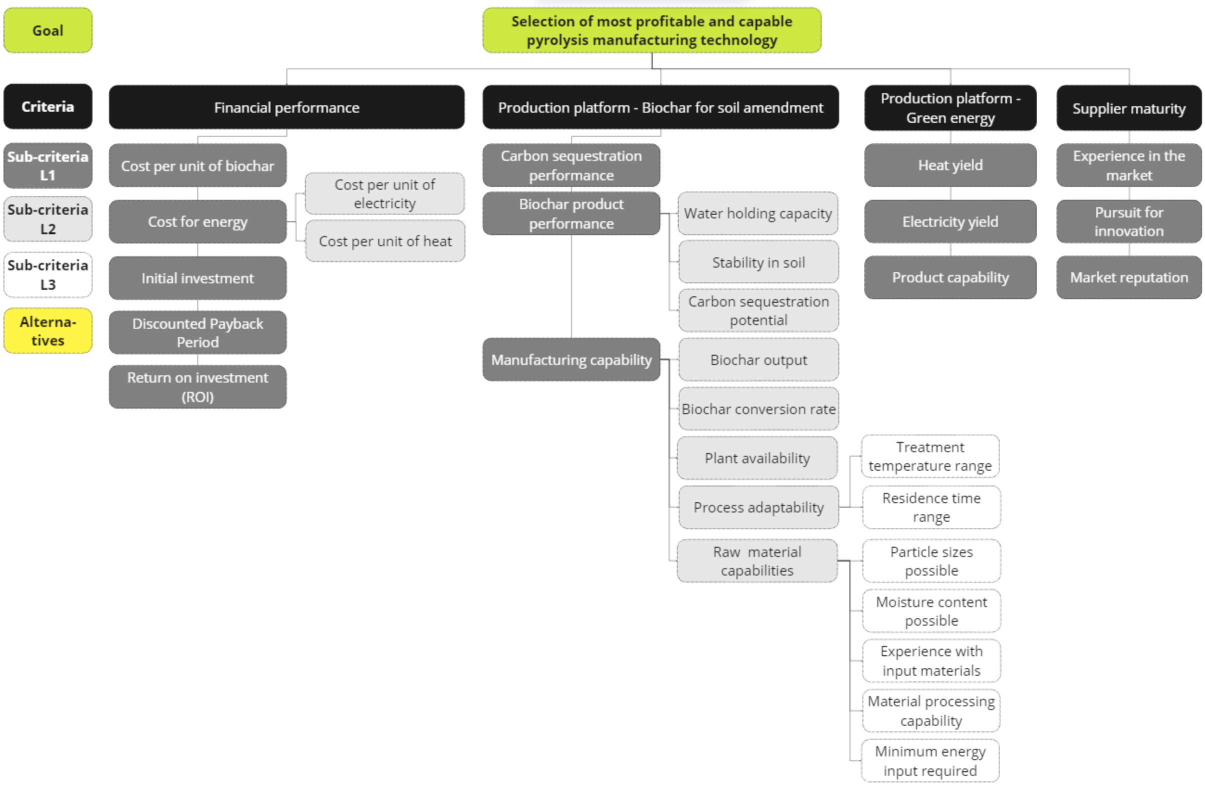


Figure 15 AHP decision hierarchy used in selection problem

5.5 Sensitivity analysis

To determine the AHP model's robustness, the author conducted a sensitivity analysis according to Triantaphyllou and Sánchez (1997) and determined the most critical criteria and the most critical measure of performance that potentially lead to a rank reversal if changed (Barzilai & Golany, 1994).

The *most critical criterion* is defined as the criterion C_k, with the smallest change of the current weight W_k by the amount of δ_{kij} changing the ranking between the alternatives A_i and A_j whereas the most critical measure of performance is defined as the minimum change of the current value of a_{ij} such that the current ranking between alternative A_i and A_j will change.

According to Triantaphyllou and Sánchez (1997) the define P_i as the final preferences for an alternative, i.e., its overall performance value as explained in chapter 5.2.

With the performance values normalized

$$\sum_{j=1}^{n} a_{ij} = 1$$

for the most critical criterion the authors suggest calculating

$$\delta_{kij}\left(W_k, A_i A_j\right) = \frac{P_j - P_i}{a_{jk} - a_{ik}} \ with \left|\delta_{kij}(W_k, A_i A_j)\right| \leq W_k$$

For the most critical measure of performance, for all alternatives A_i and A_j with i ≠ j and each criterion we calculate

$$\delta_{kij}\left(W_j, a_{ki} a_{ij}\right) = \frac{P_i - P_k}{P_i - P_k + W_j(a_{kj} - a_{ij} + 1)} \ with \left|\delta_{kij}(W_j, a_{kj}, a_{ij})\right| \leq W_j$$

The sensitivity analysis further analyses the outcome of the AHP model through financial moderator variables like the raw material price oriented towards the price index for energy wood (Carmen e.V., 2023), the biochar sales price oriented towards the current expectation of the company (Ziegner & Milla, 2022) , the carbon removal certificate sales price oriented towards the CORCCHAR index (puro.earth, 2023) , the heat sales price oriented towards the German price index for heat (DESTATIS, 2023b) and the electricity sales price oriented towards the German natural gas and electricity prices (DESTATIS, 2023a).

5.6 Pyrolysis technology & alternatives

After introducing the reader pyrolysis technology, its functionality, and key principles as well as process parameters, with a focus on the subsystems SUB_2, the material transformation and SUB_3 the waste energy recovery from the material transformation process (see Figure 16) this section of chapter 5 provides an overview on how and which types of technology alternatives were selected and answers sub-research question SQ 5.2 *Which alternatives are subject to selection?* and explains their configuration as well as benefits on a scientific basis answering SQ 5.3.

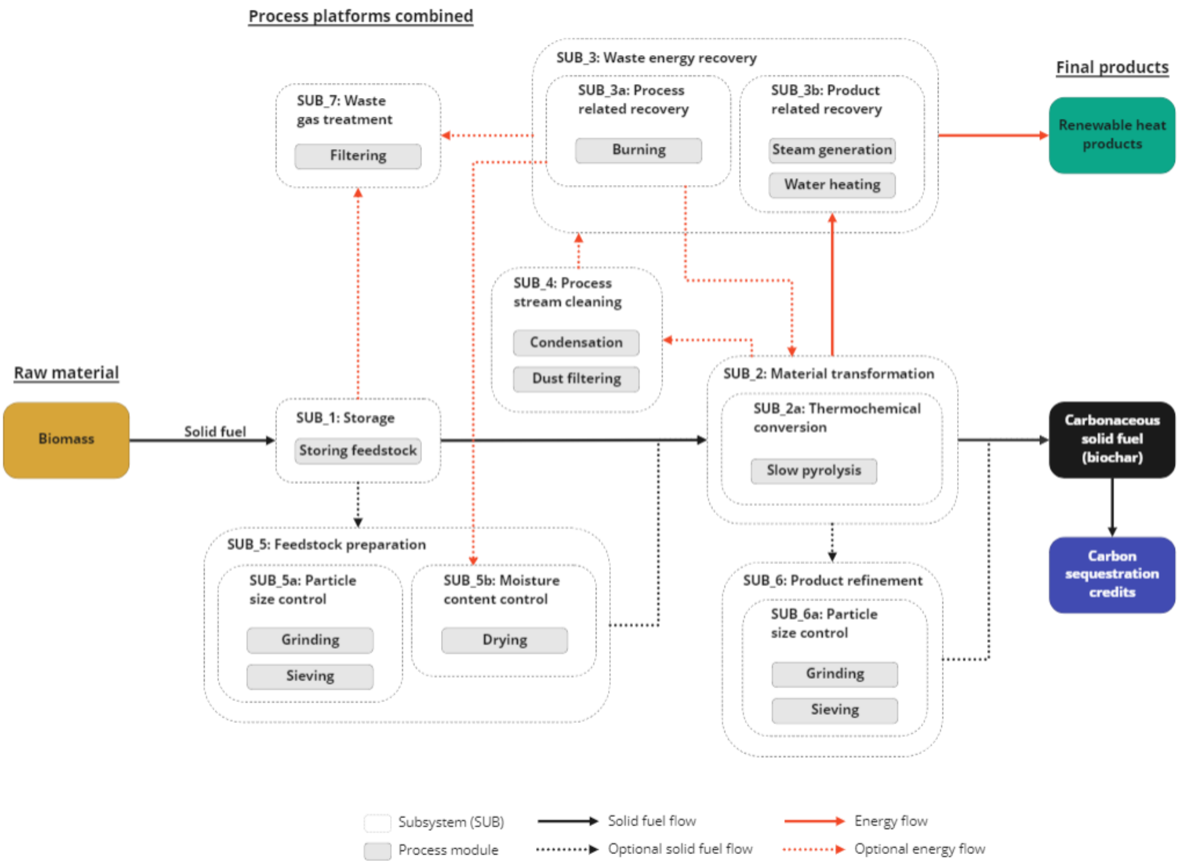


Figure 16 Process platform for biochar production and green heat as integrated manufacturing system

5.6.1 Pyrolysis Technology

Internationally acknowledged as a strategy with substantial potential to meet climate change goals is carbon capture and storage (CCS). Although this technique has been recognized, it has not been widely used despite the technological maturity of many CCS technologies. There is a possible demand to collect 95% or an even larger percentage of total gaseous carbon emissions when taking into account even stricter climate commitments. One of the biggest issues facing society now may be managing solid organic waste, the decomposition of which has significant potential to contribute to climate change (Porshnov, 2022, p. 2). Additionally, the thermochemical valorization of biomass into sustainable energy through pyrolysis is regarded as the most feasible method in terms of commercialization, due to its often touted technological maturity, market readiness and output products (Dhyani & Bhaskar, 2019). The interest of ongoing research is increasingly shifting towards the large-scale development and industrialization of pyrolysis systems (Mong et al., 2022).

Plenty of technological approaches are currently being taken and developed to substitute energy provided by fossil fuels. Main drivers are resource availability, technological constraints as well as environmental and ecological benefits. Pyrolysis technology is increasingly gaining attention due to its ability to generate a wide range of sustainable products such as biooil, biochar, syngas and ash and its use for the generation of renewable energy in form of heat and electricity (Dhyani & Bhaskar, 2019, p. 217; Roy & Dias, 2017, p. 59).

The technology is currently undergoing various improvement initiatives focusing on optimization of feedstock logistics, updating reactor configurations, optimizing energy efficiency and biomass heating rates (Roy & Dias, 2017, p. 65).

The core process is taking place in the pyrolysis reactor, the heart of the value creation process. Research focuses on testing different reactor configurations on a myriad of feedstocks. 10-15% of the whole investment cost for a pyrolysis system is usually required for the reactor (Bridgwater, 2012, p. 70). Apart from the reactor further technology modules for biomass preparation, storage and handling, drying, grinding, product collection, storage and further downstream processing units, if required, are part of a plant setup (Bridgwater, 2012, p. 70).

The most commonly used reactor configurations include the fluidized-bed reactor (FBR), the circulating fluidized-bed reactor (CFB), the ablative plate reactor, the auger/screw reactor, the rotating cone reactor, the cyclone/vortex reactor, and the rotating kiln reactor. These different reactor configurations enable to achieve and adapt the yields of respective pyrolysis products and are used in different applications to process lignocellulosic biomass in most cases (Dhyani & Bhaskar, 2019, p. 231). Respective manufacturing processes are due to their nature subject to high safety standards, because toxic and highly explosive gases are generated during the process.

Pyrolysis is the thermal conversion of solid fuel in an atmosphere under oxygen exclusion (Weber & Quicker, 2018). Output products are composed of liquid or gaseous substances that can be used as fuel and biochar containing the ash of the biomass as well as fixed carbon contents. So called pyrolysis vapors develop through conversion of a part of the solid matter inside the reactor. This mixture consists of condensable and non-condensable gases (Raveendran & Ganesh, 1996). Whereas the condensable gases can be further processed into a liquid fuel through condensation the permanent, non-condensable gases remain gaseous. The latter contain carbon monoxide, carbon dioxide, hydrogen, and low-molecular-weight hydrocarbons. Properties of the final products of the pyrolysis process mainly depend on feedstock composition and properties and process parameters of the pyrolysis process (Soria-Verdugo, 2019, pp. 155–156) as will also be explained further below.

The production of char products as well as liquid fuels made possible by pyrolysis technology is seen as clear advantage towards other conversion processes that solely focus on the generation of energy (Campbell et al., 2018, p. 333).

Heat transfer, heat supply and volatile residence time have the highest influence on product yields and their final composition. These factors further enable a classification of pyrolysis processes as slow, intermediate, or fast/flash pyrolysis (Collard et al., 2016, p. 82). A clear delineation is not possible due to the variety in system layouts and the high heterogeneity of feedstock types and respective process conditions to achieve a desired yield of the products (Hagemann et al., 2018).

Slow pyrolysis is characterized by long reaction times, low temperatures, and slow heating rates. It has the potential to provide together with intermediate pyrolysis the most balanced product yield regarding liquid, solid and gaseous fuel (see Table 14). Most common reactor types used to conduct slow pyrolysis are the auger/screw reactors, cylindrical fixed-bed, batch, rotary kiln and packed bed reactors (Collard et al., 2016; Garcia-Nunez et al., 2017; Mong et al., 2022; Raza et al., 2021; H. Tan et al., 2021; K. H. Tan et al., 2011).

Compared to slow pyrolysis and fast pyrolysis heating rates take intermediate values. Residence times are significantly shorter than for slow pyrolysis systems, but do not reach values of fast or flash pyrolysis. Although the lower yield of condensable gases (up to 55%) is obtained in this process, it provides an advantage of being more flexible. Biomass decomposition reactions can be more easily controlled and allow for better process optimization. Additionally, the process accepts larger particle sizes (Collard et al., 2016; Dhyani & Bhaskar, 2019). As for slow pyrolysis systems, the most used reactors for this mode are auger and screw reactors in which the feedstock is transported mechanically through the reactor (Collard et al., 2016).

The goal of fast pyrolysis is to decompose the biomass quickly compared to intermediate and slow pyrolysis. As for the other two modes, vapors, aerosols, charcoal, and gas are the final products of this process. The condensable vapors forming during the process are subsequently condensed to yield biooil. Very high heating rates and hence transfer of heat into the particles are essential for fast pyrolysis. In this regard the feedstock particles must be small due to the poor thermal conductivity of biomass. Carefully controlled reaction temperatures and short vapor residence times as indicated in Table 14 are key to avoid secondary cracking of pyrolysis products and prevent an increase of solid fuel content and maximize biooil output. This is achieved through a rapid removal of the products from the reaction environment using the inert gas flow. The condensable gases building are condensed to biooil (Bridgwater, 2012; Collard et al., 2016; Dhyani & Bhaskar, 2019).

Commonly used reactor types for fast pyrolysis include fluidized bed reactors (FBR), ablative plate reactors (APR), rotating cone reactors (RCR), cyclone and vortex reactors (CVR) and ultimately attempts have been made to apply microwave pyrolysis (Bridgwater, 2012; Collard et al., 2016; Dhyani & Bhaskar, 2019; H. Tan et al., 2021; K. H. Tan et al., 2011).

Fast pyrolysis and gasification can generate a solid fuel with high carbon content. However, this is to be seen as a by-product, which does not achieve the quality standards required for many applications (Weber & Quicker, 2018, p. 241).

Table 14 Pyrolysis modes adapted from Collard et al. (2016), Quicker and Weber (2016, p. 23) and Bridgwater (2012)

Parameter	**Slow pyrolysis**	**Intermediate pyrolysis**	**Fast pyrolysis**
Heating rates (°C/s)	0.1-1	1-10	10-200
Particle size (mm)	5-50	1-50	<1
Residence time	Hours-days	5-30s	1-2s
Reaction temperature (°C)	~400	~500	~500
Liquid fuel yield in %	25-30	40-50	60-75
Solid fuel yield in %	30-40	25-30	12-20
Gas yield in %	25-35	25	13-20

5.6.2 Selecting the alternatives

As the previous sections already describe, the biochar market is in an early developmental stage with different technology configurations and suppliers entering the market. Figure 17 shows the technology suppliers research process used in this thesis.

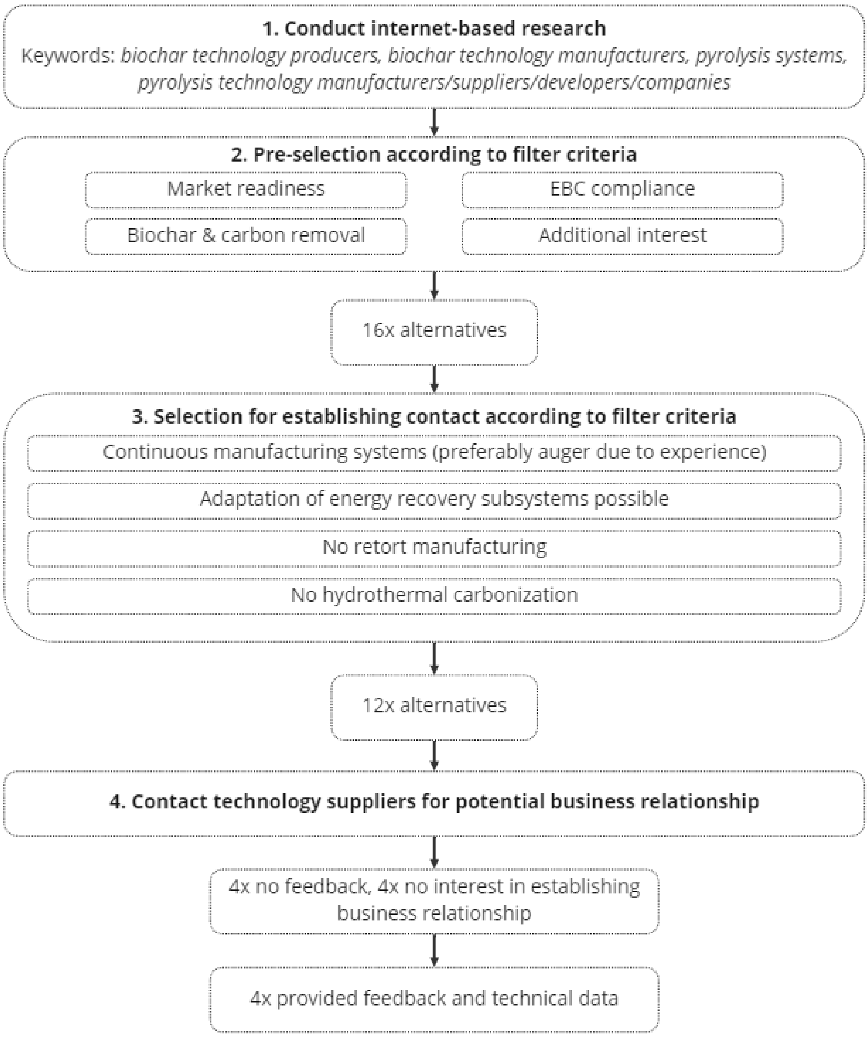


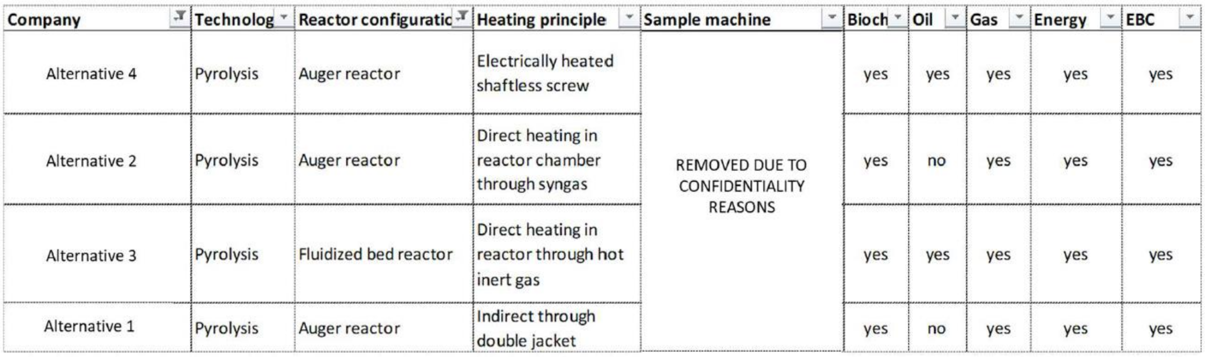
Figure 17 Pyrolysis suppliers technology research process

First, internet-based research was conducted based using the keywords presented in Figure 17. Subsequently, suppliers found were pre-selected according to the following criteria:

- Market readiness – Plants must have achieved industrial status/commercial size and moved beyond pilot level application.
- Focus – Biochar production for soil amendment and carbon removal (fast pyrolysis providers have been omitted from selection as well as hydrothermal carbonization approaches).
- Proven regulatory compliance – Suppliers must have experience with EBC certification.
- Interest – Additional interest in the different technologies voiced by top management was considered as well.

Overall, 16 alternatives could be identified for further investigation. Through retrieving information from patents as well as company websites the suppliers were further classified according to their manufacturing system and reactor configuration, heating principle of the material transformation process, potential adaptation of waste heat recovery systems. Retort manufacturing principles were omitted from the selection due to their limited scalability and inability to process large feedstock quantities in a continuous process (Ighalo et al., 2022).[5] Hydrothermal carbonization technologies were omitted as well due to their higher complexity and lower carbon yield (Rodriguez Correa et al., 2019). This led to the selection of 12 suppliers which were further contacted for a potential business relationship. Only four suppliers ultimately agreed to provide relevant data (Table 15).[6] With only 12 suppliers that have currently achieved technology readiness level (TRL) 8 or 9, the sample size is rated as adequate for the analysis purposes (EBI, 2023).

Table 15 Technology alternatives selected for investigation



Company	Technolog	Reactor configuratic	Heating principle	Sample machine	Bioch	Oil	Gas	Energy	EBC
Alternative 4	Pyrolysis	Auger reactor	Electrically heated shaftless screw	REMOVED DUE TO CONFIDENTIALITY REASONS	yes	yes	yes	yes	yes
Alternative 2	Pyrolysis	Auger reactor	Direct heating in reactor chamber through syngas		yes	no	yes	yes	yes
Alternative 3	Pyrolysis	Fluidized bed reactor	Direct heating in reactor through hot inert gas		yes	yes	yes	yes	yes
Alternative 1	Pyrolysis	Auger reactor	Indirect through double jacket		yes	no	yes	yes	yes

5.6.3 Auger and screw reactors (ASR)

Alternatives 1, 2, and 4 are auger and screw reactors. One fundamental difference of auger and screw reactors (ASR) is the fact that the biomass is moved mechanically by an endless helical screw through the reaction zone in the reactor (see Figure 18). Common reactor configurations include a rotating helical enclosed screw which moves the biomass into the reactor, blends the mixture of biomass with or without solid heat carriers and controls the residence time (Campuzano et al., 2019).

The reactor can be heated internally through ceramic or steel balls as heat carriers or externally through the reactor walls. Another key difference is that ASR cannot achieve ultra-short residence times. Auger and screw reactors can be used for slow pyrolysis as well as intermediate pyrolysis systems (Bridgwater, 2012; Campuzano et al., 2019; Collard et al., 2016).

Although the ASR might have some disadvantages regarding fast pyrolysis processes compared to FBR, due to its advantages listed below in Table 16 this reactor configuration is regarded as one of the most attractive for pyrolysis today. Additionally, these reactor configurations are also employed with two helical rotating screws resulting in an even better mixing behavior of the feedstock and heat carrying media. Further, these twin-auger reactors are more energy efficient, and achieve a better feedstock devolatilization allowing to execute fast pyrolysis processes as well (Campuzano et al., 2019).

Table 16 Advantages/disadvantages of ASR according to Dhyani and Bhaskar (2019), Bridgwater (2012) and (Campuzano et al., 2019)

Advantages	**Disadvantages**
▪ Compact configurations possible ▪ Portable, allow for decentralized construction on site ▪ High solid fuel yield	▪ Difficult to also achieve short residence times compared to FBR, and AR, more secondary reactions occurring ▪ Risk for plugging

---

[5] See appendix B

[6] See appendix A and E

▪ Suitable for heterogenous feedstocks	▪ Mechanical wear and tear on moving parts at high temperatures
▪ Suitable for feedstocks that are difficult to handle	▪ Mixing effectiveness could be reduced
▪ Good axial dispersion	▪ Special screw flighting required to achieve adequate mixing behavior resulting in higher maintenance cost
▪ Particles exposed to higher process uniformity under thermal conditions	
▪ Residence times controlled by rotational speed and inert gas flow	
▪ Possibility to construct vertical, horizontal, and inclined configurations	
▪ Low liquid fuel yield	

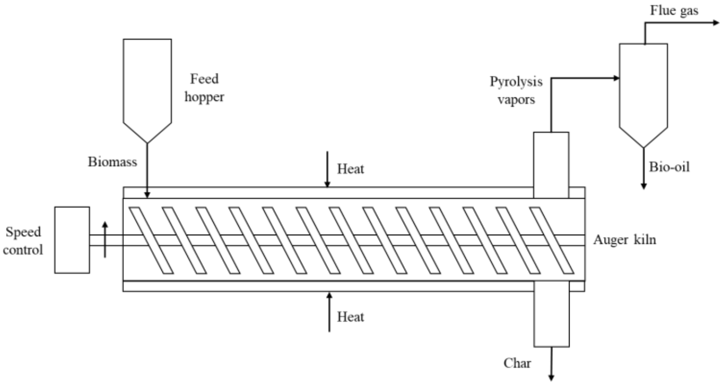


Figure 18 Auger/Screw Reactor adapted from Campuzano et al. (2019)

5.6.4 Fluidized bed reactors (FBR)

Alternative 3 is a fluidized bed reactor. The fluidized bed reactor (FBR), a moving bed reactor, is one of the most popular reactor configurations, especially used for fast pyrolysis using solid reactants, i.e., biomass. In this reactor configuration, a fluidization medium, a gas, is routed through the biomass at high velocity, causing the mass to behave like a fluid. The gas is heated and can be used on some occasions together with inert sand as heating medium to achieve heating of the biomass particles. Other forms of the fluidized bed reactor include bubbling fluidized beds (BFB) in which the movement of the solid reactant is more stationary (Bridgwater, 2012; Dhyani & Bhaskar, 2019). Heat transfer into the biomass is facilitated through heating materials inside the fluidized bed reactor. Inert sand or other alloyed materials are usually used to serve as heat carrier media (Mong et al., 2022).

Table 17 Advantages/disadvantages of fluidized bed reactors (FBR) according to Bridgwater (2012) and Dhyani and Bhaskar (2019)

Advantages	**Disadvantages**
▪ High heating rates can be achieved	▪ Careful selection of feed particle size required
▪ Uniform heat transfer possible	▪ Particle size is limiting the heating rate
▪ Uniform mass transfer	▪ Low partial pressures for condensable vapors due to high inert gas flow
▪ Good control over reaction parameters	▪ Relatively low char yield of 15%
▪ High liquid yields from wooden input material on dry matter basis	

Due to their configuration, FBR are ideally suited for fast pyrolysis processes, ensuring continuous productivity. As explained above vapor and solid residence time can be controlled through the inert gas flow. Char is removed from the reactor through ejection and entrainment together with the pyrolysis vapors developing. Using cyclones, the solid fuel is separated from the condensable gases which can be subsequently quenched to obtain biooil (see Figure 19). The char yield is usually around

15% of the final products. Similar particle sizes of the char to the feedstock particles can be achieved, depending on the reactor configuration and gas velocities (Campbell et al., 2018).

FBR have experienced remarkable interest due to their capability of being scaled for large-scale industrial application (Campuzano et al., 2019, p. 373).

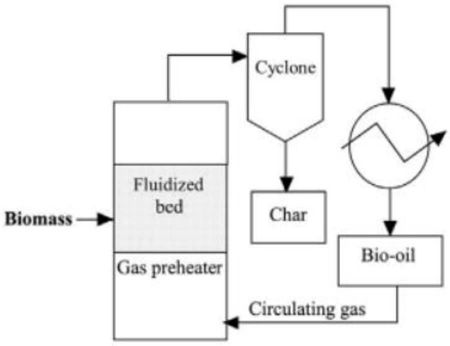


Figure 19 Fluidized bed reactor (FBR) process scheme (Dhyani & Bhaskar, 2019)

5.7 Chapter summary

Providing an answer to SQ 5.1 *Which is the best selection methodology for the technology selection problem?* the Analytic Hierarchy Process (AHP) is chosen as the ideal method, leveraging platform-based design theory, for technology selection. AHP enables stakeholders to prioritize criteria, make informed decisions through trade-off analysis, and foster inclusive discussions across different domains. It provides quantitative outputs for ranking and selecting the most suitable technology, while sensitivity a sensitivity analysis according to Triantaphyllou and Sánchez (1997) ensures robustness. AHP's structured approach and multicriteria analysis are advantageous. However, it may not fully capture the complexity inherent in platform-based design theory. Nevertheless, the benefits of AHP outweigh its limitations in this context.

Answering SQ 4 *Which are the selection criteria imposed by the company's high variety strategy on potential technology alternatives?* In total, 26 criteria have been extracted and ultimately chosen from the literature for evaluation of the technology alternatives. The decision hierarchy for the AHP was structured into four sub-levels including the different criteria. The criteria on sub-level one include financial performance, the two production platforms, and supplier maturity.

Referring to SQ 5.2 *Which alternatives are subject to selection and how were they chosen?* Internet-based research was conducted using specific keywords, resulting in the pre-selection of suppliers based on criteria such as market readiness, focus on biochar production, regulatory compliance, and management interest. Sixteen alternatives were identified and further classified based on manufacturing system, reactor configuration, and waste heat recovery potential. Suppliers using retort manufacturing principles and hydrothermal carbonization technologies were excluded. Twelve suppliers were contacted, but only four agreed to provide data. With 12 suppliers at technology readiness level 8 or 9, the sample size is considered sufficient for analysis. The investigated alternatives exhibit the following reactor types: Three of them are auger and screw reactors (ASR) and one is a version of a fluidized bed reactor (FBR).

Answering SQ 5.4 *What are the benefits of each type of alternative?* Auger and screw reactors offer several advantages, including compact configurations, portability, high solid fuel yield, suitability for heterogeneous and difficult-to-handle feedstocks, good axial dispersion, and control over residence times. They allow for construction in vertical, horizontal, and inclined configurations. However, they have some disadvantages, such as low liquid fuel yield, difficulty in achieving short residence times compared to other reactor types, increased occurrence of secondary reactions, risk of plugging, mechanical wear and tear on moving parts at high temperatures, reduced mixing effectiveness, and the need for special screw flighting, resulting in higher maintenance and investment costs.

Fluidized bed reactors offer several advantages, including the ability to achieve high heating rates, uniform heat transfer, uniform mass transfer, and good control over reaction parameters. They also provide high liquid yields from wooden input material on a dry matter basis. However, they have some disadvantages, such as the requirement for careful selection of feed particle size, limitation on heating rate due to particle size, low partial pressures for condensable vapors resulting from high inert gas flow, and a relatively low char yield of 15%.

6 Results

This chapter presents the results, with section 6.1 concerning expert choice and software, 6.2 providing the results of the pairwise comparison study. 6.3 explains how data was normalized for the AHP model and provides an overview of developed utility functions to test the model. Section 6.4 concerns the synthesis of results answering SQ 6.1 *Which integrated manufacturing system alternative is the most profitable one satisfying all requirements of all production platforms to the highest extent?* and SQ 6.2 *Which integrated manufacturing system is the best one for each production platform?* Section 6.4 further covers the scenario analysis and section 6.5 closes with a summary of the chapter.

6.1 Expert choice & software

The experts were recruited inside company X. A function-based, as well as a unit-based selection was conducted to involve the most relevant stakeholders affected by the selection of the technology. Table 18 presents an overview of the stakeholders selected. In total seven experts could be determined with differences in experience with the technologies already leveraged by the company.

Table 18 Company stakeholders selected for evaluation

Position	Unit	Functions
Business development manager	Site development	Product Marketing Sales
Chief executive officer	Site development	Sales Finance & controlling
Key account manager	Biochar & substrates	Sales
Research associate	Biochar & substrates	R&D
Head of product development	Industrial materials	R&D
Carbon removal manager	Carbon credits	Sales
Head of production	Site & operations	Supply chain management

To retrieve the pairwise comparisons from the different stakeholders selected, the AHP-OS survey software tool developed by Goepel (2018) was used. The tool allows to efficiently conduct online AHP surveys and evaluate the survey responses of the different stakeholders. Additionally, stakeholders were supplied with information about the functionality of the AHP, a complete description of decision goal and criteria, and a manual on how to conduct the survey using the software[7]. The stakeholders were requested to provide feedback and comments about the selection and number of criteria through the company's intranet in advance before sending out the AHP survey. Subsequently, the model was further constructed in the Super Decisions Software developed by Saaty (Mu & Pereyra-Rojas, 2016).

6.2 AHP results

The following section presents the results of the stakeholder survey conducted with the AHP-OS developed by Goepel (2018). First the section investigates the decision hierarchy and consolidated priorities as well as the consolidated global priorities. Subsequently, the section presents the synthesis results of the decision-making model regarding the selected alternatives and depicts the performances for each production platform described in the previous chapters. The section then follows up with a

---

[7] See appendix E

sensitivity analysis illustrating rank reversals regarding the alternatives.[8] The section concludes by describing the consistency of judgements as well as the group consensus among the judgements of the stakeholders.

AHP hierarchy and consolidated stakeholder priorities

As can be inferred from Figure 20 on the criteria level 1, highest priority was assigned to the biochar production platform for soil amendment with a local weight (LW) of 0.340, followed by the production platform for green energy with a local weight of 0.313, the financial performance with a local weight of 0.202, and finally the supplier maturity with a local weight of 0.149.

On sub-criteria level 2 for the production platform for soil amendment, the biochar product performance (LW=0.440) is rated as more important than the carbon sequestration performance (LW=0.286) of the manufacturing system as well as the manufacturing capability (LW=0.274). On level 3 for biochar product performance, the stability in soil (LW=0.449) as well as the carbon sequestration potential (0.344) outweigh the water holding capacity (LW=0.208).

For the manufacturing capability as part of the production platform for biochar for soil-amendment the stakeholders considered the plant availability (LW=0.263) as the most important sub-criterion on level 3, closely followed by the biochar output (LW=0.251) the biochar conversion rate (LW=0.190) and raw material capabilities (LW=0.151) and process adaptability (0.145).

For the process adaptability on level 4, the treatment temperature range (LW=0.695) is considered more important than the adaptability of the residence time (LW=0.305).

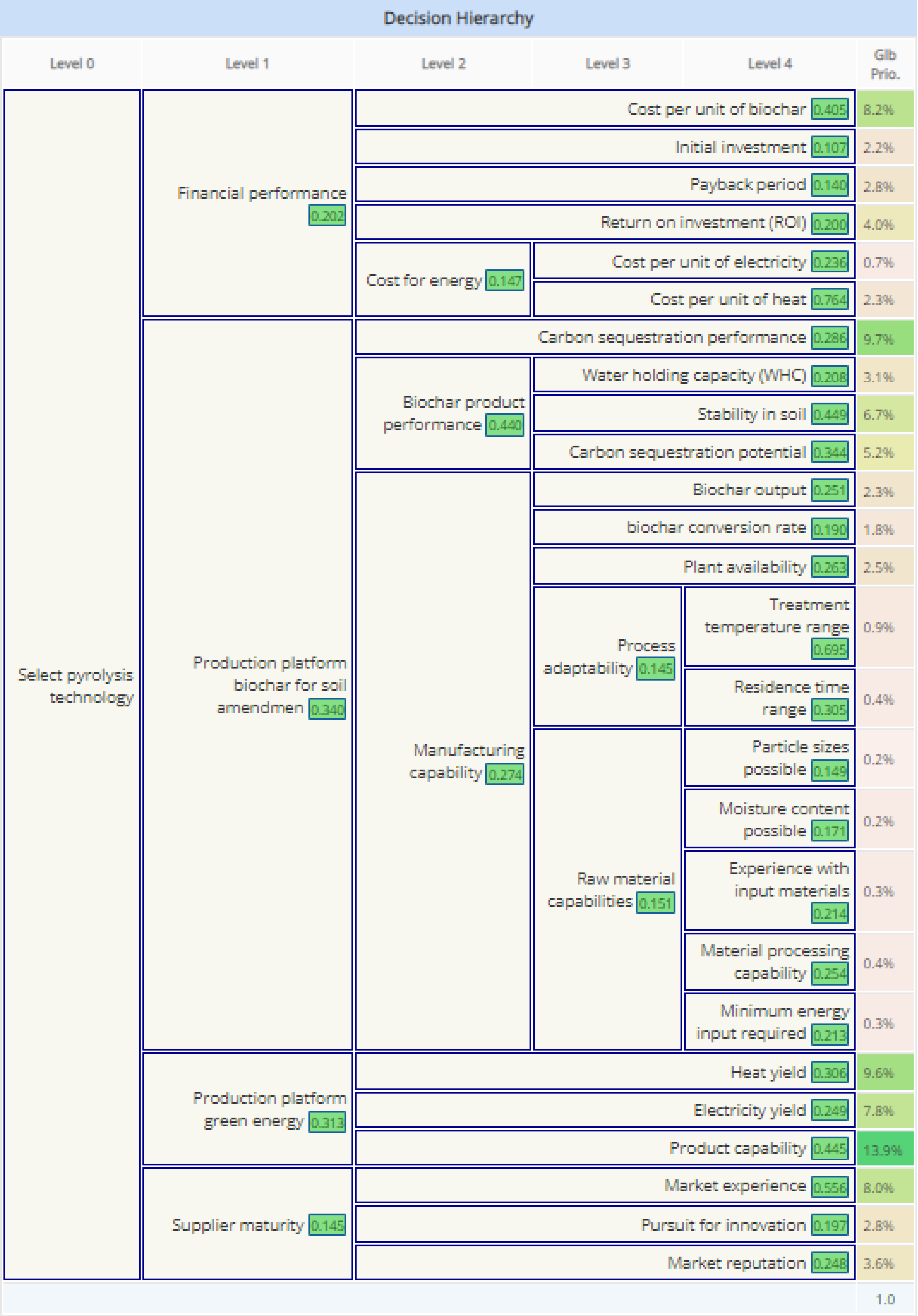
Analyzing the raw material capability on level 4 the most important criterion is the material processing capability (LW=0.254) followed by a manufacturer's experience with input materials (LW=0.214), the minimum energy input required (LW=0.213), the moisture content possible (LW=0.171) and the particle sizes possible (LW=0.149).

For the production platform for green energy as the second most important criterion on criteria level 1, the stakeholders considered the product capability (LW=0.445), i.e., a technology configuration's ability to produce all energy products, such as electricity, steam, hot water, warm water as the most important criterion, followed by the heat yield (LW=0.306), which is substantial for the generation of the green heat products. This is closely followed by the electricity yield (LW=0.249).

---

[8] See appendix D

The financial performance on the third place on criteria level 1, exhibits the following ranking of sub-criteria on level 2: The stakeholders considered the cost per unit of biochar (LW=0.405) as the most important sub-criterion, followed by the return on investment (0.200) the cost for energy (LW=0.147), the payback period (LW=0.140), as well as the initial investment (LW=0.107).



Decision Hierarchy

Level 0	Level 1	Level 2	Level 3	Level 4	Glb Prio.
Select pyrolysis technology	Financial performance 0.202	Cost per unit of biochar 0.405			8.2%
		Initial investment 0.107			2.2%
		Payback period 0.140			2.8%
		Return on investment (ROI) 0.200			4.0%
		Cost for energy 0.147	Cost per unit of electricity 0.236		0.7%
			Cost per unit of heat 0.764		2.3%
	Production platform biochar for soil amendmen 0.340	Carbon sequestration performance 0.286			9.7%
		Biochar product performance 0.440	Water holding capacity (WHC) 0.208		3.1%
			Stability in soil 0.449		6.7%
			Carbon sequestration potential 0.344		5.2%
		Manufacturing capability 0.274	Biochar output 0.251		2.3%
			biochar conversion rate 0.190		1.8%
			Plant availability 0.263		2.5%
			Process adaptability 0.145	Treatment temperature range 0.695	0.9%
				Residence time range 0.305	0.4%
			Raw material capabilities 0.151	Particle sizes possible 0.149	0.2%
				Moisture content possible 0.171	0.2%
				Experience with input materials 0.214	0.3%
				Material processing capability 0.254	0.4%
				Minimum energy input required 0.213	0.3%
	Production platform green energy 0.313	Heat yield 0.306			9.6%
		Electricity yield 0.249			7.8%
		Product capability 0.445			13.9%
	Supplier maturity 0.145	Market experience 0.556			8.0%
		Pursuit for innovation 0.197			2.8%
		Market reputation 0.248			3.6%
					1.0

Figure 20 AHP hierarchy with consolidated priorities

On sub-criteria level 3 for the cost of energy, the cost per unit of heat (LW=0.764) is more important than the cost per unit of electricity (LW=0.236).

Finally, for the supplier maturity, the most important criterion is the market experience (LW=0.556), followed by the market reputation (LW=0.248) and the pursuit for innovation (LW=0.197).

The global priority distribution as presented in Figure 21, suggests that the most important criterion is the product capability of the manufacturing platform for the production platform for green energy with a global weight (GW) of 13.9% as determined by the stakeholders. This is followed by the carbon sequestration performance of the whole system with 9.7%, the heat yield with 9.6%, the cost per unit of biochar with 8.2%, a supplier’s market experience with 8.0%, and the electricity yield of the manufacturing system, with a GW of 7.8%.

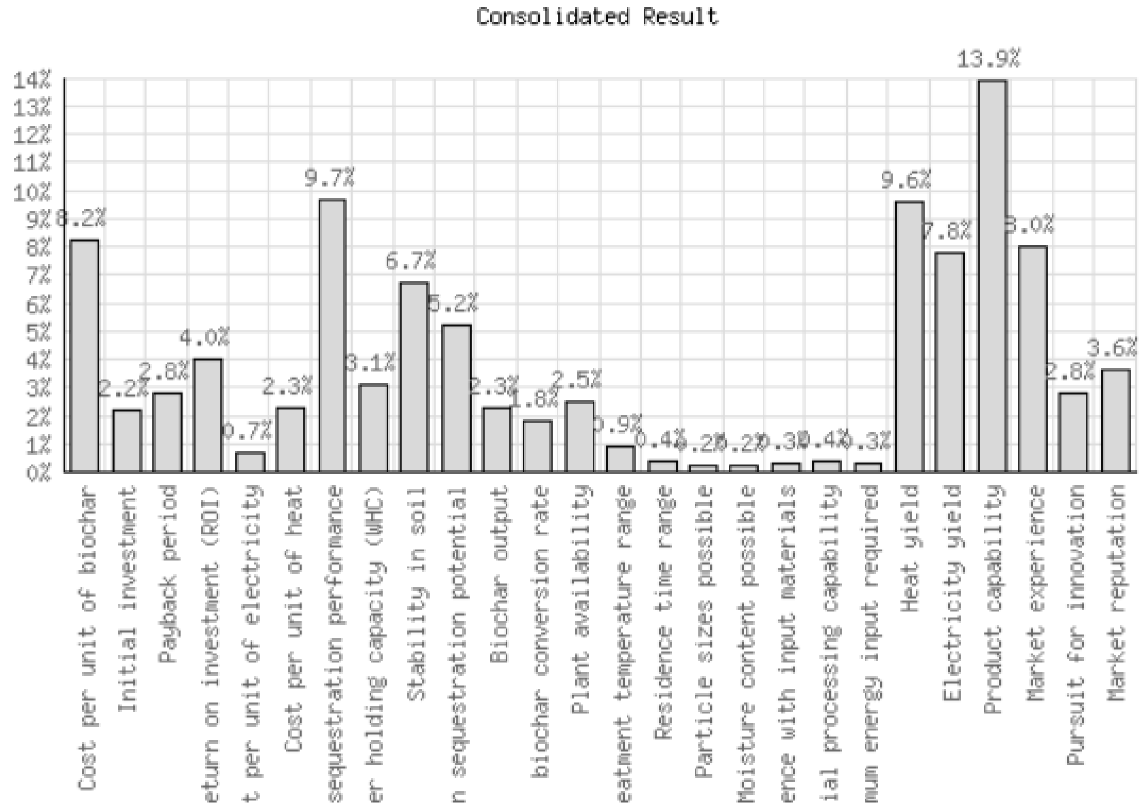


Figure 21 Global priorities distribution

6.3 Normalization of data

To successfully process underlying data for the different alternatives the transformation to a common comparable scale is necessary. All underlying data of the criteria is measured in different units (i.e., velocity, acceleration, electricity consumption, cost etc.). Vafaei et al. (2016) and Vafaei et al. (2020) investigated five different normalization techniques for the AHP. The authors differentiated between cost and benefit criteria and suggested approaches including respective formulas to conduct a normalization for the criteria. After establishing pairwise comparison matrices for a set of sample alternatives, the authors calculated the Pearson correlation and mean r values for the global weights of the alternatives and the Spearman correlation for the ranks of the alternatives to determine the applicability of the investigated normalization techniques for the AHP. They concluded that a combination of max-normalization with the linear-sum method to renormalize the values to an interval of [0,1] is the most appropriate normalization technique for the AHP.

Table 19 Normalization techniques adapted from Vafaei et al. (2016) and Vafaei et al. (2020)

Normalization technique	Type of criteria	Formula
Linear: Max	Maximization objective	$\mathrm{n_{ij}} = \frac{\mathrm{r_{ij}}}{\mathrm{r_{max}}}$
	Minimization objective	$\mathrm{n_{ij}} = 1 - \frac{\mathrm{r_{ij}}}{\mathrm{r_{max}}}$
Linear: Sum	Maximization objective	$\mathrm{n_{ij}} = \frac{\mathrm{r_{ij}}}{\sum_{i=1}^{m} \mathrm{r_{ij}}}$
	Minimization objective	$\mathrm{n_{ij}} = \frac{1/\mathrm{r_{ij}}}{\sum_{i=1}^{m} 1/\mathrm{r_{ij}}}$

$$with\ n_{ij} as\ normalized\ value\ of\ alternative\ i\ for\ criterion\ j$$
$$with\ r_{ij}\ as\ real\ value\ of\ alternative\ i\ for\ criterion\ j$$
$$with\ r_{max}\ as\ maximum\ real\ value\ of\ all\ alternatives\ for\ criterion\ j$$

Table 20 presents the normalized criteria scores for the alternatives selected for an evaluation using linear utility functions for the different criteria and performing the normalization according to the steps suggested by Vafaei et al. (2016) and Vafaei et al. (2020).

Table 20 Normalization according to Vafaei et al. (2016) using linear utility functions for criteria[9]

	Linear max normalization acc					**Linear sum normalization acc. to V**			
Alternatives A_i		A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4
Criteria (C_k)	Normalized values					Normalized values			
Production platform Biochar for soil amendment	n_{ij}	n_{1j}	n_{2j}	n_{3j}	n_{4j}	n_{1j}	n_{2j}	n_{3j}	n_{4j}
CORC factor (max)	n_{i1}	0.94	1.00	0.80	0.82	0.26	0.28	0.22	0.23
Water holding capacity (max)	n_{i2}	0.74	1.00	0.69	0.37	0.26	0.36	0.25	0.13
Stability in soil (min)	n_{i3}	0.19	0.00	0.76	0.05	0.19	0.00	0.76	0.05
Carbon sequestration potential (max)	n_{i4}	0.88	0.98	0.97	1.00	0.23	0.26	0.25	0.26
Biochar output (max)	n_{i5}	0.49	0.41	1.00	0.74	0.19	0.16	0.38	0.28
Biochar conversion rate (max)	n_{i6}	0.84	1.00	0.50	0.88	0.26	0.31	0.15	0.27
Plant availability (max)	n_{i7}	1.00	0.94	1.00	0.89	0.26	0.25	0.26	0.23
Treatment temperature range (max)	n_{i8}	0.67	0.44	0.00	1.00	0.32	0.21	0.00	0.47
Residence time range (max)	n_{i9}	0.50	0.50	0.00	1.00	0.25	0.25	0.00	0.50
Raw material capabilities									
Particle sizes possible (max)	n_{i10}	1.00	0.70	0.70	0.50	0.34	0.24	0.24	0.17
Moisture content possible (max)	n_{i11}	0.80	1.00	0.40	0.40	0.31	0.38	0.15	0.15
Experience with input materials (max)	ni_{12}	0.89	0.56	0.11	1.00	0.35	0.22	0.04	0.39
Material processing capability (max)	n_{i13}	0.67	0.67	0.33	1.00	0.25	0.25	0.13	0.38
Minimum lower heating value required (LHV) (min)	n_{i14}	0.42	0.42	0.77	0.00	0.26	0.26	0.48	0.00
Production platform green energy									
Heat yield (max)	n_{i15}	0.20	0.27	0.65	1.00	0.09	0.13	0.31	0.47
Electricity yield (max)	n_{i16}	0.07	0.12	1.00	0.12	0.05	0.09	0.77	0.09
Product capability (max)	n_{i17}	0.67	0.67	0.67	1.00	0.22	0.22	0.22	0.33
Supplier maturity									
Experience in the market (max)	n_{i18}	0.36	0.07	1.00	0.29	0.21	0.04	0.58	0.17
Pursuit for innovation (max)	n_{i19}	0.25	0.25	1.00	0.25	0.14	0.14	0.57	0.14
Market reputation (max)	n_{i20}	1.00	0.33	0.67	1.00	0.33	0.11	0.22	0.33
Financial performance									
Cost per unit of biochar (min)	n_{i21}	0.00	0.05	0.59	0.09	0.00	0.07	0.80	0.12
Cost for energy									
Cost per unit of heat (min)	n_{i22}	0.00	0.35	0.09	0.30	0.00	0.47	0.12	0.41
Cost per unit of electricity (min)	n_{i23}	0.00	0.31	0.39	0.38	0.00	0.29	0.36	0.35
Initial investment (min)	n_{i24}	0.39	0.57	0.00	0.45	0.28	0.41	0.00	0.32
Discounted Payback period (min)	n_{i25}	0.00	0.49	0.46	0.54	0.00	0.33	0.31	0.36
Return on investment (RoI) (max)	n_{i26}	0.13	1.00	0.88	0.95	0.05	0.34	0.30	0.32

Utility functions for normalization

As indicated in the criteria description, the general scale chosen to normalize the raw data for the different alternative follows a linear distribution. Given the preferences of the decisions makers as presented in Figure 20 it appears reasonable to further analyze the synthesis of results taking into consideration different utility functions for normalizing the criteria of cost per unit of biochar, carbon sequestration performance, stability in soil, and market experience. For other highly weighted criteria such as the heat yield, electricity yield and product capability a linear scale seems feasible. Increasing the yields by 1 unit provides the same marginal return on utility. The product capability could be differentiated according to margins that could be realized depending on the energy product. However

---

[9] For a review of the raw input data for the different alternatives refer to appendix C

sufficient insights into the customer demand for each product are not available to company X now. Therefore, the utility function for this criterion is kept linear.

For the carbon sequestration performance, the stability in soil, the market experience, and the biochar price the following functions approximate potential utilities used to determine an alternative's performance factor for the respective criterion (see Figure 22 - Figure 25). The exemplary functions were first plotted graphically and then adapted to represent the relevant value ranges for the criteria.

Carbon sequestration performance	$f(x) = 1 - e^{-1.35x}$	An s-shaped curve was selected for the carbon sequestration performance. A value below one ton provides low utility. The utility increases strongly after one ton indicated by the steeper slope of the graph. The carbon sequestration performance that could potentially be achieved per ton of biochar applied to soil is 3.5t/CO_2 (see point B in Figure 22) Respective emissions occurring in the supply chain need to be accounted for.[10] Analyzing the CORC factors achieve by the biochar manufacturers in the puro.earth registry, a CORC factor of 2.5 seems to be reasonable for achieving a 90% (see point A in Figure 22) utility rate for this criterion according to the supplier CORC factors seen in the puro.earth registry.
Stability in soil	$g(x) = \frac{1}{1 + 0.6 \times 25000^{x-0.7}}$	A reverse s-shaped graph was chosen for the stability in soil. Values over one virtually provides no utility. To achieve a sufficient stability in soil the H/C_{org} ratio of a biochar needs to achieve a value of 0.4 (see point D in Figure 23) to become certified according to the EBC and achieve a sequestration duration of more than 100 years (EBC, 2012-2022; puro.earth, 2022). In the future this threshold might be further reduced, however achieving 99% utility at a H/C_{org} ratio of 0.25 (see point C in Figure 23) seems to be reasonable.
Market experience	$i(x) = -0.5^{0.7x} + 1$	With each additional manufacturing plant built on industrial level, a technology supplier gains additional experience. The additional utility for this criterion is expected to decrease at a faster rate after the third plant. Achieving 76% utility with the third plant installed seems reasonable (see point E in Figure 24). With five plants a supplier reaches 90% and with ten

---

[10] See chapter 3.2

		plants 99% of utility for this criterion (see points F and G in Figure 24)).
Cost per ton of biochar	$h(x) = \frac{1}{1 + 0.3 \times 1.036^{x-235}}$	According to the market analysis conducted by company X an appealing range for the biochar production cost starts a 400.00€/t moving down to 99% utility at 135.00€/t (see point H in Figure 25) (Ziegner & Milla, 2022). At 205.00€/t a 90% utility level is reached. Therefore, a reverse s-shaped graph is chosen for the cost per ton of biochar utility function.

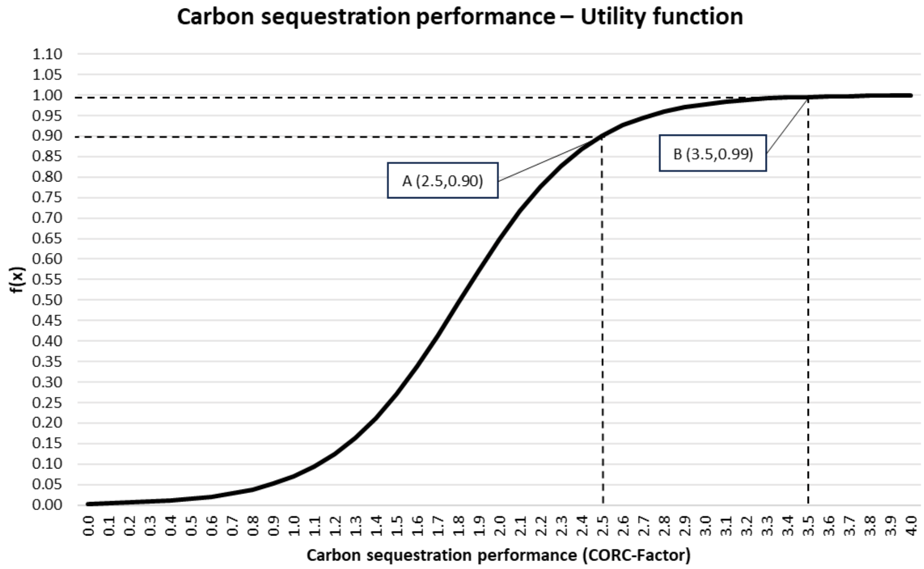


Figure 22 Potential utility function criterion carbon sequestration performance

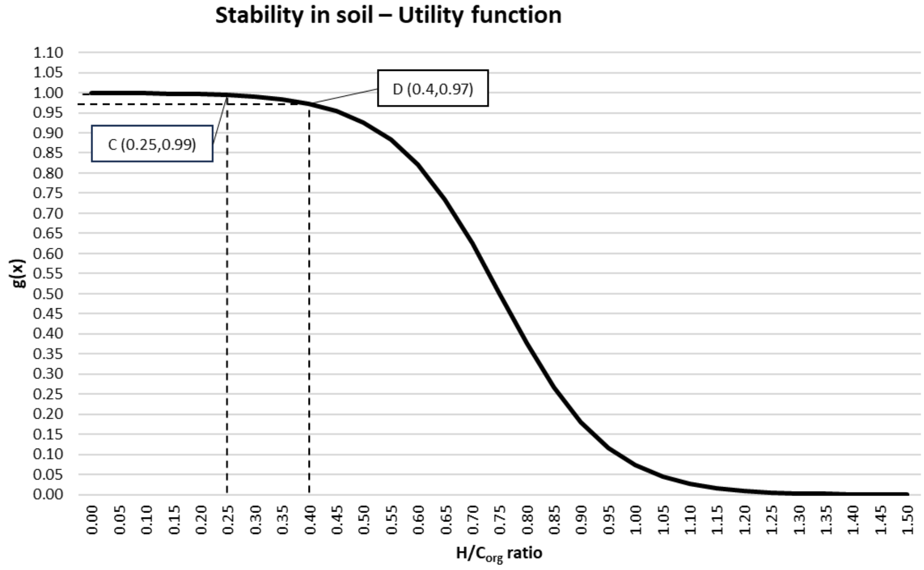


Figure 23 Potential utility function criterion stability in soil

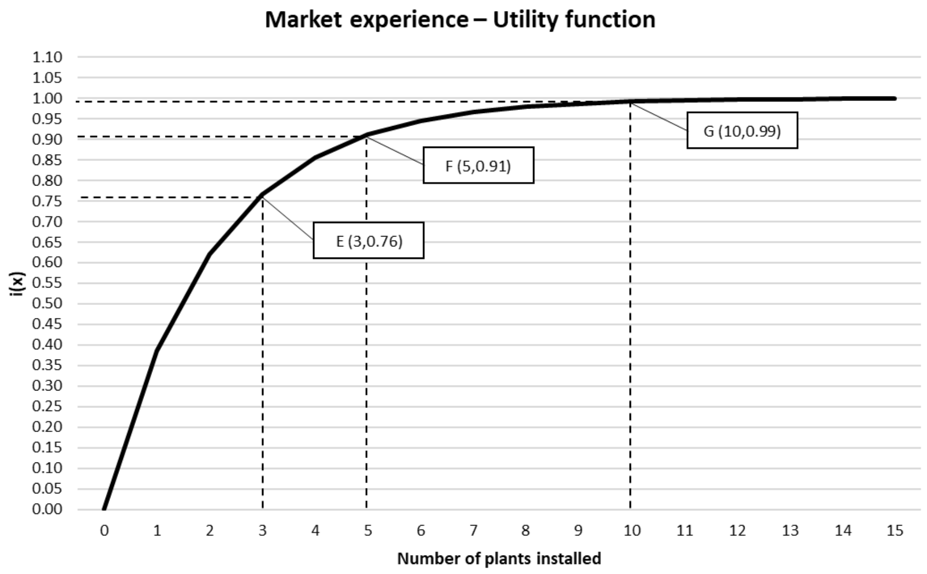


Figure 24 Potential utility functions for criterion market experience

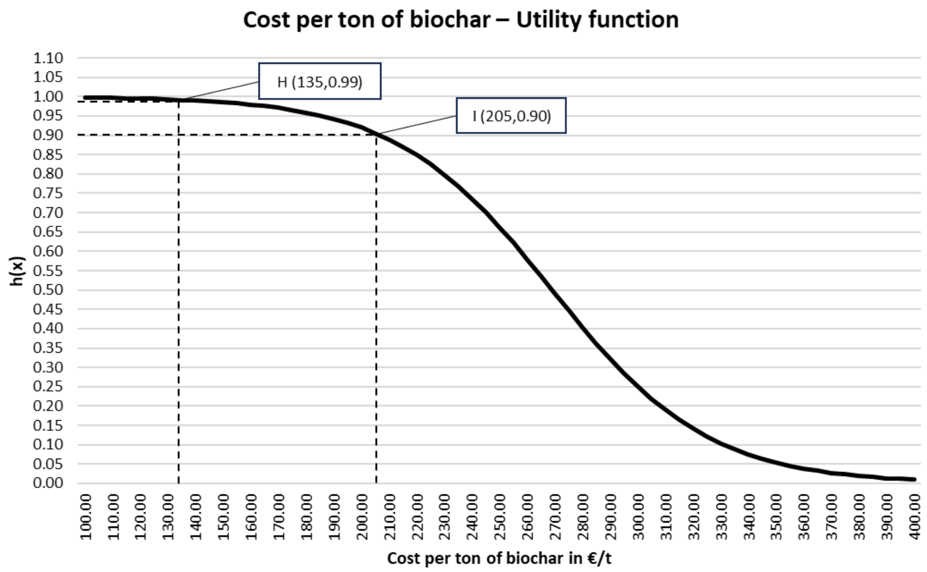


Figure 25 Potential utility functions for criterion cost per unit of biochar

The normalized scores for the selected criteria using the utility functions can be seen in Table 21.

Table 21 Normalization using equations established for a) carbon sequestration performance, b) stability in soil, c) market experience, and d) cost per ton of biochar

		Normalization acc. to Vafei et al. (2016,				**Linear sum normalization acc. to V**			
Alternatives A_i		A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4
Criteria (C_k)	Normalized values					Normalized values			
Production platform Biochar for soil amendment	n_{ij}	n_{1j}	n_{2j}	n_{3j}	n_{4j}	n_{1j}	n_{2j}	n_{3j}	n_{4j}
CORC factor (max)	n_{i1}	0.94	1.00	0.80	0.82	0.26	0.28	0.22	0.23
Water holding capacity (max)	n_{i2}	0.74	1.00	0.69	0.37	0.26	0.36	0.25	0.13
Stability in soil (min)	n_{i3}	0.9972	0.9958	0.9992	0.9962	0.26	0.26	0.26	0.26
Carbon sequestration potential (max)	n_{i4}	0.97	0.99	0.90	0.92	0.26	0.26	0.24	0.24
Biochar output (max)	n_{i5}	0.49	0.41	1.00	0.74	0.19	0.16	0.38	0.28
Biochar conversion rate (max)	n_{i6}	0.84	1.00	0.50	0.88	0.26	0.31	0.15	0.27
Plant availability (max)	n_{i7}	1.00	0.94	1.00	0.89	0.26	0.25	0.26	0.23
Treatment temperature range (max)	n_{i8}	0.67	0.44	0.00	1.00	0.32	0.21	0.00	0.47
Residence time range (max)	n_{i9}	0.50	0.50	0.00	1.00	0.25	0.25	0.00	0.50
Raw material capabilities									
Particle sizes possible (max)	n_{i10}	1.00	0.70	0.70	0.50	0.34	0.24	0.24	0.17
Moisture content possible (max)	n_{i11}	0.80	1.00	0.40	0.40	0.31	0.38	0.15	0.15
Experience with input materials (max)	ni_{12}	0.89	0.56	0.11	1.00	0.35	0.22	0.04	0.39
Material processing capability (max)	n_{i13}	0.67	0.67	0.33	1.00	0.25	0.25	0.13	0.38
Minimum lower heating value required (LHV) (min)	n_{i14}	0.42	0.42	0.77	0.00	0.26	0.26	0.48	0.00
Production platform green energy									
Heat yield (max)	n_{i15}	0.20	0.27	0.65	1.00	0.09	0.13	0.31	0.47
Electricity yield (max)	n_{i16}	0.07	0.12	1.00	0.12	0.05	0.09	0.77	0.09
Product capability (max)	n_{i17}	0.67	0.67	0.67	1.00	0.22	0.22	0.22	0.33
Supplier maturity									
Experience in the market (max)	n_{i18}	0.91	0.38	1.00	0.86	0.29	0.12	0.32	0.27
Pursuit for innovation (max)	n_{i19}	0.25	0.25	1.00	0.25	0.14	0.14	0.57	0.14
Market reputation (max)	n_{i20}	1.00	0.33	0.67	1.00	0.33	0.11	0.22	0.33
Financial performance									
Cost per unit of biochar (min)	n_{i21}	0.00	0.00	0.35	0.00	0.00	0.00	1.00	0.00
Cost for energy									
Cost per unit of heat (min)	n_{i22}	0.00	0.35	0.09	0.30	0.00	0.47	0.12	0.41
Cost per unit of electricity (min)	n_{i23}	0.00	0.31	0.39	0.38	0.00	0.29	0.36	0.35
Initial investment (min)	n_{i24}	0.39	0.57	0.00	0.45	0.28	0.41	0.00	0.32
Discounted Payback period (min)	n_{i25}	0.00	0.49	0.46	0.54	0.00	0.33	0.31	0.36
Return on investment (RoI) (max)	n_{i26}	0.13	1.00	0.88	0.95	0.05	0.34	0.30	0.32

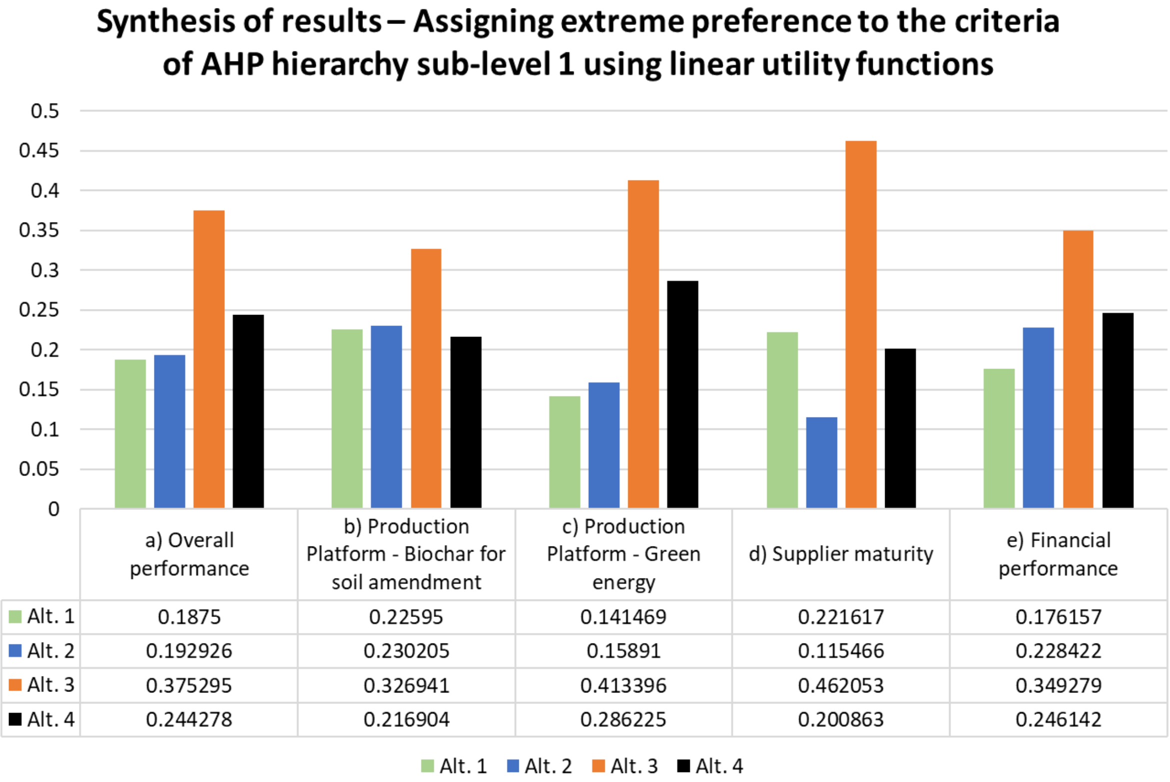
6.4 Synthesis of results & sensitivity analysis

Synthesis of results

Figure 26 shows the synthesis of results for the overall performance over all criteria and assigning extreme preference to one of the criteria on sub-level one of the AHP hierarchy. The results for the overall performance according to the stakeholder weightings, and four further categories on the main criteria levels are presented. For the results on criteria sub-level one the respective criterion was weighed with extreme importance (level 9) compared to the other criteria to determine the best alternative (alt.) for each case and to verify whether there would be a rank reversal in case of assigning extreme preference.

Answering SQ 6.1, the best alt. with the highest overall performance (Figure 26 a)) is alt. 3 with a normalized performance value of 0.375295 (see Figure 26) followed by alt. 4 with 0.244278, alt. 2 with

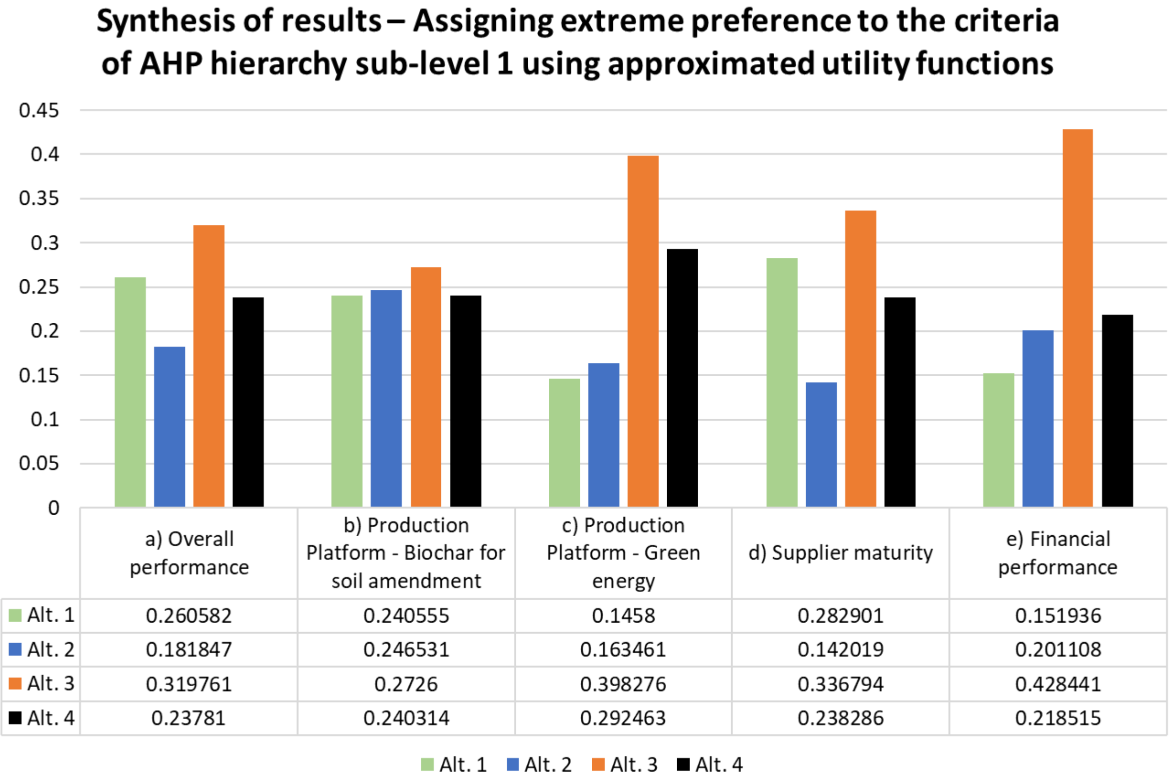
0.192926 and ultimately alt. 1 with a performance value of 0.1875 closely following alt. 2. Assigning extreme preference to the production platform for biochar for soil amendment (Figure 26 b)) results in a rank reversal with alt. 4 delivering the worst performance compared to the others. Alt. 1 moves to the third place and alt. 2 to the second. Alt. 3 remains the highest performing. Prioritizing the production platform for green energy (Figure 26 c)) leads to the same results as for the overall performance with again alt. 3 outperforming the remaining alternatives. For the criterion of supplier maturity alt. 3 remains in the first place as well, followed by alt. 1, alt. 4 and alt 2 in the last place (Figure 26 d)). Prioritizing the financial performance over all other criteria leads to the same results as for the overall performance (Figure 26 e)). These further four scenarios all show the superiority of alt. 3 towards all other alternatives answering SQ 6.2.



	a) Overall performance	b) Production Platform - Biochar for soil amendment	c) Production Platform - Green energy	d) Supplier maturity	e) Financial performance
🟩 Alt. 1	0.1875	0.22595	0.141469	0.221617	0.176157
🟦 Alt. 2	0.192926	0.230205	0.15891	0.115466	0.228422
🟧 Alt. 3	0.375295	0.326941	0.413396	0.462053	0.349279
⬛ Alt. 4	0.244278	0.216904	0.286225	0.200863	0.246142

Figure 26 Synthesis of results using linear utility functions, a) Overall performance, b) production platform - biochar for soil amendment, c) production platform - green energy, d) supplier maturity, e) financial performance

Using the utility functions for normalization introduced in section Normalization of data6.3 we can see a rank reversal for the overall performance of the alternatives. Alternative moves from the last place to the second-place overtaking alternatives 2 and 4. Alternative 3 remains at the top in every case (see Figure 27). Assigning extreme importance to the production platform for biochar for soil amendment (see Figure 27 b)) the difference in overall performance of the alternatives diminishes. The same occurs if the criteria production platform green energy, supplier maturity and financial performance are assigned extreme preference. In every case, apart from case e), the performance scores for alternative 1 increase. The performance scores for alternative 3 decrease in every case apart from case e). For alternative 2 the performance scores decrease for cases a) and e) and increase for b), c), and d). Alternative 4 experiences an increase of the performance scores in cases a), d), and e), and increase for case b), and c). Overall, introducing the utility functions to the model levels the performance scores, especially regarding the performance scores for alternative 3.



	a) Overall performance	b) Production Platform - Biochar for soil amendment	c) Production Platform - Green energy	d) Supplier maturity	e) Financial performance
🟩 Alt. 1	0.260582	0.240555	0.1458	0.282901	0.151936
🟦 Alt. 2	0.181847	0.246531	0.163461	0.142019	0.201108
🟧 Alt. 3	0.319761	0.2726	0.398276	0.336794	0.428441
⬛ Alt. 4	0.23781	0.240314	0.292463	0.238286	0.218515

Figure 27 Synthesis of results using approximated utility functions, a) Overall performance, b) production platform - biochar for soil amendment, c) production platform - green energy, d) supplier maturity, e) financial performance

Most critical criterion weight according to Triantaphyllou and Sánchez (1997)

Comparing alternatives 1 and 2, it becomes evident that the most critical criterion weight is the one for market reputation, changing the global weight by $\delta_{20,1,2}$ = +8.6% results in a rank reversal between alt. 1 and alt. 2. Increasing the global weight for stability in soil by $\delta_{3,1,2}$ = +10.03% would result in a rank versal between alternative 1 and alternative 2 (see Table 22).

Comparing alternatives 1-3, 1-4, 2-3, 2-4, and 3-4 no reasonable rank reversal is evident changing a global weight by a low percentage rate except for the stability in soil. This criterion provokes a change between alt. 1 and alt. 2 as well if its global weight is increased by a

The *Absolute-Top* (or AT) *critical criterion* is the most critical criterion with the smallest change δ_{kij} in global weight changing the ranking of the best (top) alternative.

This criterion is the residence time range, which would result in a rank reversal between alternative 3 and 4 if its global weight is increased by a change of $\delta_{9,3,4}$ = +29.35%.

The *Absolute-Any* (or AA) *critical criterion* is the most critical criterion with the smallest change δ_{kij} in global weight changing any ranking of alternatives. This is the market reputation again.

Concluding the sensitivity analysis regarding the most critical criteria, the model is robust, disregarding any required global weight increases or decreases $\delta_{k,i,j}$ >10.03% (see Table 22).

Table 22 Sensitivity analysis for the most critical criterion weight according to Triantaphyllou and Sánchez (1997)

	Global weights		**Sensitivity Analysis acc. to Triantaphyllou & Sánchez (1997)**						
Alternatives A_i				A_1-A_2	A_1-A_3	A_1-A_4	A_2-A_3	A_2-A_4	A_3-A_4
Criteria (C_k)	Global weights		Most critical criterion weight						
Production platform Biochar for soil amendment	W_k	Value	δk_{ij}	$\delta_{k,1,2}$	$\delta_{k,1,3}$	$\delta_{k,1,4}$	$\delta_{k,2,3}$	$\delta_{k,2,4}$	$\delta_{k,3,4}$
CORC factor (max)	W_1	9.7%	$\delta_{1,i,j}$	n/f	-584.68%	-266.73%	-368.63%	-130.94%	-1821.13%
Water holding capacity (max)	W_2	3.1%	$\delta_{2,i,j}$	n/f	-1449.27%	-63.06%	-193.16%	-28.53%	n/f
Stability in soil (min)	W_3	6.7%	$\delta_{3,i,j}$	-10.03%	n/f	-58.50%	n/f	n/f	n/f
Carbon sequestration potential (max)	W_4	5.2%	$\delta_{4,i,j}$	n/f	n/f	n/f	-4671.70%	n/f	-1622.79%
Biochar output (max)	W_5	2.3%	$\delta_{5,i,j}$	-64.21%	n/f	n/f	n/f	n/f	n/f
Biochar conversion rate (max)	W_6	1.8%	$\delta_{6,i,j}$	n/f	-217.53%	n/f	-135.39%	-173.81%	-123.40%
Plant availability (max)	W_7	2.5%	$\delta_{7,i,j}$	-131.80%	n/f	-288.34%	n/f	-444.88%	n/f
Treatment temperature range (max)	W_8	0.9%	$\delta_{8,i,j}$	-18.15%	-72.93%	n/f	-100.32%	n/f	-30.98%
Residence time range (max)	W_9	0.4%	$\delta_{9,i,j}$	n/f	-92.12%	n/f	-84.48%	n/f	-29.35%
Raw material capabilities									
Particle sizes possible (max)	W_{10}	0.2%	$\delta_{10,i,j}$	-18.46%	-222.63%	-48.47%	n/f	-93.49%	n/f
Moisture content possible (max)	W_{11}	0.2%	$\delta_{11,i,j}$	n/f	-149.70%	-54.33%	-91.52%	-27.94%	n/f
Experience with input materials (max)	W_{12}	0.3%	$\delta_{12,i,j}$	-14.64%	-75.67%	n/f	-121.45%	n/f	-42.19%
Material processing capability (max)	W_{13}	0.4%	$\delta_{13,i,j}$	n/f	-184.25%	n/f	-168.97%	n/f	-58.69%
Minimum lower heating value required (LHV) (min)	W_{14}	0.3%	$\delta_{14,i,j}$	n/f	n/f	-32.14%	n/f	-24.79%	n/f
Production platform green energy									
Heat yield (max)	W_{15}	9.6%	$\delta_{15,i,j}$	n/f	n/f	n/f	n/f	n/f	-89.56%
Electricity yield (max)	W_{16}	7.8%	$\delta_{16,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Product capability (max)	W_{17}	13.9%	$\delta_{17,i,j}$	n/f	n/f	n/f	n/f	n/f	-132.06%
Supplier maturity									
Experience in the market (max)	W_{18}	8.0%	$\delta_{18,i,j}$	-11.46%	n/f	-200.59%	n/f	n/f	n/f
Pursuit for innovation (max)	W_{19}	2.8%	$\delta_{19,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Market reputation (max)	W_{20}	3.6%	$\delta_{20,i,j}$	-8.60%	-207.28%	n/f	n/f	n/f	-132.06%
Financial performance									
Cost per unit of biochar (min)	W_{21}	8.2%	$\delta_{21,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Cost for energy									
Cost per unit of heat (min)	W_{22}	2.3%	$\delta_{22,i,j}$	n/f	n/f	n/f	-59.96%	-97.01%	-51.35%
Cost per unit of electricity (min)	W_{23}	0.7%	$\delta_{23,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Initial investment (min)	W_{24}	2.2%	$\delta_{24,i,j}$	n/f	-82.69%	n/f	-52.10%	-72.23%	-46.42%
Discounted Payback period (min)	W_{25}	2.8%	$\delta_{25,i,j}$	n/f	n/f	n/f	-1092.38%	n/f	-262.59%
Return on investment (RoI) (max)	W_{26}	4.0%	$\delta_{26,i,j}$	n/f	n/f	n/f	-507.70%	-360.51%	-618.69%

Most critical measure of performance according to Triantaphyllou and Sánchez (1997)

The lowest percentage increase for a criterion value provoking a rank reversal between alternative 1 and 2 would be an increase of $\delta_{15,1,2}$ = +23.94% for the heat yield of alternative 1 (see Table 23). For any other potential scenarios, the percentage increases necessary are $\delta_{k,I,j}$ > +100%.

The Absolute-Top (or AT) critical measure of performance is the most critical criterion with the smallest change in value of a_{ij} changing the ranking of the best (top) alternative. In this case there is no potential rank reversal. Alternative 3 is dominant in every aspect.

The Absolute-Any (or AA) critical measure of performance is the most critical measure with the smallest change in value of a_{ij} changing any ranking of alternatives. This is again the increase in heat yield for alternative 1.

Table 23 Sensitivity analysis for the most critical measure of performance according to Triantaphyllou and Sánchez (1997)

	Global weights		**Sensitivity Analysis acc. to Triantaphyllou & Sánchez (1997)**						
Alternatives A_i				A_1-A_2	A_1-A_3	A_1-A_4	A_2-A_3	A_2-A_4	A_3-A_4
Criteria (C_k)	Global weights		Most critical measure of performance						
Production platform Biochar for soil amendment	W_k	Value	δk_{ij}	$\delta_{k,1,2}$	$\delta_{k,1,3}$	$\delta_{k,1,4}$	$\delta_{k,2,3}$	$\delta_{k,2,4}$	$\delta_{k,3,4}$
CORC factor (max)	W_1	9.7%	$\delta_{1,i,j}$	-23.99%	n/f	-804.92%	n/f	-232.36%	n/f
Water holding capacity (max)	W_2	3.1%	$\delta_{2,i,j}$	-129.10%	n/f	n/f	n/f	n/f	n/f
Stability in soil (min)	W_3	6.7%	$\delta_{3,i,j}$	-54.36%	n/f	n/f	n/f	-1128.22%	n/f
Carbon sequestration potential (max)	W_4	5.2%	$\delta_{4,i,j}$	-55.75%	n/f	n/f	n/f	n/f	n/f
Biochar output (max)	W_5	2.3%	$\delta_{5,i,j}$	-594.28%	n/f	n/f	n/f	n/f	n/f
Biochar conversion rate (max)	W_6	1.8%	$\delta_{6,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Plant availability (max)	W_7	2.5%	$\delta_{7,i,j}$	-345.04%	n/f	n/f	n/f	n/f	n/f
Treatment temperature range (max)	W_8	0.9%	$\delta_{8,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Residence time range (max)	W_9	0.4%	$\delta_{9,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Raw material capabilities									
Particle sizes possible (max)	W_{10}	0.2%	$\delta_{10,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Moisture content possible (max)	W_{11}	0.2%	$\delta_{11,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Experience with input materials (max)	W_{12}	0.3%	$\delta_{12,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Material processing capability (max)	W_{13}	0.4%	$\delta_{13,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Minimum lower heating value required (LHV) (min)	W_{14}	0.3%	$\delta_{14,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Production platform green energy									
Heat yield (max)	W_{15}	9.6%	$\delta_{15,i,j}$	-23.94%	n/f	-171.92%	n/f	-99.48%	n/f
Electricity yield (max)	W_{16}	7.8%	$\delta_{16,i,j}$	-30.78%	n/f	n/f	n/f	n/f	n/f
Product capability (max)	W_{17}	13.9%	$\delta_{17,i,j}$	n/f	n/f	-117.94%	n/f	-71.66%	n/f
Supplier maturity									
Experience in the market (max)	W_{18}	8.0%	$\delta_{18,i,j}$	-40.16%	n/f	n/f	n/f	-252.60%	n/f
Pursuit for innovation (max)	W_{19}	2.8%	$\delta_{19,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Market reputation (max)	W_{20}	3.6%	$\delta_{20,i,j}$	-214.66%	n/f	n/f	n/f	n/f	n/f
Financial performance									
Cost per unit of biochar (min)	W_{21}	8.2%	$\delta_{21,i,j}$	-27.69%	n/f	-979.98%	n/f	-299.40%	n/f
Cost for energy									
Cost per unit of heat (min)	W_{22}	2.3%	$\delta_{22,i,j}$	-129.28%	n/f	n/f	n/f	n/f	n/f
Cost per unit of electricity (min)	W_{23}	0.7%	$\delta_{23,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Initial investment (min)	W_{24}	2.2%	$\delta_{24,i,j}$	-335.76%	n/f	n/f	n/f	n/f	n/f
Discounted Payback period (min)	W_{25}	2.8%	$\delta_{25,i,j}$	-105.70%	n/f	n/f	n/f	n/f	n/f
Return on investment (RoI) (max)	W_{26}	4.0%	$\delta_{26,i,j}$	-58.58%	n/f	n/f	n/f	n/f	n/f

Most critical criterion weight using utility functions

Table 25 shows the sensitivity analysis conducted for the criterion weights after implementation of the exemplary utility functions to the AHP model. The global weights for market reputation and experience in the market are the most sensitive criteria weights with a change in weight of $\delta_{20,1,2}$ = +11.02% resulting in a rank reversal between alt. 1 and alt. 2 and a change in weight of $\delta_{19,1,2}$ = +14.46% also resulting in a rank reversal between alt. 1 and alt. 2.

Table 24 Sensitivity analysis according to Triantaphyllou and Sánchez (1997) for the most critical criterion weight using utility functions for a) carbon sequestration performance, b) stability in soil, c) market experience and d) cost per ton of biochar

	Global weights		**Sensitivity Analysis acc. to Triantaphyllou & Sánchez (1997)**						
Alternatives A_i				A_1-A_2	A_1-A_3	A_1-A_4	A_2-A_3	A_2-A_4	A_3-A_4
Criteria (C_k)	Global weights		Most critical criterion weight						
Production platform Biochar for soil amendment	W_k	Value	δk_{ij}	$\delta_{k,1,2}$	$\delta_{k,1,3}$	$\delta_{k,1,4}$	$\delta_{k,2,3}$	$\delta_{k,2,4}$	$\delta_{k,3,4}$
CORC factor (max)	W_1	9.7%	$\delta_{1,i,j}$	n/f	-452.75%	-263.84%	-268.51%	-118.15%	-1187.41%
Water holding capacity (max)	W_2	3.1%	$\delta_{2,i,j}$	n/f	-1122.25%	-62.38%	-140.70%	-25.74%	n/f
Stability in soil (min)	W_3	6.7%	$\delta_{3,i,j}$	-6675.16%	n/f	-31679.22%	n/f	n/f	n/f
Carbon sequestration potential (max)	W_4	5.2%	$\delta_{4,i,j}$	n/f	-926.74%	-626.49%	-684.74%	-354.29%	-1581.83%
Biochar output (max)	W_5	2.3%	$\delta_{5,i,j}$	-82.35%	n/f	n/f	n/f	n/f	n/f
Biochar conversion rate (max)	W_6	1.8%	$\delta_{6,i,j}$	n/f	-168.45%	n/f	-98.62%	-156.82%	-80.46%
Plant availability (max)	W_7	2.5%	$\delta_{7,i,j}$	-169.02%	n/f	-285.21%	n/f	-401.41%	n/f
Treatment temperature range (max)	W_8	0.9%	$\delta_{8,i,j}$	-23.27%	-56.48%	n/f	-73.08%	n/f	-20.20%
Residence time range (max)	W_9	0.4%	$\delta_{9,i,j}$	n/f	-71.34%	n/f	-61.54%	n/f	-19.13%
Raw material capabilities									
Particle sizes possible (max)	W_{10}	0.2%	$\delta_{10,i,j}$	-23.68%	-172.40%	-47.95%	n/f	-84.35%	n/f
Moisture content possible (max)	W_{11}	0.2%	$\delta_{11,i,j}$	n/f	-115.92%	-53.74%	-66.67%	-25.21%	n/f
Experience with input materials (max)	W_{12}	0.3%	$\delta_{12,i,j}$	-18.78%	-58.60%	n/f	-88.46%	n/f	-27.51%
Material processing capability (max)	W_{13}	0.4%	$\delta_{13,i,j}$	n/f	-142.67%	n/f	-123.08%	n/f	-38.27%
Minimum lower heating value required (LHV) (min)	W_{14}	0.3%	$\delta_{14,i,j}$	n/f	n/f	-31.79%	n/f	-22.37%	n/f
Production platform green energy									
Heat yield (max)	W_{15}	9.6%	$\delta_{15,i,j}$	n/f	n/f	n/f	n/f	n/f	-58.39%
Electricity yield (max)	W_{16}	7.8%	$\delta_{16,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Product capability (max)	W_{17}	13.9%	$\delta_{17,i,j}$	n/f	n/f	n/f	n/f	n/f	-86.11%
Supplier maturity									
Experience in the market (max)	W_{18}	8.0%	$\delta_{18,i,j}$	-14.64%	n/f	-471.97%	n/f	n/f	n/f
Pursuit for innovation (max)	W_{19}	2.8%	$\delta_{19,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Market reputation (max)	W_{20}	3.6%	$\delta_{20,i,j}$	-11.02%	-160.51%	n/f	n/f	n/f	-86.11%
Financial performance									
Cost per unit of biochar (min)	W_{21}	8.2%	$\delta_{21,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Cost for energy									
Cost per unit of heat (min)	W_{22}	2.3%	$\delta_{22,i,j}$	n/f	n/f	n/f	-43.68%	-87.53%	-33.48%
Cost per unit of electricity (min)	W_{23}	0.7%	$\delta_{23,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Initial investment (min)	W_{24}	2.2%	$\delta_{24,i,j}$	n/f	-64.03%	n/f	-37.95%	-65.17%	-30.27%
Discounted Payback period (min)	W_{25}	2.8%	$\delta_{25,i,j}$	n/f	n/f	n/f	-795.70%	n/f	-171.21%
Return on investment (RoI) (max)	W_{26}	4.0%	$\delta_{26,i,j}$	n/f	n/f	n/f	-369.81%	-325.28%	-403.39%

Most critical measure of performance using utility functions

Table 25 shows the sensitivity analysis conducted for the most critical measure of performance after implementation of the utility functions to the AHP model. The most critical measures of performance are the heat yield requiring a change in value of $\delta_{15,1,2}$ = +32.92% and the cost per unit of biochar requiring a change in value of $\delta_{21,1,2}$ = +42.06% resulting in a rank reversal between alternatives 1 and 2.

Table 25 Sensitivity analysis according to Triantaphyllou and Sánchez (1997) for the most critical measure of performance using utility functions for a) carbon sequestration performance, b) stability in soil, c) market experience and d) cost per ton of biochar

	Global weights		**Sensitivity Analysis acc. to Triantaphyllou & Sánchez (1997)**						
Alternatives A_i				A_1-A_2	A_1-A_3	A_1-A_4	A_2-A_3	A_2-A_4	A_3-A_4
Criteria (C_k)	Global weights		Most critical measure of performance						
Production platform Biochar for soil amendment	W_k	Value	δk_{ij}	$\delta_{k,1,2}$	$\delta_{k,1,3}$	$\delta_{k,1,4}$	$\delta_{k,2,3}$	$\delta_{k,2,4}$	$\delta_{k,3,4}$
CORC factor (max)	W_1	9.7%	$\delta_{1,i,j}$	-32.99%	n/f	-732.23%	n/f	-170.86%	n/f
Water holding capacity (max)	W_2	3.1%	$\delta_{2,i,j}$	-260.55%	n/f	n/f	n/f	n/f	n/f
Stability in soil (min)	W_3	6.7%	$\delta_{3,i,j}$	-57.66%	n/f	n/f	n/f	-658.66%	n/f
Carbon sequestration potential (max)	W_4	5.2%	$\delta_{4,i,j}$	-88.52%	n/f	n/f	n/f	n/f	n/f
Biochar output (max)	W_5	2.3%	$\delta_{5,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Biochar conversion rate (max)	W_6	1.8%	$\delta_{6,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Plant availability (max)	W_7	2.5%	$\delta_{7,i,j}$	-17233.23%	n/f	n/f	n/f	n/f	n/f
Treatment temperature range (max)	W_8	0.9%	$\delta_{8,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Residence time range (max)	W_9	0.4%	$\delta_{9,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Raw material capabilities									
Particle sizes possible (max)	W_{10}	0.2%	$\delta_{10,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Moisture content possible (max)	W_{11}	0.2%	$\delta_{11,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Experience with input materials (max)	W_{12}	0.3%	$\delta_{12,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Material processing capability (max)	W_{13}	0.4%	$\delta_{13,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Minimum lower heating value required (LHV) (min)	W_{14}	0.3%	$\delta_{14,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Production platform green energy									
Heat yield (max)	W_{15}	9.6%	$\delta_{15,i,j}$	-32.92%	n/f	-166.94%	n/f	-81.80%	n/f
Electricity yield (max)	W_{16}	7.8%	$\delta_{16,i,j}$	-43.23%	n/f	n/f	n/f	n/f	n/f
Product capability (max)	W_{17}	13.9%	$\delta_{17,i,j}$	n/f	n/f	-115.18%	n/f	-60.43%	n/f
Supplier maturity									
Experience in the market (max)	W_{18}	8.0%	$\delta_{18,i,j}$	-58.15%	n/f	n/f	n/f	-172.08%	n/f
Pursuit for innovation (max)	W_{19}	2.8%	$\delta_{19,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Market reputation (max)	W_{20}	3.6%	$\delta_{20,i,j}$	-698.98%	n/f	n/f	n/f	n/f	n/f
Financial performance									
Cost per unit of biochar (min)	W_{21}	8.2%	$\delta_{21,i,j}$	-42.60%	n/f	n/f	-1515.62%	-244.17%	n/f
Cost for energy									
Cost per unit of heat (min)	W_{22}	2.3%	$\delta_{22,i,j}$	-261.11%	n/f	n/f	n/f	n/f	n/f
Cost per unit of electricity (min)	W_{23}	0.7%	$\delta_{23,i,j}$	n/f	n/f	n/f	n/f	n/f	n/f
Initial investment (min)	W_{24}	2.2%	$\delta_{24,i,j}$	-8301.12%	n/f	n/f	n/f	n/f	n/f
Discounted Payback period (min)	W_{25}	2.8%	$\delta_{25,i,j}$	-193.23%	n/f	n/f	n/f	n/f	n/f
Return on investment (RoI) (max)	W_{26}	4.0%	$\delta_{26,i,j}$	-90.02%	n/f	n/f	n/f	n/f	n/f

6.4.1 Scenario analysis

According to the expected market developments, five further scenarios are considered to change the performance measures for the different alternatives through calculation of the financial criteria of payback period, cost per unit of biochar, return on investment, cost per unit of electricity and cost per unit of heat using scenarios. Potential scenarios target the moderator variables raw material price, sales price for biochar, the sales price development for CO2 removal certificates, the sales price development for heat, and the sales price for electricity (see Figure 28). The goal of this scenario analysis is to investigate potential rank reversals (Barzilai & Golany, 1994; Wijnmalen & Wedley, 2008) caused by factoring in these market developments for the evaluation of the different alternatives.

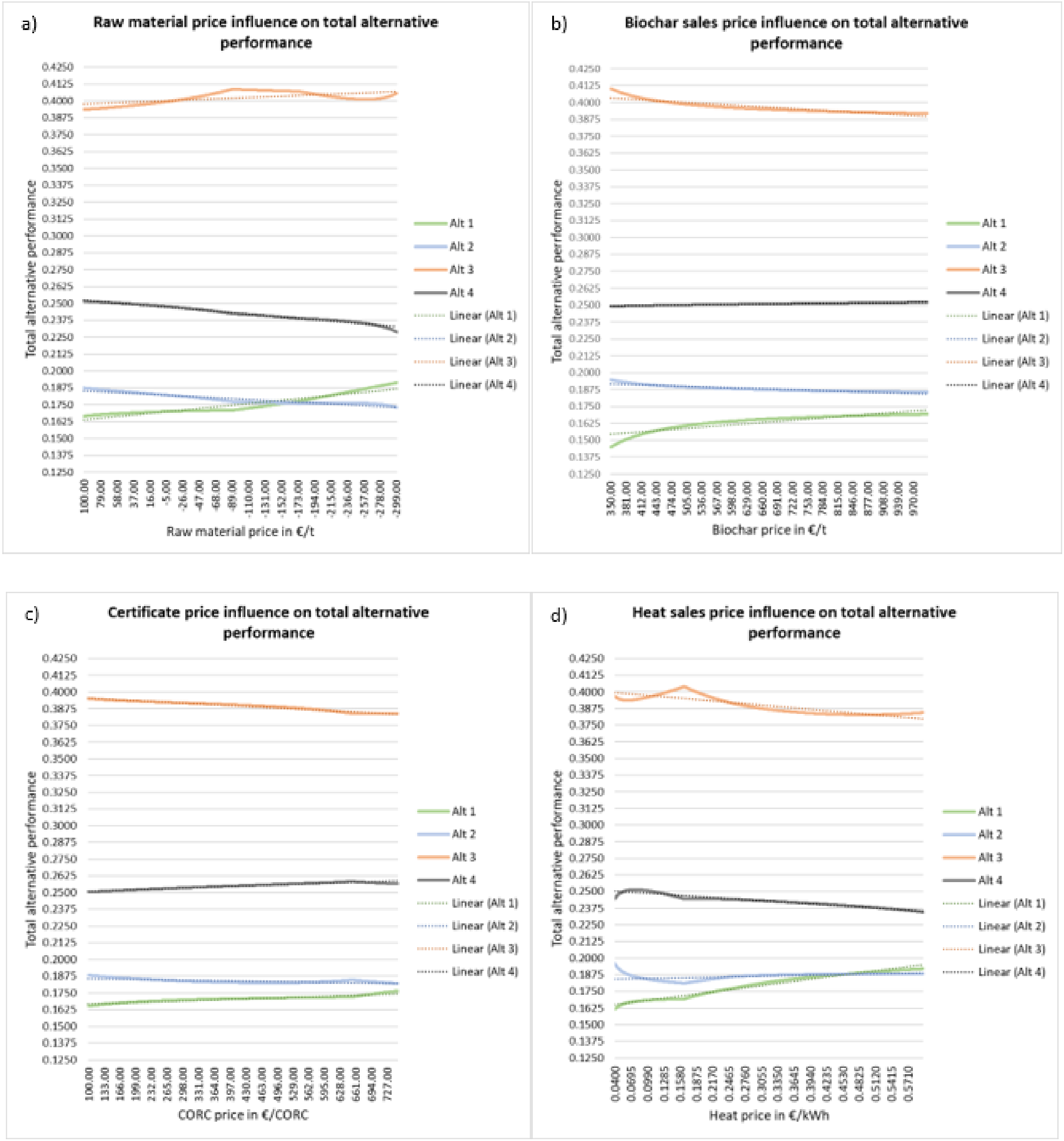
As Figure 28 a) shows the total alternative performance over the raw material price in an interval between 100.00€/t to -300.00€/t. A negative input material price represents an additional revenue stream. The total alternative performance factors for alternatives 1 and 3 increase the lower the material price indicated by the positive slope of their functions. The slopes of the functions of alternative 2 and 4 are negative with decreasing raw material price. We can see a rank reversal occurring between alternative 1 and 2 at a negative raw material price of -159.00€. At this point the performance factors for alternative 1 and 2 are at parity. Further rank reversals which might be expected for alternatives 1 and 4 with further decreasing negative raw material price lie beyond any reasonable scenario.

Figure 3 b) shows the influence of the biochar sales price on the alternatives' total performance factor in an interval between 350.00€/t to 1,000.00€/t. The total performance factors for alternatives 2 and 3 slightly decrease with a higher biochar price than the ones for alternatives 1 and 2 increase indicated by the slopes of their functions. The figure does not indicate any potential rank reversal changing the biochar price in the present interval.

Figure 28 c) presents the carbon removal certificate price's influence on the performance of the alternatives in an interval from 100.00€ to 750.00€. The total alternative performance factors slightly decrease for alternative 3 and alternative 2 with increasing carbon removal certificate price indicated by the negative slope of the functions. The slopes of the functions for alternatives 1 and 4 are positive, indicating an increase in their performance factor. A potentially expected rank reversal between alternative 1 and 2 lies outside of the investigated interval. Increasing the carbon removal certificate price has no effect on the ranking of the four alternatives.

In Figure 28 d) changing the heat price in an interval between 0.04 €/kWh to 0.6 €/kWh decreases the total performance factors for alternatives 3 and 4 indicated by their negative slopes. The performance factor curves for alternatives 1 and 2 are positive with a higher slope for alternative 1. The figure shows a rank reversal between alternative 1 and 2 at a price of 0.4614 €/kWh. The analysis shows no further rank reversal in the interval presented.

Finally, in Figure 28 e) the electricity price is changed in an interval between 0.0111 €/kWh to 0.30 €/kWh. The performance factors for alternatives 1 and 3 increase while the ones for alternatives 2 and 4 decrease. No rank reversal occurs in the interval presented.


a)
Raw material price influence on total alternative performance
Total alternative performance
0.4250
0.4125
0.4000
0.3875
0.3750
0.3625
0.3500
0.3375
0.3250
0.3125
0.3000
0.2875
0.2750
0.2625
0.2500
0.2375
0.2250
0.2125
0.2000
0.1875
0.1750
0.1625
0.1500
0.1375
0.1250
100.00
79.00
58.00
37.00
16.00
-5.00
-26.00
-47.00
-68.00
-89.00
-110.00
-131.00
-152.00
-173.00
-194.00
-215.00
-236.00
-257.00
-278.00
-299.00
Raw material price in €/t
Alt 1
Alt 2
Alt 3
Alt 4
Linear (Alt 1)
Linear (Alt 2)
Linear (Alt 3)
Linear (Alt 4)
b)
Biochar sales price influence on total alternative performance
Total alternative performance
350.00
381.00
412.00
443.00
474.00
505.00
536.00
567.00
598.00
629.00
660.00
691.00
722.00
753.00
784.00
815.00
846.00
877.00
908.00
939.00
970.00
Biochar price in €/t
Alt 1
Alt 2
Alt 3
Alt 4
Linear (Alt 1)
Linear (Alt 2)
Linear (Alt 3)
Linear (Alt 4)
c)
Certificate price influence on total alternative performance
Total alternative performance
100.00
133.00
166.00
199.00
232.00
265.00
298.00
331.00
364.00
397.00
430.00
463.00
496.00
529.00
562.00
595.00
628.00
661.00
694.00
727.00
CORC price in €/CORC
Alt 1
Alt 2
Alt 3
Alt 4
Linear (Alt 1)
Linear (Alt 2)
Linear (Alt 3)
Linear (Alt 4)
d)
Heat sales price influence on total alternative performance
Total alternative performance
0.0400
0.0695
0.0990
0.1285
0.1580
0.1875
0.2170
0.2465
0.2760
0.3055
0.3350
0.3645
0.3940
0.4235
0.4530
0.4825
0.5120
0.5415
0.5710
Heat price in €/kWh
Alt 1
Alt 2
Alt 3
Alt 4
Linear (Alt 1)
Linear (Alt 2)
Linear (Alt 3)
Linear (Alt 4)

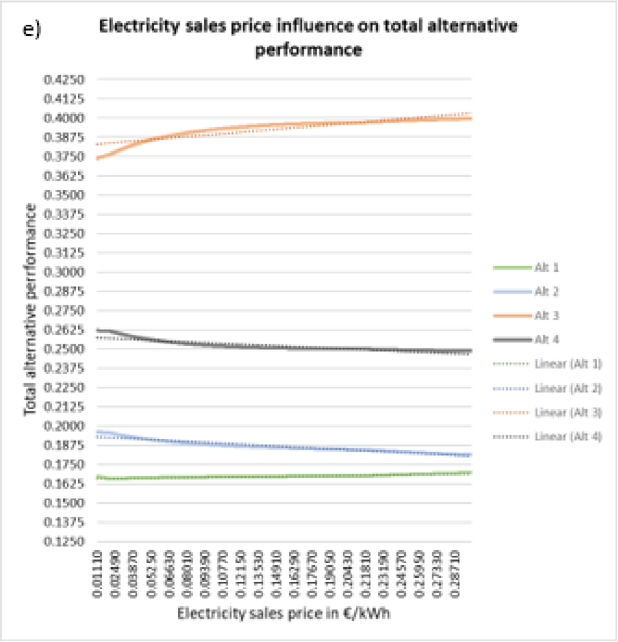
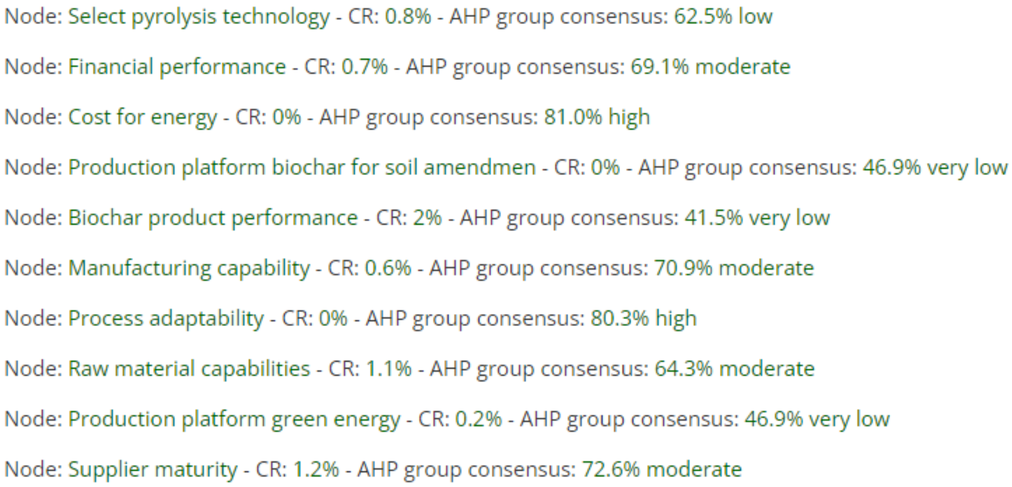


Figure 28 Scenario analysis of total alternative performance for moderator variables a) raw material price, b) biochar sales price, c) CO2 certificate price, d) heat sales price, and e) electricity sales price

6.4.2 Consistency and group consensus

Before conducting the AHP survey, decision makers were advised to consider the consistency of their pairwise comparisons. The AHP-OS software indicates the consistency ratio for each pairwise comparison by showing the percentage achieved to the stakeholders while conducting the survey. In case consistency exceeds the threshold of 10% the software further recommends adaptations to the individual stakeholders to improve consistency of judgement. The maximum consistency ratio achieved for the aggregated individual judgements (AIJ) using the geometric mean of the decision makers' individual rankings ranges from 0.0% for the nodes of process adaptability and the cost for energy to a maximum of 2.0% for the node of biochar product performance, ranging below the threshold of 10%. The rankings are therefore consistent (see Figure 29).



Node: Select pyrolysis technology - CR: 0.8% - AHP group consensus: 62.5% low

Node: Financial performance - CR: 0.7% - AHP group consensus: 69.1% moderate

Node: Cost for energy - CR: 0% - AHP group consensus: 81.0% high

Node: Production platform biochar for soil amendmen - CR: 0% - AHP group consensus: 46.9% very low

Node: Biochar product performance - CR: 2% - AHP group consensus: 41.5% very low

Node: Manufacturing capability - CR: 0.6% - AHP group consensus: 70.9% moderate

Node: Process adaptability - CR: 0% - AHP group consensus: 80.3% high

Node: Raw material capabilities - CR: 1.1% - AHP group consensus: 64.3% moderate

Node: Production platform green energy - CR: 0.2% - AHP group consensus: 46.9% very low

Node: Supplier maturity - CR: 1.2% - AHP group consensus: 72.6% moderate

Figure 29 Consistency ratio by node and AHP group consensus

For determining the group consensus of the AHP ratings, Goepel (2018) differentiates between five levels of consensus:

- Very low consensus: below 50% (disagreement
- Low consensus: 50% to 67.5%
- Moderate consensus: 67.5% to 75%
- High consensus: 75% to 87.5%
- Very high consensus: above 87.5% (excellent agreement)

Values of below 50% indicate that there is practically no consensus withing the group and a high diversity of judgement. Values above 87.5% indicate a high overlap of priorities and excellent agreement of judgements from the group members.

As depicted in Figure 29 for the overall goal of selecting the most profitable and capable pyrolysis technology configuration only low group consensus was achieved with an AHP group consensus of 62.5%. For the sub-criteria of the production platform for biochar for soil amendment, the biochar product performance, and the production platform for green energy practically no agreement among the stakeholders could be achieved indicated by a group consensus of 46.9%, 41.5%, and 46.9% respectively. The level of consensus for all other nodes ranges from moderate to very high. No excellent agreement was achieved among the stakeholder judgements.

Stakeholder group consensus with regard to the technology selection goal indicates that the stakeholder preferences are not well aligned. This might result from the fact that the startup as well as the market is in an early stage of development. Differentiating between the production platforms and preferring one over the other might not be intuitive to the stakeholders due to the fact that all inherent benefits and value streams need to be monetarized to render a business case profitable.

Further, depending on the respective function and the position of a stakeholder and unit of the stakeholder the preferences are different. Site development for example might prefer the potential to convert renewable energy using the technology due to a higher potential for adoption of the technology by the market compared to BCR. The carbon removal officer assigned higher emphasis on the production platform for biochar for soil amendment, especially on the carbon sequestration performance.

6.5 Chapter summary

Chapter 6 presents the findings of an Analytic Hierarchy Process (AHP) study conducted to select an integrated pyrolysis manufacturing system. Seven experts from various units, including site development, biochar and substrates, industrial materials, carbon credits, and site operations, participated in pairwise comparisons. These experts represented different functions such as product, marketing, sales, finance, R&D, and supply chain management.

The study involved the identification of 26 criteria, with the stakeholders determining the global weights (GW) for each criterion through conducting pairwise comparisons. On criteria level one the most important criterion is the production platform for biochar for soil amendment followed by the production platform for green energy, the financial performance and ultimately the supplier maturity. The most important criterion on global level, with a GW of 13.9%, was the product capability of the manufacturing platform for green energy. Other significant criteria included carbon sequestration performance (9.7%), heat yield (9.6%), cost per unit of biochar (8.2%), supplier's market experience (8.0%), and electricity yield of the manufacturing system (7.8%).

Data normalization was performed using two approaches: linear max normalization and linear sum. Additionally, utility functions were introduced for four important criteria carbon sequestration performance, stability in soil, market experience, and cost per unit of biochar, to test the model for robustness and evaluate potential rank reversals.

Apart from assessing the overall alternative performance score the synthesis of results was conducted by assigning extreme preferences to the criteria in the AHP hierarchy sub-level 1 to evaluate the impact on the suggested ranking of alternatives. Answering SQ 6.1 *Which integrated manufacturing system alternative is the most profitable one satisfying all requirements of all production platforms to the highest extent?* (i.e., exhibits the highest overall performance score) the synthesis of results revealed that alternative 3, a two-step pyrolysis gasification reactor, was superior when using both linear utility functions and the utility functions suggested. Alternative 3 is followed by alternative 4, 2 and ultimately 1. However, a rank reversal was observed between alternatives 1, 2, and 4 for overall alternative performance score when the utility functions were applied to the model.

Answering SQ 6.2 *Which integrated manufacturing system is the best one for each production platform?* further analysis demonstrated that assigning extreme preferences to the criteria on hierarchy sub-level 1 yielded consistent results when using both linear utility functions and suggested utility functions.

Additionally, a sensitivity analysis according to Triantaphyllou and Sánchez (1997) was conducted to test the model for robustness. The analysis revealed that the market reputation and stability in soil exhibit the most critical criteria weights , resulting in rank reversals between alternatives 1 and 2 when using linear utility functions. However, when suggested utility functions were applied, market reputation and experience remained significant, while heat yield and cost per unit of biochar became the most critical performance measures.

Finally, a scenario analysis was conducted changing moderator variables for the calculation of the financial criteria. Biochar sales price, biomass price, the carbon certificate sales price, and the heat and electricity sales price were changed over different intervals. The sensitivity analysis confirmed the model's robustness, as changes in raw material price and heat sales price had the highest influence on the rankings. However, these changes were highly improbable, further validating the model's reliability.

It was noted that stakeholder consensus regarding preference assignments to different criteria was low, potentially due to insufficient preparation or the strategic orientation phase of the startup company involved in the study.

7 Discussion

The research objective of this thesis was to identify the most profitable and capable integrated manufacturing system for the valorization of waste biomass into green energy, biochar, and CO2 sequestration certificates. This objective was approached through a platform-based design perspective for non-assembled products, taking into account current technology and market developments. To achieve this, the research question was formulated: Which *pyrolysis technology alternative* is the most profitable and capable for the realization of a high variety strategy for *biochar production, green energy* and *carbon removal* taking a *platform-based design perspective for non-assembled products?*

To address this research question, the second chapter introduced the theory of platform-based design to the reader, with a focus on platform-based design for non-assembled products. The chapter further explained different platform concepts, including product-, process-, raw-material, and production platform, in the context of biochar systems. Chapter 3 and 4 also discussed the requirements for raw material selection, processes, and products based on biochar theory. Subsequently, chapter 5 established a comprehensive set of criteria for the evaluation of integrated pyrolysis manufacturing systems, which were subsumed under four clusters in line with the research goal: the production platform for biochar for soil amendment, the production platform for green energy, supplier maturity, and financial performance.

To determine potential alternatives for evaluation, currently available alternatives on the market were researched and filtered. Data was then requested from the suppliers for the evaluation of the alternatives based on the comprehensive set of criteria established in the previous step. Finally, the author performed an Analytic Hierarchy Process (AHP) analysis, including retrieval of pairwise comparisons from relevant decision makers as well as an evaluation of the alternatives based on data provided by the suppliers. A sensitivity analysis was conducted to determine the robustness of the AHP model.

This discussion takes up platform-based design theory and the notion of commonality again and reflects on its applicability to biochar systems. Subsequently, it focuses on answering the following sub-research questions and provides an answer for the overall research question.

SQ 6.1 Which integrated manufacturing system alternative is the most profitable one satisfying all requirements of all production platforms to the highest extent?

SQ 6.2 Which integrated manufacturing system is the best one for each production platform?

7.1 Biochar systems & platform-based design for non-assembled products

Commonality is touted as one of the leading paradigms of platforming for products, processes and raw materials according to Lager (2017) and R. Andersen (2022). The goal is to identify common subsystems to reduce complexity of products, processes and raw materials selection and thus realize cost savings and efficiency gains in product development and process configuration.

Product structure - Biochar functionalities

The arrangement of functional elements according to K. Ulrich (1995) and developed for assembled products also applies to the non-assembled biochar product. The same functions of the product can be leveraged over different customer segments and satisfy customer needs in different final applications as seen for the production platform for biochar for soil amendment. As becomes apparent, the physical and chemical properties of the carbonaceous material translate directly into its functionalities, a main difference to assembled products. A function structure as for assembled products and in accordance with Lager (2016), Lager (2017) and Meyer and Dalal (2002) can be developed based on the inherent physical and chemical properties and the resulting benefits with incorporation into soil. However, a hierarchy between functional elements as suggested by K. Ulrich (1995) can (at least at the current state of product development in the biochar industry) not be identified. Although research on biochar products claims a high diversity of applications and different versatile range of benefits being requested by different customers, the main appealing functionalities are its water holding capacity as well as inherent carbon sequestration potential (Köhler, 2022; Lehmann & Joseph, 2015). Furthermore, with the application of biochar to soil, all resulting benefits usually unfold for the material, only different functionalities are more emphasized by customers depending on the type of application, i.e., for agricultural applications compared to soil remediation purposes. It remains to be determined whether the specific chemical properties of biochar can be tailored by adapting process parameters and raw material selection to further develop one functionality of the product and hence further differentiating the material according to its functionalities (Ippolito et al., 2020; Lehmann & Joseph, 2015; Marshall et al., 2019; Weber & Quicker, 2018).

From the perspective of a manufacturing company, biochar product differentiation currently happens through processing various raw materials through the same integrated pyrolysis manufacturing system (Ziegner & Milla, 2022). As according to A.-L. Andersen et al. (2022), R. Andersen et al. (2022) and Lager (2017) the process is in this case at the heart of innovation. But rather than comparing different biochar products and trying to find commonalities in processes, industry practitioners take a bottom-up approach and try to utilize the products of the material transformation process to the highest extent possible with an integrated philosophy. The identification of commonalities converges with the raw material selection. Here it becomes apparent that all different value propositions, for biochar for soil amendment, green energy and carbon removal impose their respective restrictions on material selection. This results in a limited focus on lignocellulosic biomass which benefits all value propositions and is oriented towards the current market developments in terms of regulations and standards available for these products (EBC, 2012-2022, 2022).

In this regard, biochar from lignocellulosic biomass appears to be a commodity at least considering wooden input material in form of agricultural or forestry residues as currently practiced by the company and the suppliers.

In that sense decoupling the production platforms from each other is hardly possible, because the central material transformation process of pyrolysis is the enabler of the production platform for green energy products (Li et al., 2019; Mong et al., 2022; Zhang et al., 2022). Naturally, biochar could be produced without the subsystem for energy recovery. However, an important value stream, necessary also for the viability of the whole system from an economic perspective, as well as additional environmental benefit considering an ecological perspective, would be lost (Garcia-Peréz et al., 2020; Pantaleo et al., 2014).

Structuring the biochar system and the interaction between its diverse products in form of solid fuels, energy products and carbon removal certificates according to the platform-based philosophy for non-assembled products advocated by Lager (2017) and assigning standardized linguistic terms to the processes which are part of a biochar system, enables practitioners to deal with the complexity of a multifaceted interrelated system and the ecologic as well as economic possibilities that biochar systems provide. Separating the process platform in different subsystems and modules helps with further understanding the interrelationships and with deconstructing the potential alternatives offered on the market.

Biochar from lignocellulosic raw materials appears to be a commodity at the moment, exhibiting a shallow product structure as R. Andersen et al. (2022) describe it, therefore a high variety strategy based on this underlying material selection is rather limited, although material refinement processes as well as a technology configuration's material processing capability might provide a basis for differentiation according to the physical properties.

However, utilizing the full potential of the thermochemical transformation process of pyrolysis and considering product diversification at the raw material level, new economic and ecologic opportunities could be identified in the long-term (Dhyani & Bhaskar, 2019; Lehmann & Joseph, 2015; Y. Yang et al., 2017). Including further customer needs such as for proper management of waste would result in a diversification of biochar products since not all types of biochar can be easily incorporated into soil due to regulatory constraints (EBC, 2012-2022, 2022). This would however require further development of the regulatory framework and needs to be based on more evident results from literature (Huygens et al., 2019).

From a biochar manufacturing company's perspective the further downstream differentiation of biochar follows a V-Type flow pattern, as described by Meyer and Dalal (2002), Lager (2017), and Samuelson and Lager (2019). Industrial customers are largely downstream manufacturers that blend the biochar product or further mechanically transform it for the final customer. This process industry characteristic trait can be confirmed for biochar systems (Köhler, 2022, 2023).

Process platforms – The pyrolysis process and integration of subsystems

For the process platforms for biochar production commonalities can in so far be identified as the two different production platforms of biochar for soil amendment and green energy restrict or contradict each other in the selection of raw materials and processes in case both product families are expected to be optimized. This starts at the general principles of the material transformation process which can either be oriented towards generating a higher output of a gaseous phase for subsequent energetical conversion into renewable energy products, or towards the solid fuel yield. Slow pyrolysis and fast pyrolysis as well as different reactor configurations and other thermochemical transformation techniques like gasification offer different possibilities in this regard (Campuzano et al., 2019; Dhyani & Bhaskar, 2019; Garcia-Nunez et al., 2017; Mong et al., 2022; Raza et al., 2021). Here, depending on the customer requirements and economic potential resulting from these needs a decision would need to be already taken whether to select one alternative configuration, or the other for optimization of a production platform's respective products and solutions to the customer. The empirical analysis of this thesis also exemplifies this matter of fact (compare alternatives 1,2 and 4 with alternative 3).
In that sense, the financial calculations and results of the AHP model as explained in the next section show that investments into the process equipment are the foundation for product development and to achieve a variety in solutions offered to the final customers confirming the findings expressed by Mogensen et al. (2022) and Lager (2017).

The input material grade, availability and price are highly variable leading to the fact that a selection of the underlying process equipment must be adapted over a longer period of time gathering data from operations. Currently there are not many industrial sized plants for biochar production existing and even with these, technology suppliers and competitors are experimenting with different raw materials to establish a knowledge base (EBI, 2023).

A clear modularity in subsystems of the biochar manufacturing process could be identified. As already explained, this helps to deconstruct the whole manufacturing process and determine potential configurations for developing a product solution for the final customer. However, again, the systems identified on the market are highly integrated rendering a deconstruction in terms of their subsystems and a potential recombination rather unlikely from the perspective of a biochar manufacturing firm which only leverages the technology rather than developing it. This is especially true, if we take a look at the different reactor heating principles which require subsystems for energy recovery, either process-related or product-related. So far equipment manufacturers exhibit proprietary rights preventing a customer for the respective technology to amend a configuration. This might change in the long term however, with further product development cycles and increasing maturity of the market as well as suppliers. Suppliers are already orienting their technology configurations towards increasing their solution offer for customers like company X, by incorporating different waste energy recovery subsystems which are applicable to their basic manufacturing configuration for biochar production.

Raw material platforms – Satisfying different requirements of the product families

Comparing the nature of the biochar product to products from process industries there is a duality in biochar regarding its homogeneity and heterogeneity. As final product quality is largely influenced by the raw material selected, there will never be one and the same biochar using the same input materials (Bridgwater, 2019; Demirbas, 2004; Guercio & Bini, 2017; Lehmann & Joseph, 2015; Muzyka et al., 2023). With biomass in the form of agricultural or forestall residues a homogenous input material stream of the same quality could never be realized. Even remarkable differences within the same production batch are prevalent (in terms chemical properties and physical properties of the feedstock material). Considering the end-to-end perspective according to Lager (2017), Samuelson and Lager (2019), Delft and Zhao (2021) is therefore crucial and renders feedstock material selection for the production platforms established a difficult task let alone the development of a feedstock material strategy due to the requirements the different product families for biochar production for soil amendment as well as green energy are imposing on a feedstock selection.

Adapting the notions from K. Ulrich (1995), K. T. Ulrich et al. (2020) and Lager (2016) a shared logic, however, can be and is identified between all products and their underlying raw material selection. Lignocellulosic biomasses and their physical and chemical composition are the most researched and feasible as well as viable feedstock material currently used by the market (D. K. Gupta et al., 2020; N. Gupta et al., 2022). These feedstock materials provide the highest benefits for biochar for soil amendment as well as for the generation of renewable energy. The inherent function structure of the material allows for it to be leveraged over several applications and market segments. In this state of the market so far, no other functionalities of the biochar have been requested by customers (Köhler, 2022, 2023). The question here would be in case the possibilities for waste management through pyrolytic conversion are further exploited and become an additional solution proposal to the final customer, also lower grade raw material could become subject of interest. This however would have to be largely correlated with a decrease in investment cost for the pyrolysis manufacturing equipment since currently high yields of renewable energy and high quality of biochar are needed to achieve overall profitability of the integrated manufacturing systems as also confirmed by Garcia-Nunez et al. (2017), Garcia-Peréz et al. (2020), and Campbell et al. (2018).

Production platforms – The differentiation between biochar and energy

Seeing the production platforms as two independent entities on a conceptual level enables us to get a better grasp of both value propositions for green energy and for biochar production for soil amendment. It helps understand the requirements and implications for both types of value propositions. Currently, the renewable heat generated as byproduct of pyrolytic conversion is seen as simply that, a byproduct which helps to scale up the biochar carbon removal business model and market. Due to the early developmental stage of the market, they function together regarding raw material selection. However, due to the requirements imposed on a raw material selection by both respective product families, a separation of both production platforms and the according adaptation of the selection requirements for the underlying manufacturing requirements might become a valuable opportunity in the long term focusing on optimization of the yield of the different products of the pyrolysis process accordingly.

As soon as the potential for pyrolytic material transformation regarding waste raw material conversion is reached and emphasized by customers and regulatory institutions, and other products are developed, for example with biochar as a platform material for chemical applications (Liu et al., 2015), these two platforms would need to be separated and generate their own lead in selecting an underlying manufacturing technology. One which might be focused on optimizing the solid fuel as such with the energy as byproduct, and the other focusing on optimizing the gaseous fuel yield for renewable energy production with the solid fuel as byproduct, each being facilitated by different technology configurations. Nevertheless, through applying a platform-based design perspective on the products and especially the raw material selection commonalities might still be identified leading to cost-savings while achieving the highest product differentiation.

7.2 Empirical results

The following sections discuss the empirical results as presented in chapter 6 and aim to explain the most remarkable results taking platform-based design for non-assembled products and current market developments into consideration.

7.2.1 AHP hierarchy and consolidated stakeholder priorities

Production platform for soil amendment

On criteria level as could be expected according to the company X’ purpose the highest priority was assigned to the production platform for soil amendment. This makes sense since biochar is the main product of the company's current integrated manufacturing system alternative enabling the value propositions for soil amendment and carbon removal credits. Biochar is the main revenue stream and the basis for biochar carbon removal (BCR).

Remarkable is the distribution on sub-criteria level 1 with a higher emphasis on the product performance than on the manufacturing capability, which includes the raw material processing capability. Regarding the manufacturing capability only the biochar output as well as the plant availability stand out. This results from the fact that currently only a few raw materials are listed as being allowed for incorporation into soil supporting the notion mentioned in the previous section (EBC, 2022). Among these, lignocellulosic biomass, especially wooden residues are the most favorable due to their inherent organic carbon content (Guo et al., 2020). This is probably the reason why about the manufacturing capabilities only these two sub-criteria were favored the most by the decision makers. In an early, young market, the goal is to realize a stable production as well as a high product output to rapidly return the investment (EBI, 2023). A high manufacturing capability of the underlying integrated system might result in the possibility for generating high flexibility (Lager, 2010, 2016; Samuelsson et al., 2016), but not be ultimately relevant for rapidly scaling up production and developing the market.

Biochar product performance and carbon sequestration performance were rated higher than manufacturing capability. For the biochar product performance both sub-criteria moderating the biochar's carbon sequestration potential to generate a potential carbon removal certificate were prioritized over the water holding capacity which is one of the most important product characteristics favored by the company's customers[11]. This indicates that apparently the factor to be optimized is the overall potential to remove carbon from the atmosphere and other factors are subordinated. This concludes with the weight factor for carbon sequestration performance and shows that the company's whole biochar product development is geared towards the generation of carbon removal certificates and less towards the improvement of soil. This is in line with the findings of Garcia-Peréz et al. (2020) and Garcia-Nunez et al. (2017)

Additionally, the fact that the biochar conversion rate was weighed lower than the biochar output, indicates that as long as a sufficient biochar output to achieve viability of a manufacturing plant, it does not matter how good the material transformation process functions in terms of optimizing the mass retention of the solid fuel, i.e., the biomass being fed into the manufacturing plant. This again confirms research on these business models and manufacturing plants as stated by Garcia-Nunez et al. (2017), Garcia-Peréz et al. (2020), Raza et al. (2021) and Mong et al. (2022). This reinforces the impression that the potential benefits of pyrolysis for waste management play a subordinate role.

Nevertheless, among the raw material capabilities the material processing capability as well as the minimum energy input required was rated the highest which seems to be contradictory to emphasizing the biochar output and plant availability on the next higher criteria level. This shows the tendency of the decision makers to keep the opportunities for further product development based on different raw materials open and could be interpreted as uncertainty about future market developments. However, on a global level these criteria play a little role in the overall selection of a final alternative.

Production platform green energy

The production platform for green energy was valued as the second most important criterion. This results from the fact that currently the revenue from energy sales is necessary to achieve viability of a pyrolysis plant (Garcia-Nunez et al., 2017; Garcia-Peréz et al., 2020). As will be seen in the section about analyzing the pyrolysis technology alternatives which require high capital expenditure for setting up a plant. From a stakeholder perspective, product capability of the machinery is the most important. That means that the goal is to being able to adapt to the customers' needs for green energy in the best way possible with a selected technology configuration. This mirrors current ongoing research endeavor to further emphasize the possibilities to convert green energy with pyrolysis systems (Guercio & Bini, 2017; Roy & Dias, 2017; WCBSD, 2022; Y. Yang et al., 2017). This field is relatively new and according to discussions with suppliers, industry stakeholders are only now reaching market readiness with the integration of energy modules to convert biomass into energy in form of electricity, hot water, warm water, and steam with their pyrolysis systems (EBI, 2023; Ziegner & Milla, 2022).

Assigning the highest local weight to the heat yield results from the fact that the company is currently scaling their business with selling renewable heat and that this is the major argument considering circular pyrolytic manufacturing processes with focus on carbon removal. Electricity sales have not yet been incorporated into the business model of the company yet. Conventional pyrolysis systems (like alternative 1 and 2) based on autothermal or allothermal heating principles (Milhé et al., 2013) do not provide sufficient a sufficient volumetric flow of syngas or a sufficient temperature or utilize that syngas for heating the reactor making a subsequent energy conversion through a gas turbine or a combined heat and power plant to generate renewable electricity not economically viable. In these cases, the syngas has already been valorized once or does not exhibit sufficient energy since the focus is on the biochar production and optimization of the solid fuel yield. Due to the capabilities of the

---

[11] See chapter 6

current technological configuration of the company and the limited knowledge about the currently diverse and rapidly developing technology landscape (Dhyani & Bhaskar, 2019; Mong et al., 2022; Raza et al., 2021) for pyrolysis technology the stakeholder's assignment of weights seems to be reasonable.

The global priorities even suggest that the product capability for green energy products is the most important. This might be again rooted in the fact that the additional benefits in form of byproducts of the pyrolysis process help in further diffusing the technology and technique for energy conversion in the market due to a higher acceptance and willingness for adoption of biochar systems as a renewable energy source instead of solely the biochar product.

Financial performance

Analyzing the weight assignments for the sub-criteria for financial performance it becomes clear that the unit cost for biochar is the most determinant factor for the whole financial performance followed by the return on investment. The importance of the unit cost for energy remains in the third place. This indicates the high importance of the biochar and its carbon removal abilities over the value proposition of renewable energy to the customer. This is also mirrored in the global priorities' distribution in which the cost per unit of biochar and the carbon sequestration performance of the overall supply chain count as fourth and third most influential sub-criteria for the overall outcome of the model. The payback period and initial investment are less important on a local as well as on a global level. This implies that from the company's and market perspective the goal is to focus on decreasing the unit costs and focusing on scaling production with the pursuit for carbon removal through biochar. However, ranking the investment cost this low is contradictory to what has been published in recent literature since investment cost for pyrolysis plant equipment needs to be reduced (Garcia-Peréz et al., 2020). Longer payback periods are to be expected.[12] This in turn also has vital implications for the search for an investor since payback periods might be longer than for typical startup investment cases pursued by venture capitalists. The fact that alternative 3 with the highest initial investment is the best performing alternative is due to its high-performance regarding product yield, especially for energy.

Supplier maturity

Finally, the supplier maturity, here the market experience is the most important determinant for the evaluation of a technology configuration. Depending on the number of industrialized plants established on customer sites it can be expected that a respective supplier has already gained extensive knowledge about the performance of their machinery in the field which might already have translated to respective adaptations in the development of manufacturing equipment and an increased data basis regarding feedstock materials, process parameters and final product properties. Market reputation as well as pursuit for innovation play a significantly lower role on local weight level as well as global weight level, but still outweigh raw material capabilities on global weight level, further reinforcing the impression that a capability for a variety of raw materials plays a subordinate role to all other factors. This is in line with the overall performance factor of alternative three, the alternative with the lowest raw material capabilities.

Stakeholder consensus

It was observed that stakeholder group consensus on is lacking, possibly due to the nascent stage of both the startup and the market. Additionally, differentiating between production platforms and selecting a preferred option proves non-intuitive to stakeholders as the need to monetize inherent

---

[12] C.f. appendix F

benefits and value streams for profitability is crucial. Furthermore, stakeholder preferences vary depending on their function and position, with site development stakeholders favoring the potential for converting renewable energy due to higher market adoption possibilities compared to other alternatives.

7.2.2 Synthesis of results for alternatives

Overall performance

Interestingly, the alternative with the highest total score for all production platforms is not a conventional slow pyrolysis technology configuration, with the highest manufacturing capability in terms of flexibility but a complex two-step pyrolysis gasification system (alternative 3), which has the lowest process adaptability and the lowest raw material capabilities. This confirms what has been said above about the current preferences of the decision makers regarding the preferred optimization of the product outputs. It makes sense, this configuration, although having the highest initial investment, has the highest output in terms of heat and electricity, the lowest biochar cost, and a relatively good carbon sequestration performance. The different subsystem configuration and valorization of the syngas allows further for generation of electricity. Despite not being able to produce steam, it still performs the best due to the unit costs and product yield delivering the best overall performance over all production platforms.

Production platform biochar for soil amendment

Also, for the production platform biochar for soil amendment alternative 3 performs the best, although slightly less than analyzing the overall performance of the different systems. This is largely caused by its lower biochar conversion rate which is due to its focus on renewable energy production and the underlying reactor configuration. Its aim is to optimize the yield of gaseous fuel. Alternative 2 takes the second place due to its high carbon sequestration potential as well as biochar conversion rate but is closely followed by alternative 1 and 4. The overall pursuit for carbon removal through biochar again influences the outcome in this case. If just soil amendment purposes were to be considered neglecting the biochar‘s potential for carbon sequestration as well as generating the highest amount of biochar from a unit of input material, then alternatives 1, 2, and 4 probably would outrank alternative 3 due to their reactor configurations and abilities to process other input materials. This production platform takes the lead in the selection of an underlying manufacturing technology according to the stakeholders’ preferences, but not due to the opportunities to tailor biochars according to specific requirements of the customer through optimizing different functionalities of the product, but mainly due to the carbon sequestration potential the biochar exhibits.

Production platform green energy

For the production platform for green energy, product capabilities, yield and cost are the most important parameters. In light of the company’s pursuit of a high variety strategy and the customer needs this makes sense. Although alternative is not the highest performing with regard to product capabilities, not being able to generate steam, it still outranks the others due to the yield and unit cost. The reactor configuration and heating principle allows for a higher gaseous yield compared to the others decreasing the cost for the products in the selected plant configuration. For scaling the biochar business model based on wooden input material this makes sense. Decarbonization of renewable heat and electricity supply is one of the main concerns of the company's customers[13].

Supplier maturity

As market experience is one of the critical performance parameters as determined by the decision makers, also alternative 3 is again the highest performant in this case. This results from the fact that this supplier overall has the highest experience with industrialized plants in the considered size and configuration, the highest patent output and a moderate reputation for the biochar carbon removal market. All suppliers have at least developed a patent for their core technology subsystem of material transformation. The weighting of market experience is almost at parity with the cost per unit of biochar, indicating that achieving a low unit cost is as important as a good reputation, which offsets the performance of alternative 1 regarding all other criteria in case supplier maturity is to be optimized.

Financial performance

The financial performance shows the same picture as the overall performance of the alternatives. Although alternative 3 has the highest overall initial investment, it still outperforms the other alternatives largely due to its low unit cost for biochar, and large heat output. As already stated, initial investment as well as return on investment are not the most important criteria, but the cost per unit of biochar. Although having a low conversion rate, the alternative manages to achieve a high output, resulting in a low unit cost for biochar.

Analyzing the potential scenarios presented in Figure 28 two rank reversals can be seen, one induced by the raw material price and one induced by changing the heat sales price. The first rank reversal indicates the influence of the feedstock material price on technology selection. Lower feedstock material prices can be achieved for waste materials such as sewage sludges (Huygens et al., 2019). With the current investment cost for the technology equipment this is a crucial variable and necessitates an expansion of the feedstock material basis for all production platforms described. The rank reversal shows the influence of the feedstock material price. Nevertheless, this rank reversal shown in Figure 28 a) is not representative for the current market since no use case with a negative raw material price of -159.00€ has been identified yet.

The rank reversal induced by the heat sales price is another remarkable fact. Renewable heat is currently used to scale the biochar market, and especially in light of the recent economic trends for transition towards renewable energy as well as the economic crises caused by geopolitical conflicts lead to an increase of cost for energy during the past two years. That is why an energy price of 0.4614 €/kWh cannot be categorically classified as unrealistic anymore. However, in the long term these prices are expected to stabilize and decrease again and make such a rank reversal unrealistic. This only further indicates the robustness of the AHP model presented.

When analyzing the different alternatives regarding their internal rate of return, only alternative 3 and 4 achieve a sufficient level of return exceeding the company's cost for capital. This would usually mean that the other technologies would need to be disregarded from a selection. However, due to the fact that the input material price as well as energy prices have a high influence on the profitability of the manufacturing systems, they might still be able to achieve profitability depending on these circumstances.

---

[13] C.f. chapter 4.2

8 Conclusion

This thesis aimed to identify the most profitable and capable integrated manufacturing system for waste biomass valorization into green energy, biochar, and CO2 sequestration certificates using a platform-based design perspective for non-assembled products, considering current technology and market developments. The research question focused on the most profitable and capable pyrolysis technology for high-variety biochar production, green heat, and carbon removal.

The author introduced platform-based design theory, explaining product-, process-, raw-material, and production platform concepts in biochar systems, and discussed raw material selection, processes, and products based on biochar theory. A comprehensive set of criteria for evaluating integrated pyrolysis manufacturing systems was established, encompassing four clusters: biochar production for soil amendment, green energy production, supplier maturity, and financial performance.

To identify potential alternatives, the author researched and filtered available options, requested data from suppliers for evaluation, and conducted an Analytic Hierarchy Process (AHP) analysis, including pairwise comparisons from decision-makers and evaluation of alternatives using supplier data.

Theoretical frameworks for platform-based design can be applied to non-assembled products such as for biochar systems. In particular, the arrangement of functional elements for assembled products according to Ulrich (1995) can be adapted to biochar systems, with the physical and chemical properties of the material dictating its functionalities. A function structure can be developed based on the inherent properties of the material and the resulting benefits when incorporated into soil. The main functionalities of biochar are water holding capacity and carbon sequestration potential, with emphasis on different functionalities depending on the specific application. Biochar product differentiation occurs through processing various raw materials using the same integrated pyrolysis manufacturing system. In this regard, decoupling established production platforms for biochar for soil amendment and green energy is difficult due to the integrated nature of these systems and the convergence of the different product requirements at the raw material basis. Biochar from lignocellulosic raw materials is currently a commodity with limited product structure, making high variety strategies based on this material selection challenging. However, utilizing the full potential of pyrolysis and diversifying product development at the raw material level could provide new economic and ecological opportunities in the long term.

Biochar production platforms for soil amendment and green energy can restrict or contradict each other in the selection of raw materials and processes. Investment in process equipment is crucial for product development and achieving a variety of solutions for final customers. Input material grade, availability, and price are highly variable, leading to the need for adaptation of the underlying process equipment over a longer period. The biochar manufacturing process exhibits clear modularity in subsystems, but the systems identified on the market are highly integrated, making deconstruction and recombination currently unlikely from the perspective of a biochar manufacturing firm. Different reactor heating principles require subsystems for energy recovery, either process-related or product-related.

Deconstructing the manufacturing process platform in subsystems including modules which are named after their function aids in assessing the alternatives based on the performance of the subsystem and facilitates managing the high complexity of the systems. As with the deconstruction of the biochar products according to their functions, also the process platform can be leveraged over the different market systems. Using platform-based design construct in technology selection, mirroring the production platforms in a decision hierarchy helps in managing the selection process of an underlying integrated pyrolysis manufacturing platform satisfying the different customer needs imposed on the product functionalities.

In the process of evaluating various pyrolysis technologies, the biochar manufacturing company X seeks to identify a production platform that prioritizes soil amendment capabilities, followed by green energy production, financial performance, and supplier maturity. The emphasis is placed on product performance, including biochar output and plant availability, rather than manufacturing capability, such as raw for material processing. This suggests that the company prioritizes biochar product performance and carbon sequestration capabilities over waste management potential offered by pyrolysis.

Green energy production is the second most crucial criterion, with stakeholders prioritizing machinery product capability and heat yield as the primary sub-criteria. The company's objective is to reduce unit costs and scale production while pursuing carbon removal through biochar, which may result in extended payback periods for plant configurations.

Financial performance is predominantly determined by the unit cost of biochar, followed by the return on investment, with the unit cost of energy ranked third. Revenue generated from energy sales is vital for ensuring the viability of a pyrolysis plant.

Supplier maturity, specifically market experience, is another important factor in evaluating a technology configuration, while market reputation and innovation pursuits are deemed less significant at both local and global weight levels.

In summary, company X currently seeks pyrolysis technology capable of manufacturing biochar from lignocellulosic material and green energy products. Key attributes for such technology include high-quality biochar production, a high carbon sequestration potential of final products, i.e., a good environmental performance of the system, high heat yield, low biochar unit cost, and high supplier maturity. These characteristics will allow the company to achieve its objectives for biochar, green heat, and carbon removal production while adopting a platform-based design perspective for non-assembled products.

The research question addresses the most profitable and capable pyrolysis technology for realizing a high variety strategy in biochar production, green heat, and carbon removal, considering a platform-based design perspective for non-assembled products. Notably, the alternative with the highest total score is not a conventional slow pyrolysis technology but a complex two-step pyrolysis gasification system (alternative 3), which has the lowest process adaptability and raw material capabilities. This result reflects the decision-makers' preference for optimizing product outputs rather than manufacturing capabilities.

Alternative 3 outperforms others in terms of heat and electricity output, biochar cost, and carbon sequestration performance, despite having the highest initial investment. The unique subsystem configuration and syngas valorization enable electricity generation, making it the best overall performer across production platforms. Although it ranks slightly lower for biochar production for soil amendment due to its lower biochar conversion rate, it still ranks highest in the green energy production platform based on yield and unit cost.

Market experience is a critical performance parameter, and alternative 3 exhibits the highest supplier maturity. Although it requires the highest initial investment, alternative 3 achieves superior financial performance due to its low biochar unit cost and large heat output.

The study further identifies raw material price and heat sales price as critical parameters, highlighting the importance of feedstock material prices and energy prices in technology selection.

Can these results be extrapolated to future selection problems for integrated pyrolysis manufacturing systems, should the company from now on orient itself towards fluidized bed reactors? The answer is no, but it serves as an orientation towards further refining the selection of future manufacturing systems. As explained, such integrated manufacturing systems are highly complex embedded in a multifactor system of interaction between raw materials, processes, and final product functionalities. Platform-based design for non-assembled products can serve as an approach to structure the technology selection process. However, depending on the specific application of the biochar and the further development of the biochar market a re-evaluation of the underlying criteria needs to be conducted. Furthermore, the technology is evolving rapidly with new technology alternatives being developed (EBI, 2023). It can currently not be determined whether the company should only procure complex two-step pyrolysis gasification systems, or auger-based systems, or ablative plate-based systems or any of the other reactor configurations. Still, pyrolysis technology offers a plethora of benefits for waste valorization, energy conversion, biochar-based product development and carbon removal. It remains to be seen which technological approach of which supplier will ultimately become the dominant design.

8.1 Theoretical Contribution

The theoretical contribution of this thesis is threefold. First, the application of platform-based design theory for non-assembled products is applied to the biochar business model. In this regard, the document at hand contributes to an expansion of the research field in the context of process industries and exemplifies platform-based design concepts for non-assembled products on a real case for biochar systems, combined with technology selection theory.

Second, the artifact of a production platform for biochar is developed and serves as comprehensive basis for further exploration of potential product-, process- or raw-material configurations, enhancing the proliferation of the business model in the industry. This production platform and the identification of commonalities in process configurations allows for determination of the core value creating process for a subsequent investigation of the necessary manufacturing equipment.

Current research focuses on how to lay out pyrolysis systems for efficient scaling of the technology considering the sale of biochar and CO2 sequestration certificates (Fawzy et al., 2022; Fawzy et al., 2021) and less on commercial plants (Roy & Dias, 2017). The emerging pyrolysis technology promises an effective solution for the conversion of biomass. To date, most of the studies revolving around the technology, focus on laboratory or pilot scale plants that are highly customized. Although economic viability of these technologies is rather low, which this thesis also confirms, technological advances and improvements to reactor and system configurations show the technologies potential to become commercially viable (Roy & Dias, 2017, p. 66).

Further it is proposed that all three value propositions of selling energy, biochar and CO2 certificates must be combined to achieve viability of the business model. Current literature provides no insights about which readily available, market ready biochar production technology to procure. Research is expressing the need for evaluation of data retrieved from industrial and operational pyrolysis units that are beyond pilot scale applications. In the past five years the application of pyrolysis for biogenic waste processing has expanded (EBI, 2023; Mong et al., 2022).

In this regard, as a third theoretical contribution the research at hand established a set of 26 evaluating criteria for pyrolysis manufacturing technology from a platform perspective. The thesis delivers key insights into the manufacturing technology provided by leading suppliers. Startups leveraging biochar carbon removal (BCR) technology are competing with a variety of different technological solutions and configurations. Through employing a well-established technology selection methodology of AHP, the thesis delivers insights into the state-of the art manufacturing technology. It remains yet to be determined which one will be critical for the competitive long-term positioning of a company with such a business model in the carbon sequestration market and towards a sustainable biomass economy.

8.2 Practical Contribution

Applying the platform-based design perspective to biochar systems has valuable implications for managerial understanding of a company's manufacturing capabilities and potential for further product- and process- as a well as organizational development. With this thesis a first step towards strategic planning from a platform perspective for biochar products and manufacturing processes is conducted. Managers could use this approach to determine further strategic opportunities. Further, the production platforms resulting from biochar systems could be evaluated using key platform metrics as proposed by Meyer and Dalal (2002).

Depending on the biochar industry's development beyond conventional soil applications, especially toward the composition and production of sustainable materials in various industries over a great variety of different applications, platform-based design philosophy can help technology managers and product development managers in process industries to identify and exploit commonalities among product ingredients, manufacturing processes and raw materials used. With each further production platform added to a company's portfolio, new requirements are imposed on managed product families, process platforms and respective subsystems as well as raw material platforms. The methodological approach taken in this thesis establishes a baseline for further expanding a company's manufacturing and processing capabilities considering a high variety strategy for non-assembled products.

Moreover, this research is taking real company data into consideration from a young startup operating in the novel and developing CDR market, leveraging BCR technology. Selecting the right technology for this market will be essential for company X's positioning. The company aims to use this research and orient its future technology sourcing at the critical supplier and technology evaluation factors. Further, this research aims to serve as a guideline for pyrolysis technology developers to further streamline their developmental processes towards the needs of potential future customers in the form of companies with similar value propositions as company X.

8.3 Limitations and further research

This study, conducted within a single company operating in the biochar market, has several limitations.

The biochar carbon removal market is new, innovative, and rapidly developing, with a high number of technology alternatives emerging. To gain more precise and generalizable insights, data from a broader range of companies like company X and suppliers should be collected and analyzed, accounting for varying company characteristics, goals, and constraints. The Analytic Hierarchy Process (AHP) method used is sensitive to the introduction of new alternatives, which may affect result consistency. By expanding the sample size, a more comprehensive understanding of the optimal selection and application of integrated pyrolysis manufacturing systems in the biochar industry can be achieved.

The criteria retrieved from literature are estimated to provide a first attempt to evaluate integrated pyrolysis manufacturing systems as presented in this work. From a theoretical as well as organizational perspective they manage to capture the decision situation with a holistic approach. However, for future research endeavors it remains to be determined statistically whether the criteria developed are sufficient. A statistical approach in the form of a factor analysis could be an approach. Refining the criteria development process is necessary to account for the evolving market landscape, technology advancements, and supplier experience. Incorporating and further detailing parameters such as maturity, patents, and number of plants, and introducing further utility functions will provide valuable insights into the industry's growth trajectory and platform adaptability. In this regard, integrating data ranges and potentially fuzzifying criteria will enable the model to accommodate uncertainties arising from variances in manufacturing system performance, supply chain changes, and raw material quality. This will enhance the robustness and versatility of the model, making it more adaptable to real-world scenarios in platform-based design for non-assembled products. Additionally, the criteria could be further refined through developing more sophisticated utility functions.

Future research in the domain of platform-based design for non-assembled products, such as those found in biochar carbon removal and integrated manufacturing systems, should consider several aspects to improve understanding and applicability of the findings:

Expanding the model to include additional product families, such as carbon removal certificates and generating a unique product family characterized by differentiation through the durability and additionality of certificates, is essential for capturing the potential of different input materials and their carbon content about biochar carbon removal.

Broadening the model to encompass further production platforms, such as industrial materials production, will facilitate a deeper exploration of the synergies between biochar systems and other industries, fostering innovation and resource optimization within the context of platform-based design for non-assembled products.

By addressing these research directions, future studies can contribute to the advancement of platform-based design for non-assembled products, providing valuable insights for industry stakeholders and decision-makers while promoting sustainable and innovative solutions for biomass valorization and carbon sequestration.

9 References

Abdullah, L., Chan, W., & Afshari, A. (2019). Application of PROMETHEE method for green supplier selection: a comparative result based on preference functions. *Journal of Industrial Engineering International*, *15*(2), 271–285. https://doi.org/10.1007/s40092-018-0289-z

Afrane, S., Ampah, J. D., Jin, C., Liu, H., & Aboagye, E. M. (2021). Techno-economic feasibility of waste-to-energy technologies for investment in Ghana: A multicriteria assessment based on fuzzy TOPSIS approach. *Journal of Cleaner Production*, *318*, 128515. https://doi.org/10.1016/j.jclepro.2021.128515

Alao, M. A., Popoola, O. M., & Ayodele, T. R. (2022). A novel fuzzy integrated MCDM model for optimal selection of waste-to-energy-based-distributed generation under uncertainty: A case of the City of Cape Town, South Africa. *Journal of Cleaner Production*, *343*, 130824. https://doi.org/10.1016/j.jclepro.2022.130824

Allohverdi, T., Mohanty, A. K., Roy, P., & Misra, M. (2021). A Review on Current Status of Biochar Uses in Agriculture. *Molecules*, *26*(18). https://doi.org/10.3390/molecules26185584

Andersen, A.-L., Andersen, R., Brunoe, T. D [Thomas Ditlev], Larsen, M. S. S., Nielsen, K., Napoleone, A., & Kjeldgaard, S. (Eds.) (2022). *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems*. Springer International Publishing.

Andersen, R. (2022). *Modular and Platform-based Product Development in the Process Industry: Enabling Efficient Product Variety Through Complexity Management* [, Unpublished]. DataCite.

Andersen, R., Brunoe, T. D [Thomas Ditlev], & Nielsen, K. (2022). Platform-based product development in the process industry: a systematic literature review. *International Journal of Production Research*, 1–24. https://doi.org/10.1080/00207543.2022.2044085

Baranitharan, P., Ramesh, K., & Sakthivel, R. (2019). Multi-attribute decision-making approach for Aegle marmelos pyrolysis process using TOPSIS and Grey Relational Analysis: Assessment of engine emissions through novel Infrared thermography. *Journal of Cleaner Production*, *234*, 315–328. https://doi.org/10.1016/j.jclepro.2019.06.188

Barzilai, J., & Golany, B. (1994). Ahp Rank Reversal, Normalization And Aggregation Rules. *Information Systems and Operational Research*, *32*(2), 57–64. https://doi.org/10.1080/03155986.1994.11732238

BMWK. (2022). *Eckpunkte für eine Nationale Biomassestrategie (NABIS).* German Ferderal Ministry for Economic Affairs and Climate Action.

Bridgwater, A. V [Anthony V.] (2012). Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy*, *38*, 68–94. https://doi.org/10.1016/j.biombioe.2011.01.048

Bridgwater, A. V [Anthony V.]. (2019). Pyrolysis of Solid Biomass: Basics, Processes and Products. In M. Kaltschmitt (Ed.), *Encyclopedia of sustainability science and technology series: Vol. 15436. Energy from organic materials (biomass)* (pp. 1221–1250). Springer. https://doi.org/10.1007/978-1-4939-7813-7_984

Campbell, R. M., Anderson, N. M., Daugaard, D. E., & Naughton, H. T. (2018). Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty. *Applied Energy*, *230*, 330–343. https://doi.org/10.1016/j.apenergy.2018.08.085

Campuzano, F., Brown, R. C., & Martínez, J. D. (2019). Auger reactors for pyrolysis of biomass and wastes. *Renewable and Sustainable Energy Reviews*, *102*, 372–409. https://doi.org/10.1016/j.rser.2018.12.014

Carmen e.V. (2023). *Energieholz-Preisindizes: "Holzprodukte zur Energieerzeugung" und "Holz in Form von Plättchen und Schnitzeln (ohne Waldhackschnitzel)"*. n.p. Carmen e.V. https://www.carmen-ev.de/service/marktueberblick/marktpreise-energieholz/energieholz-preisindizes/

Christie-Miller, T., & Harvey, V. (2022). *Removal reconsidered: Carbon Dioxide Removal in the Voluntary Carbon Market.* BeZero Carbon Ltd. https://a.storyblok.com/f/133849/x/752899d2a6/bezero-carbon-removal-reconsidered-cdr-in-the-vcm-jun22.pdf

Chuang, M., Yang, Y.-S., & Lin, C.-T. (2009). Production technology selection: Deploying market requirements, competitive and operational strategies, and manufacturing attributes. *International Journal of Computer Integrated Manufacturing*, *22*(4), 345–355. https://doi.org/10.1080/09511920802209066

Collard, F.-X., Carrier, M., & Görgens, J. F. (2016). Fractionation of Lignocellulosic Material With Pyrolysis Processing. In S. I. Mussatto (Ed.), *Biomass fractionation technologies for a lignocellulosic feedstock based biorefinery* (pp. 81–101). Elsevier. https://doi.org/10.1016/B978-0-12-802323-5.00004-9

Delft, S. von, & Zhao, Y. (2021). Business models in process industries: Emerging trends and future research. *Technovation*, *105*, 102195. https://doi.org/10.1016/j.technovation.2020.102195

Demirbas, A. (2004). Effect of initial moisture content on the yields of oily products from pyrolysis of biomass. *Journal of Analytical and Applied Pyrolysis*, *71*(2), 803–815. https://doi.org/10.1016/j.jaap.2003.10.008

DESTATIS. (2023a). *Erdgas- und Stromdurchschnittspreise*. n.p. Statistisches Bundesamt Bundesrepublik Deutschland. https://www.destatis.de/DE/Themen/Wirtschaft/Preise/Erdgas-Strom-DurchschnittsPreise/_inhalt.html

DESTATIS. (2023b). *Wärmepreisindex*. n.p. Statistisches Bundesamt Bundesrepublik Deutschlan. https://www.destatis.de/DE/Themen/Wirtschaft/Preise/Verbraucherpreisindex/Tabellen/Waermepreisindex.html#242156

Dhyani, V., & Bhaskar, T. (2019). Pyrolysis of Biomass. In A. Pandey, C. Larroche, E. Gnansounou, S. K. Khanal, C.-G. Dussap, & S. Ricke (Eds.), *Biomass, Biofuels, Biochemicals. Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels / edited by Ashok Pandey, Christian Larroche, Claude-Gilles Dussap, Edgard Gnansounou, Samir Kumar Khanal, and Steve Ricke* (pp. 217–244). Academic Press. https://doi.org/10.1016/B978-0-12-816856-1.00009-9

Diehlmann, F., Zimmer, T., Glöser-Chahoud, S., Wiens, M., & Schultmann, F. (2019). Techno-economic assessment of utilization pathways for rice straw: A simulation-optimization approach. *Journal of Cleaner Production*, *230*, 1329–1343. https://doi.org/10.1016/j.jclepro.2019.04.369

Dutta, P., Jaikumar, B., & Arora, M. S. (2022). Applications of data envelopment analysis in supplier selection between 2000 and 2020: a literature review. *Annals of Operations Research*, *315*(2), 1399–1454. https://doi.org/10.1007/s10479-021-03931-6

EBC. (2012-2022). *European Biochar Certificate - Richtlinien für die Zertifizierung von Pflanzenkohle: Version 10.2.* Carbon Standards International AG. http://www.european-biochar.org

EBC. (2022). *Positive list of permissible biomasses for the production of biochar: European Biochar Certificate.* Carbon Standards International AG. https://www.european-biochar.org/media/doc/2/positivliste_en_2020.pdf

EU-ESCO. (2021). *Energy Contracting: Successful Energy Service Business Models.* European Association of Energy Service Companies. https://euesco.org/wp-content/uploads/2021/06/101006_euesco_ContractingFlyer_A4_final_low.pdf

European Biochar Industry Consortium. (March 2023). *European Biochar - Market Report 2022-2023*. Freiburg. European Biochar Industry Consortium (EBI). https://www.biochar-industry.com/market-overview/

Farooq, S., & O'Brien, C. (2012). A technology selection framework for integrating manufacturing within a supply chain. *International Journal of Production Research*, *50*(11), 2987–3010. https://doi.org/10.1080/00207543.2011.588265

Farooq, S., & O'Brien, C. (2007). An analytical Approach to strategic Technology Selection. *International Journal of Innovation and Technology Management.* Advance online publication. https://doi.org/10.1109/PICMET.2005.1509682

Fawzy, S., Osman, A. I., Mehta, N., Moran, D., Al-Muhtaseb, A. H., & Rooney, D. W. (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, S., Osman, A. I., Yang, H., Doran, J., & Rooney, D. W. (2021). Industrial biochar systems for atmospheric carbon removal: a review. *Environmental Chemistry Letters*, *19*(4), 3023–3055. https://doi.org/10.1007/s10311-021-01210-1

Forman, E., & Peniwati, K. (1998). Aggregating individual judgments and priorities with the analytic hierarchy process. *European Journal of Operational Research*, *108*(1), 165–169. https://doi.org/10.1016/S0377-2217(97)00244-0

Garcia-Nunez, J. A [J. A.], Pelaez-Samaniego, M. R [M. R.], Garcia-Perez, M. E., Fonts, I., Abrego, J., Westerhof, R. J. M., & Garcia-Perez, M. (2017). Historical Developments of Pyrolysis Reactors: A Review. *Energy & Fuels*, *31*(6), 5751–5775. https://doi.org/10.1021/acs.energyfuels.7b00641

Garcia-Peréz, M., Garcia-Nunez, J. A [Jesus Alberto], Pelaez-Samaniego, M. R [Manuel Raul], Kruger, C. E., Fuchs, M. R., & Flora, G. E. (2020). Sustainability, Business Models, and Techno-Economic Analysis of Biomass Pyrolysis Technologies. In I. R. Management Association (Ed.), *Critical explorations. Sustainable business: Concepts, methodologies, tools, and applications* (pp. 1339–1373). IGI Global Business Science Reference (an imprint of Global). https://doi.org/10.4018/978-1-5225-9615-8.ch060

Ghodake, G. S., Shinde, S. K., Kadam, A. A., Saratale, R. G., Saratale, G. D., Kumar, M., Palem, R. R., AL-Shwaiman, H. A., Elgorban, A. M., Syed, A., & Kim, D.-Y. (2021). Review on biomass feedstocks, pyrolysis mechanism and physicochemical properties of biochar: State-of-the-art framework to speed up vision of circular bioeconomy. *Journal of Cleaner Production*, *297*, 126645. https://doi.org/10.1016/j.jclepro.2021.126645

Goepel, K. D. (2018). Implementation of an Online Software Tool for the Analytic Hierarchy Process (AHP-OS). *International Journal of the Analytic Hierarchy Process*, *10*(3). https://doi.org/10.13033/ijahp.v10i3.590

Guercio, A., & Bini, R. (2017). 15 - Biomass-fired Organic Rankine Cycle combined heat and power systems. In E. Macchi & M. Astolfi (Eds.), *Organic Rankine Cycle (ORC) Power Systems* (pp. 527–567). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100510-1.00015-6

Guo, M., Song, W., & Tian, J. (2020). Biochar-Facilitated Soil Remediation: Mechanisms and Efficacy Variations. *Frontiers in Environmental Science*, *8*, Article 521512. https://doi.org/10.3389/fenvs.2020.521512

Gupta, D. K., Gupta, C. K., Dubey, R., Fagodiya, R. K., Sharma, G., A., K., Noor Mohamed, M. B., Dev, R., & Shukla, A. K. (2020). Role of Biochar in Carbon Sequestration and Greenhouse Gas Mitigation. In J. S. Singh & C. Singh (Eds.), *Biochar Applications in Agriculture and Environment Management* (pp. 141–165). Springer International Publishing. https://doi.org/10.1007/978-3-030-40997-5_7

Gupta, N., Mahur, B. K., Izrayeel, A. M. D., Ahuja, A., & Rastogi, V. K. (2022). Biomass conversion of agricultural waste residues for different applications: a comprehensive review. *Environmental Science and Pollution Research*, *29*(49), 73622–73647. https://doi.org/10.1007/s11356-022-22802-6

Hagemann, N., Spokas, K., Schmidt, H.-P., Kägi, R., Böhler, M. A., & Bucheli, T. D. (2018). Activated Carbon, Biochar and Charcoal: Linkages and Synergies across Pyrogenic Carbon's ABCs. *Water*, *10*(2). https://doi.org/10.3390/w10020182

Hamzeh, R., & Xu, X. (2019). Technology selection methods and applications in manufacturing: A review from 1990 to 2017. *Computers & Industrial Engineering*, *138*, 106123. https://doi.org/10.1016/j.cie.2019.106123

Huygens, D., Delgado Sancho, L., Saveyn, H. G. M., Tonini, D., & Eder, P. (2019). *Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009): Process and quality criteria, and assessment of environmental and market impacts for precipitated phosphate salts & derivates, thermal oxidation materials & derivates and pyrolysis & gasification materials*. *EUR: Vol. 29841*. Publications Office of the European Union.

IBI. (2023). *Biochar for soil health.* International Biochar Initiative (IBI). https://biochar-international.org/soil-health/

Ighalo, J. O., Eletta, O. A., & Adeniyi, A. G. (2022). Biomass carbonisation in retort kilns: Process techniques, product quality and future perspectives. *Bioresource Technology Reports*, *17*, 100934. https://doi.org/10.1016/j.biteb.2021.100934

Ippolito, J. A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizabal, T., Cayuela, M. L., Sigua, G., Novak, J., Spokas, K., & Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar*, *2*(4), 421–438. https://doi.org/10.1007/s42773-020-00067-x

Ji, P., & Jiang, R. (2003). Scale transitivity in the AHP. *Mathematical Modelling*, *54*(8), 896–905. https://doi.org/10.1057/palgrave.jors.2601557

Kafuku, J. M., Mat Saman, M. Z., & Yusof, S. M. (2019). Application of Fuzzy Logic in Selection of Remanufacturing Technology. *Procedia Manufacturing*, *33*, 192–199. https://doi.org/10.1016/j.promfg.2019.04.023

Kaltschmitt, M. (Ed.). (2019). *Encyclopedia of sustainability science and technology series: Vol. 15436*. *Energy from organic materials (biomass)*. Springer. https://doi.org/10.1007/978-1-4939-7813-7

Kaltschmitt, M., Hartmann, H., & Hofbauer, H. (2016). *Energie aus Biomasse: Grundlagen, Techniken und Verfahren* (3., aktualisierte Auflage). Springer Vieweg.

Knapp, J. S., & Bromley-Challoner, K. (2003). Recalcitrant organic compounds. In D. D. Mara & N. J. Horan (Eds.), *Handbook of water and wastewater microbiology* (pp. 559–595). Academic Press. https://doi.org/10.1016/B978-012470100-7/50035-2

Knizia, J. (2023, February 14). *Pyrolysis Technology Selection - AHP Criteria Presentation: Internal company meeting.* Novocarbo GmbH, Hamburg.

Kocsis, T., Ringer, M., & Biró, B. (2022). Characteristics and Applications of Biochar in Soil-Plant Systems: A Short Review of Benefits and Potential Drawbacks. *Applied Sciences*, *12*(8). https://doi.org/10.3390/app12084051

Köhler, L.-J. (2022). *Company x - Customer Survey Q4 2022: Unpublished internal company document*. Hamburg. Company x.

Köhler, L.-J. (2023, January 13). Interview by J. Knizia. Hamburg.

Kuntze, B. (2020). Verfahren und Vorrichtung zur Aufspaltung fester Brennstoffe durch thermische Zersetzung mittels partieller Oxidation (EP 3 858 952 A1). Europe.

Ladygina, N., & Rineau, F. (Eds.). (2013). *Biochar and soil biota* (1st edition). Taylor & Francis. https://doi.org/10.1201/b14585

Lager, T. (2010). *Managing Process Innovation: From Idea Generation To Implementation*. World Scientific Publishing Company.

Lager, T. (2016). Managing Innovation & Technology in the Process Industries: Current Practices and Future Perspectives. *Procedia Engineering*, *138*, 459–471. https://doi.org/10.1016/j.proeng.2016.02.105

Lager, T. (2017). A conceptual framework for platform-based design of non-assembled products. *Technovation*, *68*, 20–34. https://doi.org/10.1016/j.technovation.2017.09.002

Lehmann, J., & Joseph, S. (2015). *Biochar for environmental management: Science, technology and implementation* (Second edition). Routledge Taylor & Francis Group. https://doi.org/10.4324/9780203762264

Lehnerd, A. P., & Meyer, M. H. (2014). *The power of product platforms*. Free Press. https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=4934625

Li, L., Yao, Z., You, S., Wang, C.-H., Chong, C., & Wang, X. (2019). Optimal design of negative emission hybrid renewable energy systems with biochar production. *Applied Energy*, *243*, 233–249. https://doi.org/10.1016/j.apenergy.2019.03.183

Liu, W.-J., Jiang, H., & Yu, H.-Q. (2015). Development of Biochar-Based Functional Materials: Toward a Sustainable Platform Carbon Material. *Chemical Reviews*, *115*(22), 12251–12285. https://doi.org/10.1021/acs.chemrev.5b00195

Lu, H. R., & El Hanandeh, A. (2019). Life cycle perspective of bio-oil and biochar production from hardwood biomass; what is the optimum mix and what to do with it? *Journal of Cleaner Production*, *212*, 173–189. https://doi.org/10.1016/j.jclepro.2018.12.025

Macchi, E [E.]. (2017). 1 - Theoretical basis of the Organic Rankine Cycle. In E. Macchi & M. Astolfi (Eds.), *Organic Rankine Cycle (ORC) Power Systems* (pp. 3–24). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100510-1.00001-6

Marshall, J., Muhlack, R., Morton, B. J., Dunnigan, L., Chittleborough, D., & Kwong, C. W. (2019). Pyrolysis Temperature Effects on Biochar–Water Interactions and Application for Improved Water Holding Capacity in Vineyard Soils. *Soil Systems*, *3*(2), 27. https://doi.org/10.3390/soilsystems3020027

McGlashan, N., Shah, N., Caldecott, B., & Workman, M. (2012). High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection*, *90*(6), 501–510. https://doi.org/10.1016/j.psep.2012.10.004

Meyer, M. H., & Dalal, D. (2002). Managing platform architectures and manufacturing processes for nonassembled products. *Journal of Product Innovation Management*, *19*(4), 277–293. https://doi.org/10.1111/1540-5885.1940277

Milhé, M., van de Steene, L., Haube, M., Commandré, J.-M., Fassinou, W.-F., & Flamant, G. (2013). Autothermal and allothermal pyrolysis in a continuous fixed bed reactor. *Journal of Analytical and Applied Pyrolysis*, *103*, 102–111. https://doi.org/10.1016/j.jaap.2013.03.011

Mogensen, M. K., Andersen, R., Brunoe, T. D [Thomas D.], & Nielsen, K. (2022). Applying Modular Function Deployment for Non-assembled Products in the Process Industry. In A.-L. Andersen, R. Andersen, T. D. Brunoe, M. S. S. Larsen, K. Nielsen, A. Napoleone, & S. Kjeldgaard (Eds.), *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems* (pp. 661–668). Springer International Publishing.

Mong, G. R., Chong, C. T., Chong, W. W. F., Ng, J.-H., Ong, H. C., Ashokkumar, V., Tran, M.-V., Karmakar, S., Goh, B. H. H., & Mohd Yasin, M. F. (2022). Progress and challenges in sustainable pyrolysis technology: Reactors, feedstocks and products. *Fuel*, *324*, 124777. https://doi.org/10.1016/j.fuel.2022.124777

Mousavi, S. A., Hafezalkotob, A., Ghezavati, V., & Abdi, F. (2022). An integrated framework for new sustainable waste-to-energy technology selection and risk assessment: An R-TODIM-R-MULTIMOOSRAL approach. *Journal of Cleaner Production*, *335*, 130146. https://doi.org/10.1016/j.jclepro.2021.130146

Mu, E., & Pereyra-Rojas, M. (2016). *Practical decision making: An introduction to the analytic hierarchy process (AHP) using super decisions V2 / Enrique Mu, Milagros Pereyra-Rojas*. *SpringerBriefs in operations research*. Springer. https://doi.org/10.1007/978-3-319-33861-3

Muzyka, R., Misztal, E., Hrabak, J., Banks, S. W., & Sajdak, M. (2023). Various biomass pyrolysis conditions influence the porosity and pore size distribution of biochar. *Energy*, *263*, 126128. https://doi.org/10.1016/j.energy.2022.126128

Ocampo, L. A., Abad, G. K. M., Cabusas, K. G. L., Padon, M. L. A., & Sevilla, N. C. (2018). Recent approaches to supplier selection: a review of literature within 2006-2016. *International Journal of Integrated Supply Management*, *12*(1/2), Article 95683, 22. https://doi.org/10.1504/IJISM.2018.095683

Oliveira, L. M. V. de, Santos, H. F. d., Almeida, M. R. de, & Costa, J. A. F. (2020). Quality Function Deployment and Analytic Hierarchy Process: A literature review of their joint application. *Concurrent Engineering*, *28*(3), 239–251. https://doi.org/10.1177/1063293X20958936

Panda, M., & Jagadev, A. K. (2018). TOPSIS in Multi-Criteria Decision Making: A Survey. In S. Patnaik (Ed.), *2nd International Conference on Data Science and Business Analytics: ICDSBA 2018 : proceedings : 21-23 September 2018, ChangSha, Hunan, China* (pp. 51–54). Conference Publishing Services, IEEE Computer Society. https://doi.org/10.1109/ICDSBA.2018.00017

Pantaleo, A., Candelise, C., Bauen, A., & Shah, N. (2014). ESCO business models for biomass heating and CHP: Profitability of ESCO operations in Italy and key factors assessment. *Renewable and Sustainable Energy Reviews*, *30*, 237–253. https://doi.org/10.1016/j.rser.2013.10.001

Pavitt, K. (1982). R&D, patenting and innovative activities: A statistical exploration. *Research Policy*, *11*(1), 33–51. https://doi.org/10.1016/0048-7333(82)90005-1

Pirmoradi, Z., Wang, G. G., & Simpson, T. W. (2014). A Review of Recent Literature in Product Family Design and Platform-Based Product Development. In T. W. Simpson, J. Jiao, Z. Siddique, & K. Hölttä-Otto (Eds.), *Advances in Product Family and Product Platform Design: Methods & Applications* (pp. 1–46). Springer New York. https://doi.org/10.1007/978-1-4614-7937-6_1

Piterou, A., & Coles, A.-M. (2021). A review of business models for decentralised renewable energy projects. *Business Strategy and the Environment*, *30*(3), 1468–1480. https://doi.org/10.1002/bse.2709

Ponta, L., Puliga, G., & Manzini, R. (2021). A measure of innovation performance: the Innovation Patent Index. *Management Decision*, *59*(13), 73–98. https://doi.org/10.1108/MD-05-2020-0545

Porshnov, D. (2022). Evolution of pyrolysis and gasification as waste to energy tools for low carbon economy. *WIREs Energy & Environment*, *11*(1). https://doi.org/10.1002/wene.421

puro.earth. (2022). *Puro.earth Biochar Methodology.* Puro.earth Oy. https://fs.hubspotusercontent00.net/hubfs/7518557/Supplier%20Documents/Puro.earth%20Biochar%20Methodology.pdf

puro.earth. (2023). *CORC Carbon Removal Indexes - CORCCHAR Index*. n.p. Puro.earth Oy. https://puro.earth/carbon-removal-index-price/

Quicker, P., & Weber, K. (2016). *Biokohle: Herstellung, Eigenschaften und Verwendung von Biomassekarbonisaten*. Springer Vieweg.

Raveendran, K., & Ganesh, A. (1996). Heating value of biomass and biomass pyrolysis products. *Fuel*, *75*(15), 1715–1720. https://doi.org/10.1016/S0016-2361(96)00158-5

Raza, M., Inayat, A., Ahmed, A., Jamil, F., Ghenai, C., Naqvi, S. R., Shanableh, A., Ayoub, M., Waris, A., & Park, Y.-K. (2021). Progress of the Pyrolyzer Reactors and Advanced Technologies for Biomass Pyrolysis Processing. *Sustainability*, *13*(19), 11061. https://doi.org/10.3390/su131911061

Rodriguez Correa, C., Hehr, T., Voglhuber-Slavinsky, A., Rauscher, Y., & Kruse, A. (2019). Pyrolysis vs. hydrothermal carbonization: Understanding the effect of biomass structural components and inorganic compounds on the char properties. *Journal of Analytical and Applied Pyrolysis*, *140*, 137–147. https://doi.org/10.1016/j.jaap.2019.03.007

Rodríquez-Machín, L., Ronsse, F., Casas-Ledón, Y., & Arteaga-Pérez, L. E. (2021). Fast pyrolysis of raw and acid-leached sugarcane residues en route to producing chemicals and fuels: Economic and environmental assessments. *Journal of Cleaner Production*, *296*, 126601. https://doi.org/10.1016/j.jclepro.2021.126601

Roy, P., & Dias, G. (2017). Prospects for pyrolysis technologies in the bioenergy sector: A review. *Renewable and Sustainable Energy Reviews*, *77*, 59–69. https://doi.org/10.1016/j.rser.2017.03.136

Saaty, R. W. (1987). The analytic hierarchy process—what it is and how it is used. *Mathematical Modelling*, *9*(3-5), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Saaty, T. L. (1994). Highlights and critical points in the theory and application of the Analytic Hierarchy Process. *European Journal of Operational Research*, *74*(3), 426–447. https://doi.org/10.1016/0377-2217(94)90222-4

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences*, *1*(1), Article 17590, 83. https://doi.org/10.1504/IJSSCI.2008.017590

Samuelson, P., & Lager, T. (2019). Managing product variety under operational constraints: A process-industrial outlook. *Journal of Business Chemistry.* Advance online publication. https://doi.org/10.17879/64159695138

Samuelsson, P., Storm, P., & Lager, T. (2016). Profiling company-generic production capabilities in the process industries and strategic implications. *Journal of Manufacturing Technology Management*, *27*(5), 662–691. https://doi.org/10.1108/JMTM-06-2015-0042

Schimmelpfennig, S., & Glaser, B. (2012). One step forward toward characterization: Some important material properties to distinguish biochars. *Journal of Environmental Quality*, *41*(4), 1001–1013. https://doi.org/10.2134/jeq2011.0146

Schmidt, H.-P., Anca-Couce, A., Hagemann, N., Werner, C., Gerten, D., Lucht, W., & Kammann, C. (2019). Pyrogenic carbon capture and storage. *International Journal of the Analytic Hierarchy Process*, *11*(4), 573–591. https://doi.org/10.1111/gcbb.12553

Shearian Sattari, M., Ghobadian, B., & Gorjian, S. (2022). A critical review on life-cycle assessment and exergy analysis of Enomoto bio-gasoline production. *Journal of Cleaner Production*, *379*, 134387. https://doi.org/10.1016/j.jclepro.2022.134387

Shehabuddeen, N., Probert, D., & Phaal, R. (2006). From theory to practice: challenges in operationalising a technology selection framework. *Technovation*, *26*(3), 324–335. https://doi.org/10.1016/j.technovation.2004.10.017

Simić, D., Kovačević, I., Svirčević, V., & Simić, S. (2017). 50 years of fuzzy set theory and models for supplier assessment and selection: A literature review. *Journal of Applied Logic*, *24*, 85–96. https://doi.org/10.1016/j.jal.2016.11.016

Singh, B., Macdonald, L. M., Kookana, R. S., van Zwieten, L., Butler, G., Joseph, S., Weatherley, A., Kaudal, B. B., Regan, A., Cattle, J., Dijkstra, F., Boersma, M., Kimber, S., Keith, A., & Esfandbod, M. (2014). Opportunities and constraints for biochar technology in Australian agriculture: looking beyond carbon sequestration. *Soil Research*, *52*(8), 739. https://doi.org/10.1071/SR14112

Soria-Verdugo, A. (2019). Pyrolysis of sludge and biomass residues. In J. Dufour, J. A. Melero, J. A. Olivares, & D. Puyol (Eds.), *Wastewater treatment residues as resources for biorefinery products and energy* (pp. 155–181). Elsevier. https://doi.org/10.1016/B978-0-12-816204-0.00008-4

Tan, H., Lee, C. T., Ong, P. Y., Wong, K. Y., Bong, C. P. C., Li, C., & Gao, Y. (2021). A Review On The Comparison Between Slow Pyrolysis And Fast Pyrolysis On The Quality Of Lignocellulosic And Lignin-Based Biochar. *IOP Conference Series: Materials Science and Engineering*, *1051*(1), 12075. https://doi.org/10.1088/1757-899X/1051/1/012075

Tan, K. H., Noble, J., Sato, Y., & Tse, Y. K. (2011). A marginal analysis guided technology evaluation and selection. *International Journal of Production Economics*, *131*(1), 15–21. https://doi.org/10.1016/j.ijpe.2010.09.027

Teoh, S. K., & Li, L. Y. (2020). Feasibility of alternative sewage sludge treatment methods from a lifecycle assessment (LCA) perspective. *Journal of Cleaner Production*, *247*, 119495. https://doi.org/10.1016/j.jclepro.2019.119495

Triantaphyllou, E., & Sánchez, A. (1997). A Sensitivity Analysis Approach for Some Deterministic Multi-Criteria Decision-Making Methods. *Decision Sciences*, *28*(1), 151–194. https://doi.org/10.1111/j.1540-5915.1997.tb01306.x

Uddin, M. N., Techato, K., Taweekun, J., Mofijur, M., Rasul, M. G., Mahlia, T. M. I., & Ashrafur, S. M. (2018). An Overview of Recent Developments in Biomass Pyrolysis Technologies. *Energies*, *11*(11), 3115. https://doi.org/10.3390/en11113115

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research Policy*, *24*(3), 419–440. https://doi.org/10.1016/0048-7333(94)00775-3

Ulrich, K. T., Eppinger, S. D., & Yang, M. C. (2020). *Product design and development* (Seventh edition). McGraw-Hill Education.

Vafaei, N., Ribeiro, R., & Camarinha-Matos, L. (2016). *Normalization Techniques for Multi-Criteria Decision Making: Analytical Hierarchy Process Case Study* (Vol. 470). https://doi.org/10.1007/978-3-319-31165-4_26

Vafaei, N., Ribeiro, R. A., & Camarinha-Matos, L. M. (2020). Selecting Normalization Techniques for the Analytical Hierarchy Process. In L. M. Camarinha-Matos, N. Farhadi, F. Lopes, & H. Pereira (Eds.), *Technological Innovation for Life Improvement* (pp. 43–52). Springer International Publishing. https://doi.org/10.1007/978-3-030-45124-0_4

Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. *European Journal of Operational Research*, *169*(1), 1–29. https://doi.org/10.1016/j.ejor.2004.04.028

van de Kaa, G., Rezaei, J., Kamp, L., & Winter, A. de (2014). Photovoltaic technology selection: A fuzzy MCDM approach. *Renewable and Sustainable Energy Reviews*, *32*, 662–670. https://doi.org/10.1016/j.rser.2014.01.044

Vörösmarty, G., & Dobos, I. (2020). A literature review of sustainable supplier evaluation with Data Envelopment Analysis. *Journal of Cleaner Production*, *264*, 121672. https://doi.org/10.1016/j.jclepro.2020.121672

Walmsley, T. G., Ong, B. H., Klemeš, J. J., Tan, R. R., & Varbanov, P. S. (2019). Circular Integration of processes, industries, and economies. *Renewable and Sustainable Energy Reviews*, *107*, 507–515. https://doi.org/10.1016/j.rser.2019.03.039

Wang, C. (2021). Production of biochar from renewable resources. In A. Khan (Ed.), *Advanced technology for the conversion of waste into fuels and chemicals. Volume 1, Biological processes* (pp. 273–287). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-823139-5.00018-6

Wang, J., Manning, D. A. C., Stirling, R., Lopez-Capel, E., & Werner, D. (2023). Biochar benefits carbon off-setting in blue-green infrastructure soils - A lysimeter study. *Journal of Environmental Management*, *325*(Pt B), 116639. https://doi.org/10.1016/j.jenvman.2022.116639

WCBSD. (2022). *Heat as a service: How to decarbonize commercial and industrial heat use with third-party capital investments.* World Business Council for Sustainable Development. https://www.wbcsd.org/Pathways/Energy/Resources/Heat-as-a-service-How-to-decarbonize-commercial-and-industrial-heat-use-with-third-party-capital-investments

Weber, K., & Quicker, P. (2018). Properties of biochar. *Fuel*, *217*, 240–261. https://doi.org/10.1016/j.fuel.2017.12.054

Werdin, J., Conn, R., Fletcher, T. D., Rayner, J. P., Williams, N. S., & Farrell, C. (2021). Biochar particle size and amendment rate are more important for water retention and weight of green roof substrates than differences in feedstock type. *Ecological Engineering*, *171*, 106391. https://doi.org/10.1016/j.ecoleng.2021.106391

Wijnmalen, D. J. D., & Wedley, W. C. (2008). Non-discriminating criteria in the AHP: removal and rank reversal. *Journal of Multi-Criteria Decision Analysis*, *15*(5-6), 143–149. https://doi.org/10.1002/mcda.430

Xu, Y., Wu, S., Huang, F., Huang, H., Yi, Z., & Xue, S. (2022). Biomodification of feedstock for quality-improved biochar: A green method to enhance the Cd sorption capacity of Miscanthus lutarioriparius-derived biochar. *Journal of Cleaner Production*, *350*, 131241. https://doi.org/10.1016/j.jclepro.2022.131241

Yang, Q., Yang, S., Qian, Y., & Kraslawski, A. (2015). Application of House of Quality in evaluation of low rank coal pyrolysis polygeneration technologies. *Energy Conversion and Management*, *99*, 231–241. https://doi.org/10.1016/j.enconman.2015.03.104

Yang, Y., Brammer, J. G., Wright, D. G., Scott, J. A., Serrano, C., & Bridgwater, A. V [A. V.] (2017). Combined heat and power from the intermediate pyrolysis of biomass materials: performance, economics and environmental impact. *Applied Energy*, *191*, 639–652. https://doi.org/10.1016/j.apenergy.2017.02.004

Yousef, S., Eimontas, J., Zakarauskas, K., & Striūgas, N. (2021). Microcrystalline paraffin wax, biogas, carbon particles and aluminum recovery from metallised food packaging plastics using pyrolysis, mechanical and chemical treatments. *Journal of Cleaner Production*, *290*, 125878. https://doi.org/10.1016/j.jclepro.2021.125878

Zabaniotou, A., Kamaterou, P., Kachrimanidou, V., Vlysidis, A., & Koutinas, A. (2018). Taking a reflexive TRL3-4 approach to sustainable use of sunflower meal for the transition from a mono-process pathway to a cascade biorefinery in the context of Circular Bioeconomy. *Journal of Cleaner Production*, *172*, 4119–4129. https://doi.org/10.1016/j.jclepro.2017.01.151

Zhang, Y., He, M., Wang, L., Yan, J., Ma, B., Zhu, X., Ok, Y. S., Mechtcherine, V., & Tsang, D. C. W. (2022). Biochar as construction materials for achieving carbon neutrality. *Biochar*, *4*(1). https://doi.org/10.1007/s42773-022-00182-x

Ziegner, C., & Milla, F. (2022). *Industrial Heat - Market Analysis DACH 2022: Unpublished internal company document*. Hamburg. Company x.

The appendix has been removed due to confidentiality reasons.