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Abstract

In the light of the increasing focus on climate changes biochar is now considered one of the Negative Emission Technologies (NET) in the toolbox. Biochar is the product of pyrolyzed biomass and has a variety of applications besides capturing and storing carbon (PyCCS). This includes the established soil improvement application and newer, less explored applications as an additive in concrete or solar dye cells. Research for new applications is ongoing. Pyrolyzed wood feedstock, called biocarbon, is already being used in the metallurgical industry to replace fossil coal. The biochar market is still immature; the production is very low and so is the demand. This thesis analyzes the market state of affairs with the objective of predicting the future of biochar as an economically viable product. Some key points for new entrants are established through Porter's five forces model and Value Chain Analysis. Some points on optimal production plant are presented. The analysis demonstrates that biochar plant size should not exceed a yearly production of 50 000 tons biochar because the costs of logistics become too large. This is due to biological constraint that limits the quantity of biomass that can be collected per area. The area required for producing the millions of tons biocarbon needed for the metallurgical industry is too large so biocarbon will not be able to replace fossil coal completely. The potential demand in the agricultural industry for biochar is even larger, several hundreds of thousands of tons, will neither be possible to produce. The potential supply will never reach the potential demand. This thesis demonstrates why the best chance of success is within the biochar for the agriculture market.

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1 Introduction

Since 2015 the Paris agreement has speeded up the pace of climate change mitigation initiatives. 196 countries committed to limit global warming to 1.5°C by year 2100 (United Nation FCCC, u.d.). United Nations' International Panel on Climate Change (IPCC) has defined several scenarios of future climate and its impact on humans in addition to mitigating measures. After that, countries have one after another approved legislative acts and initiatives concerning combatting climate change and make the economy more circular and sustainable. The European Union (EU) adopted the ambitious "European Green Deal" in 2019. Their goal is to be the first climate-neutral continent by 2050 (European Commission, 2019). They aim to reduce their greenhouse gases (GHG) emissions by 55% compared to the 1990 levels. Several regions and countries have followed with similar acts.

Emissions from fossil fuels such as gas, oil and coal are the main sources of the GHG. They add carbon dioxide (CO_2) to the atmosphere and the carbon cycle. Most of the consumption of fossil fuels originates from electricity production and transportation. Fossil fuels are also an important ingredient in plastics and metal production. Technologies and methods relying on biomasses that can replace these exist but are immature. Many of these projects are not economically viable yet and are pushed through by legislative forces or governments. A complete phase-out of fossil fuels is not possible within the set timeframe of the Paris Agreement. Therefore, a vast amount of money and effort are put into Carbon Capture and Storage (CCS) technologies. By combining CCS measures with their regular activity, companies are becoming "net-zero" emitters.

Biomasses mainly consists of carbon which is released to the atmosphere as CO_2 when decomposing. By pyrolyzing biomasses most of the carbon are concentrated into "black carbon", also called biochar. The concentration of pure carbon can go above 90%. Producing biochar and storing it in the ground instead of letting the biomasses decompose and release CO_2 is one way of removing carbon from the carbon cycle. Biochar has several other applications and some yet to be discovered. There are many ongoing studies around the world on how to use biochar, and for what purposes. The commercial production is still at a very small scale, but larger plants are being constructed. Industrialized production is just around the corner.

This thesis conducts a market analysis which aims at answering the question “how will the future of the biochar market look like?” First the product and status of the market demand and market supply today are presented. Then, the presented numbers are analyzed with the objective to make predictions for the future. The analysis also includes input from legislative trends. EU is an important driving-force for mitigating climate changes and becoming more sustainable, therefore the European market is emphasized in this analysis. At the end the predictions for the future are presented.

2 Biochar - state of affairs

2.1 Definition of biochar and biocarbon

Definition

Biochar is made of organic material, referred to as biomass, that has been through the process of pyrolysis. The US Energy Information Agency (2022) defines the term biomass as “*renewable organic material that comes from plants and animals*”. Biocarbon is a type of biochar. The two main differences lie in the feedstock content and application. Biocarbon is made from wood only whereas biochar is made from all kinds of biomasses. This includes wood, leaves, bark, plant residues and other. Further, biocarbon is used in the metallurgical industry and biochar is used other places, particularly in the agriculture. Figure 1 presents of what biochar looks like.

Figure 1: picture of biochar (farm2energy.com)

Characteristics

Like fossil coal, biochar is a black solid material consisting mainly of a high percentage of fixed carbon. Fossil coal has been through the natural process of high temperature and pressure over a geological time (buried underground with no presence of oxygen) and biochar is made by humans through pyrolysis (applying high temperature and absence of oxygens but at a much shorter time span).

Biochar is described with certain characteristics such as porosity, density, surface area, heating values, pH, electrical conductivity, Cation Exchange Capacity (CEC).

Carbon cleanness (or the number of pollutants or ash), carbon content and heating value usually defines the quality. Pollutants are toxicants such as heavy metals or Polycyclic Aromatic Hydrocarbons (PAH). The heavy metals usually increase in concentration in the biochar compared to the input feedstock. PAHs are complex carbon-containing molecules that tend to stick to particles or appear as gas. PAHs indice cancer and should be avoided. At the higher end of the pyrolysis temperature scale these molecules will eventually also decompose.

The amount of ash depends largely on the molecular composition of the feedstock. The ash components are all those that are not moisture, volatiles, or carbon. It can be very small concentrations of K, Ca or Mg that most feedstocks contain small amounts of. As mentioned earlier bark and leaves contain more of these ash components than the wood itself. If there is a requirement regarding maximum ash content in the biochar, only wood is pyrolyzed. Bark and leaves are removed. This type of biochar is called biocarbon.

Pyrolysis

Pyrolysis is the chemical decomposition of organic materials through the application of heat (Wikipedia, 2023). In this decomposition process there is no or very little oxygen present which distinguishes the process from combustion (burning) where abundant amounts of oxygen are present. Pyrolysis is an old technique that has been used for since the antiquity to produce charcoal from coal. All material that undergoes pyrolysis decompose into moisture, volatiles, fixed carbon and ash. The relative amounts vary depending on the molecular composition of the input material. The end products at these very high temperatures are the gaseous phase; the moisture (water) and volatiles, and the solids; the fixed caron and ash. Once the gaseous phase cools down a part of the gas condensates into a liquid, often referred to as “pyrolysis oil”. The gas and liquids produced from pyrolysis are combustible and can be used as fuels or for heating. They are classified as a renewable energy source. Picture 2 shows jars of bio-gas and biochar.

Figure 2: picture showing waste feedstock and pyrolysis products biochar and bio-gas (syngas) (Vow ASA, 2021)

The gas is often referred to as “pyrolysis gas”. It generally contains methane (CH_4), hydrogen (H_2), carbon dioxide (CO_2), carbon monoxide (CO) and some smaller amounts of ethane (C_2H_6). Approximately 40% of the gas is methane and the second largest concentration is from the component carbon monoxide. Carbon monoxide is toxic to humans so precautions must be made in handling the pyrolysis gas. The pyrolysis gas much be handled in some way before released into the atmosphere.
There are several parameters to change to optimize the end product.

- Heating rate
- Maximum temperature attained
- Residence time

Based on these parameters slow pyrolysis is characterized by a heating rate of 45-50deg°C/min and approximately 1 hour residence time. This is also called the conventional pyrolysis. Fast pyrolysis has a heating rate 120-130 deg°C/min and a shorter residence time, only roughly 20 minutes. Saleh Al Arni (2017) investigated the differences between slow and fast pyrolysis when pyrolyzing sugar cane bagasse and found that slow pyrolysis gave a higher gas yield than the fast pyrolysis which gave a higher liquid yield. He also found that an increase in temperature lead to more gas in the slow pyrolysis but a higher solid yield in the fast pyrolysis. For both methods the hydrogen (H_2) yield increased with higher temperature.

Several pyrolysis technologies are available. The process is the same; apply heat but no oxygen to decompose organic material. The difference lies in how the organic material is heated up to desired temperature.

Charcoal produced from wood in charcoal piles dates to the antiquity (Wikipedia, u.d.). Charcoal generates much more heat and is lighter hence easier to transport than wood. It was used for iron smelting even back then. Later on, fossil coal has replaced wood charcoal in these applications.

The modern pyrolysis technologies apply direct current, fuel combustion, or micro-wave assisted pyrolysis to apply the heat necessary in the process. Heating is done by direct current which take advantage of the Joule effect when sending current through a resistive material. This heat together with absence of oxygen pyrolyzes the organic material. Heating through fuel combustion can either be fossil fuels like hydrocarbon gases or diesel. Other furnaces exploit the pyrolysis gas, one of the pyrolysis end products. This makes the furnace self-driven (after the start-up period where other gas sources are needed). The last technology mentioned, micro-wave assisted pyrolysis, creates heat through sending electromagnetic micro-waves into the organic material. This technology use dielectric heating operating at specific frequencies (Hadiya, et al., 2022). These waves induce motion of polar molecules such as for instance water.

Optimization of the parameters described above are helpful when designing the pyrolysis process to maximize the desired output ingredient. The gas and condensate produced from pyrolysis are used as biofuels whereas the solids, the biochar, have other applications that will be investigated in more in detail in chapter 2.2.

Ingredients and end product

The previous chapter briefly touched upon that when biomass is subject to a pyrolysis process four main outputs are produced: biochar, pyrolysis gas, pyrolysis oil and ash. The respective yields of each output component depend on the composition of the input.

So what can be pyrolyzed? Basically, everything can be pyrolyzed. If the input has a high content of carbon, like biomass, then the output will have a high biocarbon yield. If the input contains a lot of Volatile Organic Compounds (VOC) that easily decomposes, the pyrolysis gas yield will be high. Examples of such materials are plastics and tyres. When pyrolyzed, these will yield much pyrolysis gas and oils, and little solids (biochar and ash). Other abundant materials considered a waste issue are sewage sludge and animal manure. Sewage is waste water, a domestic, industrial or agricultural effluent.

Three main types of molecule groups constitute the term biomass. They are ligning, cellulose, and hemicellulose. Payam Danesh et al. (2023) summarizes some findings in their publication. Firstly, raw materials containing more lignin and little moisture produces high-yield biochar. Secondly, heating rate and residence time affect yield, porosity and surface are of the biochar. The article also mentions applications within several areas such as water pollutants removal, as a revision of soil, as a composite additive, a catalyst and as a material for electrochemistry, for supercapacitors, and for batteries.

When producing biocarbon, the bark and leaves are removed from the wood feedstock. This is due to the relatively high quantity of other elements than carbon that turns into ash during pyrolysis. This decreases the carbon concentration to a level that is below the requirement from the metallurgical industry. Pyrolyzing any type of biomass produced what is called biochar, a much wider term.

2.2 Demand

In the emerging markets for biochar and biocarbon, demand is still sparse but the current trends of where the industry output is directed are clear. Some of the most prominent areas of application are presented below. At the end other research are briefly mentioned.

Metallurgical industry

Fossil coal plays a critical role in the production of metals. The carbon is the reduction agent that purifies the metals in the melting ovens. Under high temperature, the oxygen atom leaves the molecule it has formed with the metal atom to form carbon dioxide, CO2, with the carbon atom instead. This chemical process is called a reduction and the carbon is the reduction agent. Coal, as any other geological rock, exists in many variations. The coal used in the metallurgical industry has particular properties and is classified as an Anthracite, also named “met coal”. This coal is the geologically most mature type (produced under highest pressure and temperature), has the highest percentage of carbon, usually above 90 %, and has the highest heat content (26-33 MJ/kg).

The world consumes several billions of tons of fossil coal each year. Over half of it goes to energy production. The world consumption will probably surpass 8 billion tons of coal in 2022. In 2021, 1110 million tons of met coal were consumed by the metallurgical industry worldwide (IEA, 2022). China’s metallurgical coal consumption alone was 720 million tons and EU’s consumption 53.8 million tons in 2021. Norway alone uses almost one million tons of fossil coal a year (VOW Green Metals AS, 2022). The IEA anticipate a growth in the trade of met coal in the coming years. Figure 3 illustrates how much of the world’s coal consumption is dedicated to the metallurgical industry.

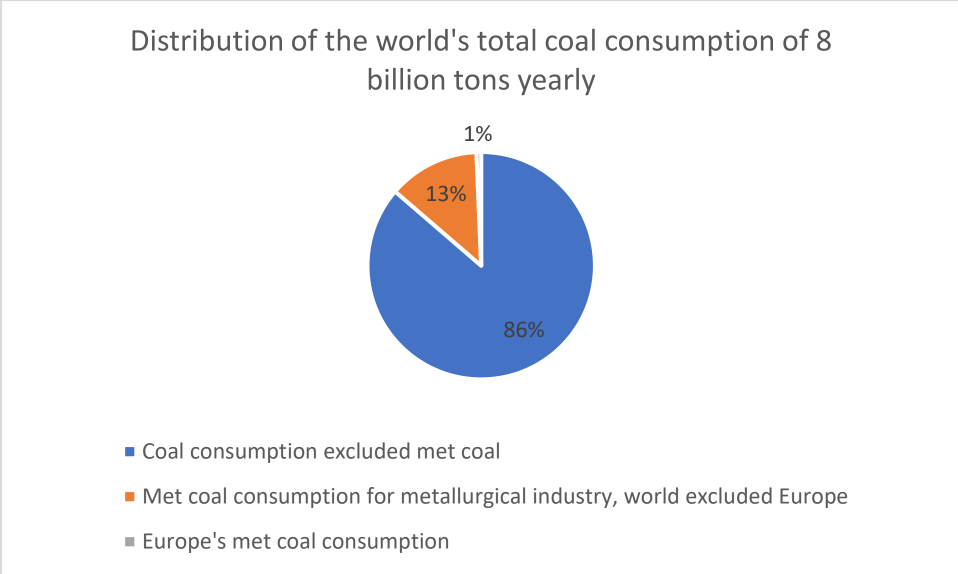

Figure 3: Worldwide yearly coal consumption

Most of the world's met coal is mined from Australia where the coal is mined from deep underground mines. In 2021 Australia had a market share of 56% and is by far the largest exporter. Other large producing countries are the US, Russia and Canada. Approximately 72% of the traded met coal is imported by the Asia Pacific Region, mainly China and India. EU accounted for 15% of the import.

Fossil coal consumption has pollution and waste issues related to it. As coal is handled and transported small particles liberates and create dust (Osborne, 2013). When adding water this turns into a slurry. If these particles are less than 1-2 µm they are referred to as Particulate Matter (PM) and is a health hazard. Furthermore, during combustion of coal, whether it be in a power plant or in a metal producing furnace, create emissions of unwanted gases. Since fossil coal contains small amounts of sulphur and nitrogen, combustion of coal emits sulphur dioxide, SO2, and nitrogen dioxide referred to as NOx emissions. They both affect health and environment and in contact with water they form sulphuric and nitric acid, known as acid rain.

Before fossil coal can be used in the metallurgical production it must go through the process of coking. The objective of this process is to purify the coal and to increase the percentage of carbon in the material. Coke is produced by slow pyrolysis of coal. This process, named coking, releases tars, oils, nitrogen compounds etc. so that the carbon

concentration increases further. In the metallurgical production the carbon is the only interesting ingredient, all other components can disturb the process.
The chemical reaction occurring is:

$$metal\ oxides + \ carbon + heat \rightarrow metal + CO_2$$

Several technologies exist with “Blast Furnace – basic oxygen furnace” (BF-BOF) is the most dominant method accounting for 70%. Hot metal is produced in the blast furnace, then refined in the basic oxygen converter to produce liquid metal. In the case of recycling metal, an “electric arc furnace” (EAF) is used to heat and liquify the scrap metal.
Coke is also used in the production of silicon, ferrosilicon and manganese which also requires a chemical reduction. Silicon, for instance, is produced from the mineral Quartz (SiO_2).

Biocarbon has many of the same properties as fossil coal. The most important one for the application in the metallurgical industry is that both have a very high content of pure carbon, ranging from 70% to above 90%. For this reason, several have studied the suitability of biocarbon in metal production. Sahar Safarian (2022) evaluated the potential of biocarbon replacing fossil coal in the steel industry and found that blending biocarbon and fossil coal was feasible and would even reduce the amount of carbon needed per ton steel produced.

Elkem (2021) examined the application of pellets made by biocarbon and pyrolysis oil in the silicon and ferrosilicon production. The study showed that these pellets exhibited promising mechanical and reactivity properties for further or even fully replacing fossil coal in the production. Currently biocarbon is mixed into the fossil coal with a percentage of 20% at the Elkem factories in Norway. Their new target is to increase the usage of biocarbon up to 50% by 2031. This target was set in October 2021 when they launched their climate roadmap which would lead them to be in line with the Paris Agreement. They aim at “net-zero” emissions by 2050.

Soil improvement remedy

Plants need nitrogen, phosphorus and potassium to thrive. The nitrogen helps leaves grow, phosphorus promotes the development of roots, flowers and seeds and potassium promotes strong stem growth (Wikipedia, 2023). Nitrogen is the most abundant element on earth and can be extracted from air during the production of nitrogen fertilizers. Both the phosphorus and potassium originate from rocks, a non-renewable source. Phosphorus is even classified as critical and listed on EU's Critical Raw Material (CRM) List (Oger, 2022).

Conventional agriculture relies on large quantities of fertilizers. In 2017, the consumption of Nitrogen based fertilizer was 10.64 million metric tons in EU alone, worldwide the consumption was 190.14 million metric tons (Statista, 2023). It is the world's 47th most traded product by $62.6 billion. The world's largest exporter is Russia with a market share of 12.1% followed by China with a market share of 11.2 %.

Fertilizers are easily washed away from the soil by water flows such as heavy rain and flooding events. It also leaches into the air as N_2O, a strong GHG, through microbial N_2O production. For this reason, fertilizers must be added to the soil frequently. The washed-out nitrogen and phosphorus accumulate in waters. This accumulation pollutes the waters and nurture the growth of algae. This is called eutrophication and makes the waters turbid and non-transparent which kill all other water life. This has been a major problem in areas such as the Baltic Sea. Eutrophication can also affect groundwater and drinking water quality. Biochar mixed into soil improves the soil's physical, chemical, and biological properties (Oliveira, Patel, Jaisi, Adhikari, & Lu, 2017). The water holding capacity, the O_2 content, and the moisture levels become higher. Pollutants are immobilized and carbon is sequestrated. Lastly the soil obtains microbial abundance, diversity, and activity. The porosity and large surface area act as a habitat for microbes such as mycorrhizal fungus and bacteria that obtain their metabolic needs from these micro-habitats. The absorptive properties of biochar retain the nutrients better so there is less leaching into both the air and the marine ecosystems. This reduces the need for continuously adding new fertilizers to the soil. Liu et al. (2019) did a global assessment of the amount of reduced nitrogen leaching from soils when adding biochar and estimated the leaching to be reduced by 12-29%

Tisserant and Cherubini (2019) discuss the potential climate effects of adding biochar to the soil, both positive and negative, through their comprehensive review of available research. Besides the decreased albedo of the soil, a decrease in solar radiation reflectivity causing a warming effect, the addition of biochar to the soil has positive effects. Further they also reviewed Life-Cycle Analysis (LCA) studies of biochar systems. They found that most studies show that the net carbon emission values are negative if the avoided emissions from degradation of the feedstock are accounted for. This means that if the pyrolyzed feedstock is a bi-product or waste from a different production process the net GHG emissions impact is negative. If there is competition for the resources (e.g. using a crop for cultivating food versus cultivating feedstock for pyrolysis) the LCA shows that the net effect is less favorable.

Cases where biproducts are pyrolyzed and used for soil remedy already exist. Zabaniotou et al. (2014) present an example where the residues from olive oil production is pyrolyzed and the biochar is mixed back into the soil. Further S. Debevc et al. (2022) describe how pyrolyzation of almond shell biomass is a good example of valorization of a waste product. Circular Carbon GmbH in Hamburg, Germany, makes a business out of pyrolyzing cocoa shells into biochar, a waste from the chocolate factory next door (Sandle, 2023). They produce biochar and burns the pyrolysis gas to produce district heat.

In Europe the European Biochar Certificate (EBC) is mandatory for all biochar sold for use in the agriculture. The biochar producer must register and follow a thorough verification process to obtain the certificate (EBC, 2022). Based on strict criteria for biomass composition, pyrolysis parameters and biochar properties guidelines are developed. These guidelines are based on well-researched and legally backed-up processes. The publication aims to encourage and ensure good control of the biochar production and its quality before putting it putting it back into the soil.

The recommended ratio of biochar mixed into soil is 1-10% depending on the soil quality according to the Norwegian producer Standard Bio through their web shop (ERA, u.d.). Refill is recommended every few years.

In EU the utilized agricultural area covered 157.4 million hectares in 2020 (European Union , 2022). This constitutes 38.4% of the total land area. Agricultural area consists of arable land, permanent grassland and permanent crops. 62.3% of the agricultural area is arable land where biochar easily could be added into the soil each year.

PyCCS and Carbon Credits

Pyrogenic Carbon Capture and Storage (PyCCS) is renowned as a Negative Emissions Technology (NET) by IPCC since 2018 (Schmidt, the Biochar Journal, 2018). Plants extract CO_2 from the atmosphere and this carbon is sequestered using pyrolysis. The carbon is then fixed in biochar instead of being released back into the atmosphere during decomposition of the biomass.

The PyCCS-marked is driven by national and supranational regulations. In Europe the EU Emissions Trading System (EU ETS) has been put in place to combat climate change and making GHG reduction economically beneficial (European Commision, u.d.). This is the world's very first major carbon market and is currently also the largest one. EU allowances, EUA, (can also be called carbon credits or emission allowances) are the financial instruments being traded. One EUA represents the right to emit:

- One ton of CO_2, or
- The equivalent amount of other strong GHGs

A pre-defined cap of EUA, or credits, is set for EU as a whole and decreases each year by 1,74%. Almost 60% of the allowances are sold on auctions at the beginning of the year. Within this cap, companies receive or buy emission allowances every year. They can trade these carbon credits as needed.

When biochar is produced and put into the ground for storage according to the EBC rules this counts as negative GHG emissions, often referred to as a Carbon sink (C-sink). This accountable net negative GHG emission can be sold as a Carbon Credit to companies that need to reduce their carbon footprint. They can also buy carbon credits to compensate for emissions above their yearly allocated quota. New players emerge in this marketplace as brokers who connects the C-sink creators with the GHG emitters who need the carbon credits. There are several such companies in the market. For the time being only companies can buy or sell these carbon credits. Such a marketplace for private persons does not yet exist.

Figure 4 shows the Carbon Credit price development of in the timespan 2020-23. Since EU each year decrease the emissions cap by 1.57% the price trend is as expected, increasing and will most likely keep increasing in the future. All other things equal, the increase in Carbon Credit price increases the profitability of producing biochar for soil improvement too.

Figure 4: Market price of Carbon Credits, 2020-23. Screenshot from Statista.com

Other research

Biochar can be produced from all kinds of biomasses, included what is considered biowaste material. With the increasing wealth and world population the amount of waste generated yearly keeps on growing. Producing biochar from this biomass waste through pyrolysis or other methods can help reduce the waste management issue. It also extracts bioenergy in terms of bio-gas or bio-oil from the biomasses. The secondary product is then the biochar. Researchers all around the world explores potential applications of biochar. This chapter has already described the metallurgical and agricultural application. The next paragraphs will mention some of the many other studies conducted on biochar.

Biochar consists of very pure black carbon. In some cases, the concentration of carbon can exceed 90%. Other materials having this high pureness of carbon are graphite and anthracite, met coal, to mention some. Both these two materials are produced through mining and are non-renewable. Because of the similarities in composition many researchers investigate the application of biochar as a substitute.

Biocarbon as a substitution for met coal in the metallurgical industry is already discussed in chapter 2.2 . Further there are studies looking at biocarbon replacing platinum as a counter electrode catalyst in dye solar cells. In this study Tiihonen et al. (2020) produced biocarbon through hydrothermal carbonization, then chemically activated it with KOH to impregnate it. At last, the biocarbon went through heat treatment at 800°C for two hours to get the appropriate nanostructure. They demonstrated that biocarbon materials show potential for application in dye solar cells.

Recently research has explored the use of biochar as building material. Adding 2 wt% as a filler and as a cement substitute in cementitious composites showed an increase of flexural strength by 15%. It also reduces the carbon footprint of the cement and helped to deal with a waste problem (Suarez-Riera, Restuccia, & Ferro, 2020).

Biochar is used as a food additive for animals. It keeps the animals healthier with better digestion because toxins are adsorped, attached to the surface of the biochar. Schmidt et al. (2019) summarize some of the historical and ongoing studies in their comprehensive article.

Biochar also has this ability to adsorb things outside the digestive system of animals and is used in activated coal filters where fossil coals historically have been used. They adsorb heavy metals, pollutants and PFAS to mention some.

As this section demonstrates, the possibilities for biochar for other applications are numerous. Nevertheless, the continuation of this thesis will only focus on biocarbon for the metallurgical industry and biochar as a soil improvement remedy and Net-Emissions Technology (NET). Biochar is a renewable resource that should be exploited more than it is today. Research all over the world demonstrates the interest for this product.

2.3 Supply

This section will investigate current suppliers of biochar, the technology providers and finish by looking at production numbers and the implication of these numbers to the market maturity.

Current suppliers

The biochar market still finds itself in its early days. The market is immature and hence there are no established large producers yet.

The biochar produced now is sold as a soil improvement remedy. A quick search on Google reveals online stores around the globe selling biochar in buckets or bags to a fairly high price per kilo. Even the American supermarket Walmart sells buckets of biochar (Walmart, u.d.).

In Norway the current production of biochar was limited to 600 tons per year in 2022. However, with 3 plants under construction the production is expected to rise to 12 000 tons annually during 2024 (Skinnes, 2022). An example of a current biochar vendor is the web shop ERA (ERA, u.d.) which sells products they have named “Croptimist” and “SoilRooster” for soil improvement. The selling price is 899 NOK for 8.5 L giving a price per liter of 106 NOK/L for the “Croptimist”. They say that 1L of biochar is enough for one pallet. (“pallekarm”, currently widely used in Norwegian kitchen gardens) A pallet’s standard dimensions are 120cm x 80cm x 20cm which gives a volume of 192 L.

In Europe the total production is limited to 20 000 tons annually (numbers from end of 2020). At the same time 72 biochar producing plants were under operation according to EBI (2021). This means that the average plant produces 278 tons biochar per year. EBI foresees an exponential growth of biochar production with new players entering the market.

One of the main reasons for the expected large growth in production is the construction of a biocarbon plant at Follum near Hønefoss by Vow Green Metals. The planned start up is in 2023 and the production capacity is 10 000 tons biocarbon per year (VOW Green Metals AS, 2022). The customer, Elkem, a large player in the metallurgical industry, will use this biocarbon as a reducing agent at their Norwegian plants as a part of their strategy to become more sustainable and environmentally friendly. The reason for this large investment in an industrial sized production plant and significant jump in production capacity is that the customer, Elkem, committed to a long-term contract with Vow Green Metals to purchase the biocarbon. This lowered the investment risk considerably for Vow Green Metals who then secured a customer for all the biochar production before even taking the first sod in the ground. Why does this plant have such a large capacity? The size of the pyrolysis reactors cannot explain the difference in production capacity alone even though they have larger dimensions. The main differences from existing plants are that there are several production lines in parallel and continuous production running all year, 24/7.

Technology providers

There are several technologies regarding the pyrolysis furnace available. The different technologies are described in chapter 2.1. There are also several companies that supply pyrolysis furnace equipment in the market.

Pyreg GmbH., a German technology company which sells biochar production equipment, have over 50 systems in production worldwide (Pyreg GmbH, u.d.). In total, those 50 plants generate approximately 8 800 tons of biochar annually, giving an average of 176 tons per year per plant. Their pyrolysis technology is based on heating by electricity.

Other biochar production companies, such as VOW ASA, also have supplied technology to European biochar plants currently in production. VOW through their subsidiaries provide pyrolysis furnaces with heating based on all three technologies.

Current production number

As mentioned in the precedent section, the annual biochar production in Europe was 20 000 tons per year by the end of 2020. These 72 plants producing this biochar then have an average production of 276 tons per year. Compared to the plant built by VOW Green Metals in Hønefoss which will alone produce 10 000 tons per year these plants are small.

The nature and size of the products presented here above demonstrates that the market for biochar as a soil amendment still is immature. The sales strategy aims at a small customer group consisting of people who have a small-scale kitchen garden at home as a hobby and are willing to pay a high price for the biochar. The production scale is clearly not suitable for industrial purposes yet.

3 Analytical Framework

This thesis conducts a market analysis of biochar. A market can be defined as "the set of actual and potential consumers of a market offer" (Andreasen & Kotler, 1987). There are many considerations to be taken, especially since this market is rather immature. As discovered in the previous chapter, there are no large production plants of biochar, yet. The demand side is still small because the demand is still small. The potential applications are still being studied. Chapter 2.1 explains what biochar is, what the market demand is and the current state of production.

Furthermore, this market analysis will look into, but not limited to:

- Market type and forces (Porter's 5 forces)
- Value chain analysis
- The different product markets

These perspectives along with the market description and a good understanding of the product intend to make predictions about the evolution of the biochar market.

This chapter intends to give a brief description of the theory behind some of the models applied to this marked analysis with the objective to predict some future states of the biochar market.

3.1 Porter's five forces

In 1979 Michael F. Porter presented a framework for investigating the competitive environment and how to use this to shape strategy. The competitive forces are manifested not only by the other market players, but also by external parties outside the industry in focus.

The five basic forces are

- Jockeying for position among current competitors, competitive rivalry
- Bargaining power of buyers
- Bargaining power of suppliers
- Threat of new entrants
- Threat of substitute products or services

Figure 5 illustrates Porter's model.

Figure 5: illustration of Perter's five forces

The competitive rivalry can be seen as the central force in the model, but it is their collective strength that determines the ultimate profit potential. Are there "intense" forces limiting the potential for more than small profits or are there only "mild" forces present allowing for quite large profits? The strengths and weaknesses of the company or industry are identified after assessing the five forces affecting the competition. Together with the ambition this guides the strategy on how to operate in the given industry to obtain the desired market position.

Porter argues these five forces are universal and applies to all industries. Because every industry has an underlying structure, a set of fundamental technical and economic characteristics, which give rise to these competitive forces. It can even be used to predict eventual profitability of an immature industry.

3.2 Value Chain Analysis

Michael E. Porter (1985) defines Value Chain as "various business activities and processes involved in creating a product or performing a service". The concept was originally developed by him. In the business world companies must make a profit to survive. Evaluating and analyzing each part of the value chain to look for improvements that lead to cost reductions is called Value Chain Analysis. Each part of the production process is evaluated separately. At the same time, it allows us to take a step back and see the bigger picture, to understand the entire value chain. From the starting point of harvesting the feedstock to the end where the biochar is purchased by the customers.

Tim Stobierski (2020) at Harvard Business School proposes a receipt of how to conduct a Value Chain Analysis:

1. Identify Activities: what are considered primary and secondary activities going into the production process?
2. Determine cost and values of these activities: What value do they add to the process?
3. Map opportunities for competitive advantages: What can be changed in order to obtain the wanted effect or advantage over competitors?

Typically, this analysis will reveal several opportunities for improvements across the entire process from start to end.

3.3 Characteristics of the different product markets

The literature describes a four-market model where the markets have quite different characteristics (McConnell, Brue, Flynn, & Grant, 2018). The end points are "pure competition" and "monopoly".

A market said to be in pure competition has the following characteristics:

- Many small and independent producers.
- Standardized product, no differentiation between producers.
- No price makers in the market. The market price is determined by the equilibrium between supply and demand.
- Free entry and exit for producers.

In a purely competitive market, the demand from the market finds the equilibrium between price and amount of sold goods. The producers make profit by having the lowest possible production costs

On the other side, a pure monopoly is characterized by:

- One single producer
- No substitute or close to substitute product available
- The producer is the price maker. The producer sets the price that maximizes the profit.
- Blocked entry. Competitors wanting to enter face barriers such as legal barriers (patents), economical barriers (economy of scales), technological or other types of barriers.

In this case the monopolist chooses the amount of goods to be produced based on profit maximization calculations. The prize will still be at the equilibrium where supply meets demand. Compared to a pure competitive market the prize for the good will be, given same supply of good into the market, higher.

The two in-between market types are monopolistic competition where there are a relatively large number of producers that all have a small market share. They sell a differentiated product meaning that it is similar but has some singularities or special effects. The price can also be differentiated. The entry and exit in this market are easy. A good example of a monopolistic market is the clothing industry. There are many producers that sell trousers. Each producer has made their trouser a little bit different from the competitors' trouser, but the usage is all the same. To compete for a market share, they invest heavily in marketing and branding.

The last market type is the oligopoly which has a few, large producers. The product can be both homogeneous or differentiated. There are barriers to entry that makes it difficult for new entrants to take a market share. Often this is related to economy of scales, high capital requirements. The producers have some degree of control over the price but must pay attention to the competitors and what they act on. If the price decreases, the others should follow to maintain market share. This sort of behavior is described by game theory which will not be explained here.

4 Analysis

The analysis in this chapter first evaluates the potential for plant size growth. Then, an assessment of the biocarbon and biochar markets is conducted. At last the Porter's five forces model is applied to the two cases to create some guidelines for new entrants to succeed.

4.1 Production – limiting factors

Currently the largest biochar plant in the world is under construction and is dimensioned for a yearly biochar production of 10 000 tons. This section explores the potential scale economies of a single plant. The discussion will also be related to the 10 000 tons plant being built in Norway to evaluate if there is room for additional expansion. The limiting factors in the production process will be assessed and an evaluation of a potential limit on size will be conducted.

A pyrolysis reactor is designed to produce a given quantity of biochar per time unit. If it is operated continuously, 24/7, and at the design capacity (maximum capacity with the associated planned down-town for maintenance and other planned work), then the plant's total production capacity can only be increased by adding more production lines in parallel, i.e. more equipment. Adding production lines is capital demanding and has add incremental fixed costs in addition to the variable cost for its operation. The required area and the consumed energy by the equipment are not considered to be large and hence are not limiting the potential production capacity increase. It is an energy intensive production process, but the assumption is that the energy supply is "infinite", either by using some of the bio-gas, or by electricity provided by the public infrastructure. Energy supply is thus not considered to be the limiting factor. In theory, that means that implementation of an infinite number of production lines in a biochar plant is feasible, thus this is not considered a limiting factor in the production.

However, the biochar production requires large volumes of feedstock. Table 1 summarizes values assumed for calculating of required masses of feedstock. The bulk densities of feedstocks are assumptions based on discussions with VOW employees (pyrolysis technology providers). The yield is a volume-based number, if one cubic meter of feedstock is pyrolyzed, 0.2 cubic meters of biochar is produced (20 %). The rest of the components in the feedstock is transformed into volatiles in the form of bio-gas and bio-oil. 1 TEU is the size of a 20-feet container, an international standard used within logistics. The value assumed for potential biomass per hectare is from a presentation given by Dr. M. Parikka (2006).

Table 1: Input parameters for calculating demand

Input parameters	
Assumed bulk density of biochar	0.2 tons/m^3
Assumed bulk density of feedstock going into biochar production	0.3 tons/m^3
Biochar Yield from pyrolysis	20 %
Volume of 1 TEU (volume of container, of type Twenty-foot Equivalent Unit)	38.5 m^3
Potential biomass per hectare (1 hectare = 10 000m2) land	77 tons

To better understand the potential size of a biochar plant, feedstock volume and its impact on logistics and transportation, i.e. the number of containers, must be calculated. If the number of trailers transporting the feedstock to the plant is too high for the road network to handle, the investment costs should also need to include improvement of the roads nearby to account for the increased traffic it imposes. This enlarged investment cost makes the project less profitable or even profitless. So first the required number of containers per year and per day is calculated, both for the input feedstock, and for the produced biochar:

Table 2: Calculations of numbers of containers with feedstock and biochar

Number of containers with feedstock		
Volume of required feedstock per year	= 10 000tons(biochar)/year / 20% yield / 0.3 tons/m^3	=166 667 m^3/year feedstock

Equivalent number of 1TEU containers of feedstock per year	= 166 667m^3/year / 38.5m^3/container	= 4 329 containers/year
Daily number of 1TEU containers (assuming 24/7 production)	= 4329containers/year / 365days/year	= 11.9 containers per day filled with feedstock
Number of containers with biochar		
Volumetric biochar production per year	= 10 000tons/year / 0.2tons/m^3	= 50 000 m^3/year biochar
Equivalent number of 1TEU container	= 50 000m^3/year / 38.5m^3/container	= 1299 containers
Daily number of 1TEU containers	= 1299/365	= 3.5 containers per day filled with biochar

These numbers indicate that a plant producing 10 000 tons of biochar each year will on average have 12 containers daily with feedstock coming in and almost 4 containers of biochar going out of the plant. One large trailer can transport two of these containers simultaneously, meaning six trailers with feedstock every day. In terms of traffic this is not affecting the road network significantly. Hence there is room for increasing the number of trailers delivering feedstock and increasing the production capacity to more than 10 000 tons yearly.

The ingredient for the biochar, the biomasses (wood, feedstock, wood waste) are collected from forests and farmed land. The biological constraints on agriculture and forest production limit the amount of biomass available per area. Hence, it requires large areas of land dedicated to biomass harvest. In Europe up to 77 tons of woody biomass can be collected per hectare. This number is lower than the global average of 109 tons/ha which is due to the tempered climate. (Dr. Parikka, 2006) One hectare is equivalent to 10 000m^2, an area of 100m x 100m.

77 tons of biomass has a volume of 257 m^3 which corresponds to 7 containers. This is just above half a day's biomass requirement for a plant producing 10 000 tons a year. The required equipment and handling to process these amounts of biomasses are substantial. These are variable costs that change with the volume of biochar production. These costs

especially include logistics, manpower, and energy to operate the machinery. The total cost (TC) also includes the building, machinery, trucks, insurance, and other fixed costs.

The model for predicting the longer-term production cost follows the long-run-average-cost curve. Initially an expansion of the plant's production capacity induces economies of scale until it reaches a minimum Average Total Cost (ATC). Afterwards the ATC will increase again and there is no longer any point of expanding from an economical point of view. For a biochar plant, the main reason for an increasing ATC is the logistics costs which eventually, as the plant size increases, causes the Marginal Cost (MC) to increase and thus the ATC. The reason for the increasing marginal cost of logistics associated with increasing plant size is the following: larger plant size requires serving a larger geographical area with trucks. This is necessary to collect sufficient feedstock volumes to utilize the larger plant's capacity in an efficient manner.

A feasible scale of production that can be run efficiently probably corresponds to a magnitude of 50 000 tons biochar in yearly production (discussions with colleague internally in VOW). After this the processing, logistics and transportation costs become too large and the biochar will no longer be competitive to fossil coal or conventional fertilizer. Neither will it have any positive effect on the climate, so not interesting as a climate friendly option either anymore. This is principally due to the carbon footprint associated with the increase in logistics and distance of transportation which will increase exponentially.

Another limiting factor is the large quantity of biproducts accompanying the biochar production, the bio-gas and bio-oil. The bio-gas in particular needs to be handled because it contains methane, a strong GHG, and CO, toxic to humans. The easiest way to handle it is to burn it which transforms it into CO_2 and large quantities of heat which needs to be exploited. It can be used for district heating is the infrastructure is in place or electricity generation using steam turbines as an example.

To terminate the analysis of the factors limiting the production capacity, two things stand out: the logistics of the large quantities of feedstock and the handling of the biproducts. At some point the capacity increase will be associated with diseconomies of scale. Similarly for the quantity of biproducts, there is a cap on the handling capacity. At some point there are no more ways to utilize the excessive heat, bio-gas and -oil. Together the logistics and the handlings of products and biproducts are the main limiting factors regarding expanding a biochar production plant size.

4.2 Biocarbon replacing fossil coal in the metallurgical industry.

In Europe alone the demand for fossil coal to the metallurgical industry was 53.4 million tons in 2021 (IEA, 2022). If biocarbon can replace fossil coal with a ratio of one-to-one, this means a demand of biocarbon of approximately 53 000 000 tons yearly. To produce this much biocarbon, Europe would have to have 5 300 plants with capacity of 10 000 tons. If the capacity were to increase to 50 000tons yearly per plant, Europe would "only" need 1060 factories.

The land area required to provide enough biomass for 53 million tons biocarbon is estimated in the Table 3.

Table 3: Calculation of area required for biomass production

Biomass required (ton)	= 53 000 000tons_biocarbon/20%yield	= 265 million tons biomass
Area required (ha)	=260 000 000 tons_biomass / 77tons/ha	= 3 376 623 ha
Area (km^2)	= 3 376 623 ha / 100ha/km^2	= 33 766 km^2

The area required to provide enough biomass for one year's biocarbon demand is 33 766km^2. or 3.376 million hectares. To put it in perspective, the total land area of France is 18.5 million hectares. This means that to cover one year's demand of biochar in Europe one would have to dedicate approximately a 6^{th} of France's land area to cultivate and harvest biomass. Figure 6 below illustrates the land area required (green square) for one year of biocarbon production equivalent to 53 million tons of biocarbon.

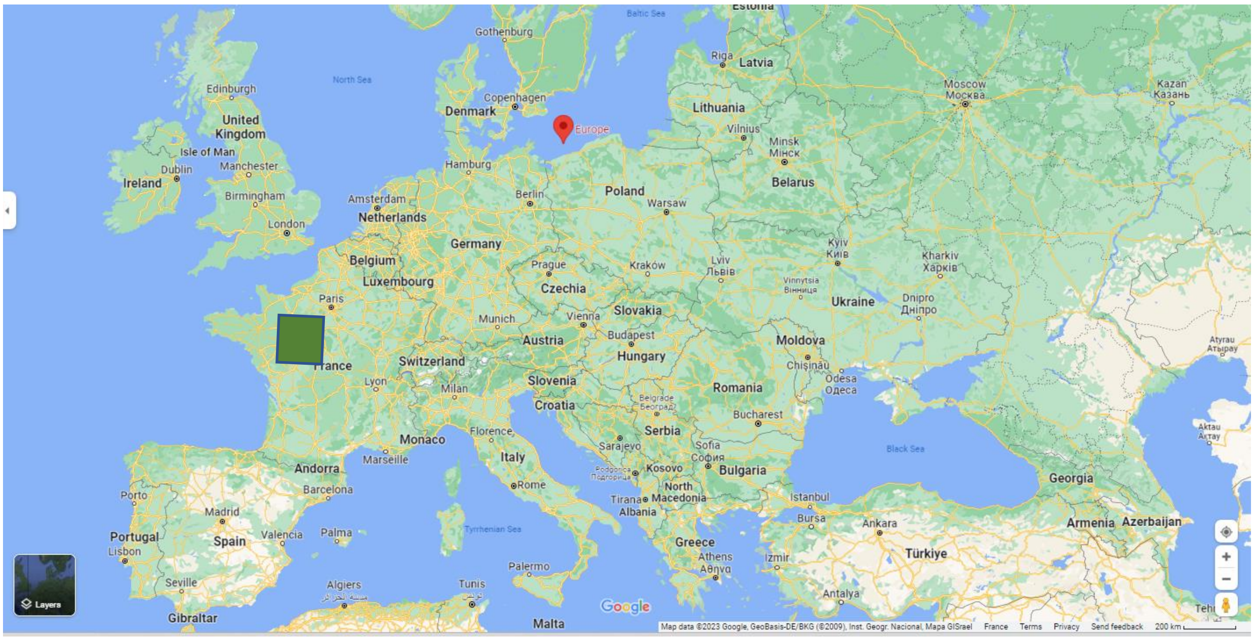

Figure 6: map of Europe with green square showing equivalent size of one year's biomass consumption

If one further assumes that it takes approximately 20 years to regrow trees and other biomass for biocarbon production, this will require an area of 67.5 million hectares. That is more than three times the size of France.

If the demand stays at 2021-levels or increases, Europe cannot become self-sufficient with biocarbon, there is not enough areas available to produce the required quantity of woody biomasses.

4.3 Biochar as soil improvement remedy

The other application in focus in this thesis is biochar as a soil improvement remedy. Mixing biochar in the soil improves the soil quality by increasing the capability of holding moisture and nutrients and increase microbial activity.

The agricultural area in EU is 157.4 million hectares of land and makes up 38.4% of the total area in the EU. Of the agricultural area, 62.3% is arable land which is suitable for biochar application. To estimate future biochar demand for this area of arable land, some assumptions are needed to do the calculations.

These assumptions are:

- Thickness of soil layer is on average 0.5 meters.
- A recommendation of adding 3% biochar to the soil, meaning 30 L biochar per cubic meter of soil.
- Refill of biochar needed due to carbon leakage. Assume refill of 1% biochar every 3 years, 10L per cubic meter of soil every 3 years.
- Biochar density of 0.2tons/m^3.
- Mixing biochar into all the arable land in EU: 62.3%*157.4 million ha is 98 million hectares.
- Also consider a conservative, low case where mixing ratio is only 1%. For the refill the assumption is 0.3% refill every 3 years.

The recommendations are based on numbers from the small-scale producer and vendor ERA (ERA, n.d.). Table 4 below calculates the estimated potential demand for first time addition of biochar into the soil, both for a mix of 3% which is considered the base case and 1% which is called the low case. The calculations are for the total area of arable land in EU and the calculations are based on the assumptions above.

Table 4: calculation of agricultural demand, first mix

What	**Calculation**	**3% mix (base case)**	**1% mix (low case)**

Biochar per square meter	$=30L/m^3 * 0.5\ m^3/m^2$	$= 15L/m^2$	$=5L/m^2$
Biochar per hectare	$=15L/m^2*10\ 000m^2/ha$	=150 000L/ha $=150m^3/ha$	$=50m^3/ha$
Biochar in tons per hectare	$=150m^3/ha*0.2tons/m^3$	=30 tons/ha	=10tons/ha
Biochar needed for entire EU area	=30tons/ha*98 million ha	=2 942.8 million tons	=980.9 million tons

The table shows that the quantity of biochar needed for mixing 3% biochar into all arable land in EU is 2942.8 million tons. If the mixing ratio is 1%, the required quantity is 980.9 million tons.

Table 5 shows the calculated recommended yearly refill volumes for EU:

Table 5: calculation of yearly biochar refill demand

What	**Calculation**	**3% mix (base case)**	**1% mix (low case)**
Refill (every 3 years)	=0.005m3/m2*10000m2/ha *98 million ha*0.2ton/m3	=980million tons	=326.7 million tons
Average yearly refill	=980 million tons/3 years	=326.7 million tons/year	=108.9 million tons/year

The potential demand for biochar in EU is 980.9 million tons yearly if conservatively assuming 1% mix ratio, with an associated yearly refill of 109 million tons. For comparison, the metallurgical industry in EU consumed 53 million tons of met coal in 2021. Just the agriculture refill demand is double the size of the demand from the metallurgical industry. Figure 7 illustrates the differences in demand. As demonstrated in chapter 4.2, even a quantity of 53 million tons yearly is not possible to produce. There are not enough areas available for cultivating wood for biocarbon production. There will neither be enough area available to produce the needed amounts of biomasses to produce this much biochar.

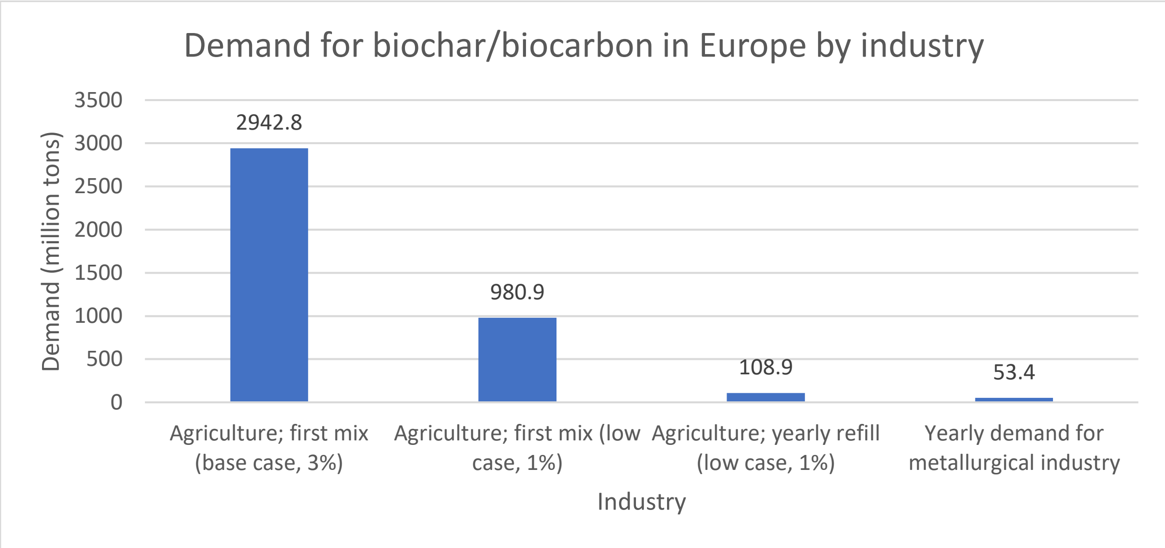

Figure 7: European demand for biochar/biocarbon sorted by industry, numbers in million tons biochar

A market equilibrium for biochar will never be obtained, the potential demand will always, according to the numbers presented above, be larger than the potential production. Together with the legislative initiatives promoting consumption of biochar in the agriculture this is a good starting point for new entrants to easily attain a market share.

4.4 Market strategy for current and future biocarbon suppliers in the metallurgical industry

Whether a biochar producer plans to target biochar for the metallurgical industry (biocarbon) or for the agriculture sector, the producer should make a market strategy. The "Porter's five forces" model is a good tool for shaping market strategy because it is applicable to all industries and assesses different external forces affecting the market situation. The theory is explained in chapter 3.1. At first, we look at the situation for the metallurgical industry.

Table 6: Porter's five forces applied to biocarbon

Force	Current state	Probable future state
Threat of substitute	- Fossil coal is already the established product in this industry. - Biocarbon is the substitute, the new product that needs to replace the established product.	- Fossil coal can still be regarded as fully qualified substitute. - New technologies possibly replacing black carbon (coal, biocarbon) as reduction agent, this would completely kill the demand for biocarbon in this industry. - Industry moving towards more recycling meaning less demand for reduction agents.
Buyers' bargaining power	- Many small buyers (metallurgical plants). - High bargaining power. buyers don't need this product; they can use fossil coal. It is a "nice-to-use" because it makes the corporate CO_2-emission numbers lower.	- Many small buyers (metallurgical plants) - Lower bargaining power. CO_2-emission taxes or legislation may force the metallurgical industry to only use biocarbon. - The buyers themselves approve sustainability goals such as "net-zero emission" forcing them to use biocarbon.

Suppliers' bargaining power	- Wood feedstock: wood is demanded by many other industries. The suppliers' bargaining power is high. - Wood residue feedstock (wood waste): suppliers see this as a waste problem. Lower suppliers' bargaining power	- Competition from other industries for wood/wood waste (biogas production, heat generation by combustion, construction) meaning high suppliers' bargaining power. - Rise in demand means increased price
Threat of new entrants	- Large initial investment costs - Demand is practically "non-existing" today. Need long-term customer commitments to create demand. This will encourage new entrants. - Currently no legislative barriers to enter	- Still large initial investment costs but will decrease as more and more plants are being built - "First-movers' advantage": Less profitability if new entrant established in proximity to a pre-existing plant. - Entry barrier in place: "Production certification" potentially needed (to ensure CO_2-equivalent emission numbers are below a certain value)
Competitive rivalry	- One large supplier (Australia) of the substitute product, fossil coal, having more than 56% market share. - Few to no large-scale producers of biocarbon.	- Many smaller production plants, where each producers own a small number of plants due to little benefits from economy of scales. - Complicated logistics and requirement of access to massive land areas. Can be economical to own the entire value chain.

The current state shows that the market for biocarbon is immature, there is no established demand of biocarbon, nor large scale production. If the biocarbon shall succeed in the metallurgical industry, it needs to be the preferred option over fossil coal and eventually replace it. The price of biocarbon needs to be competitive compared to fossil coal in a transition period. Abundance of wood feedstock and access to large amounts of investment capital are also needed to ensure that sufficient production capacities are being built.

For the future there will probably be many smaller producers due to the upper limits on plant size (Chapter 4.1). Most likely there will also be stricter regulations regarding GHG emissions than today, taxes on CO_2-emissions, and some kind of production certification process to ensure proper production and handling of biochar and the biproducts. The market will be more regulated than today. The trends are clear, guidelines are in the making and regulations are coming. Yet, due to the nature of the market it is likely that the pricing of the biocarbon will be determined by the equilibrium between supply and demand as explained by the model of the purely competitive market in chapter 3.3. Biocarbon will not be able to replace fossil coal completely simply because the potential demand oustrips the potential production volumes. So, if fossil coal is not phased out by prohibition or CO_2-taxes, biocarbon must be priced at a competitive level compared to fossil coal to be the preferred option.

4.5 Market strategy for current and future biochar suppliers in the agriculture

This chapter looks at the current and potential future state of biochar used in the agriculture.

Table 7: Porter's five forces applied to biochar

Force	**Current state**	**Probable future state**
Threat of substitute	- There are no true substitutes for biochar as a soil improvement remedy, but it is not strictly needed. Farmers have cultivated crops for centuries without biochar. - Fertilizers, both organic and artificial, are partially substitutes but requires more frequently addition. The	- Legislation going towards less use of artificial fertilizer making organic ones, and soil improvement remedies, more attractive. - New technologies for industrial food production - More organic farming (EU aims at 25% organic farming withing

	legislative wish is to diminish use due to water pollution.	2030 resulting in less use of additives in the soil).
Buyers' bargaining power	- Many small buyers (farmers) each buying small quantities of biochar.	- Farmers may go together and buy larger quantities to obtain a larger buyers' power.
Suppliers' bargaining power	- Can use almost all sorts of biomasses, also biomass waste. Lower suppliers' bargaining power.	- Competition from other industries for biomasses (bio-gas production) meaning high suppliers' bargaining power. - Rise in demand means rise in price.
Threat of new entrants	- Large initial investment costs. - Demand is enormous and the small production plant size makes it easy for new entrants to take a small market piece by building a production plant. - Lower profitability for both parties if new entrant establishes nearby existing plant. "First-movers' advantage". - Currently no legislative barriers to enter.	- Still large initial investment costs but will go down as more and more plants are built. - Production certification "EBC Biochar Certification" to be able to mix the biochar into the soil. - Lower profitability for both producers if new entrant establishes nearby existing plant. "First-movers' advantage". Should establish new plants
Competitive rivalry	- No large-scale producers of biochar. - A few small producers selling biochar as a "niche" product, at a very high price.	- Many smaller production plants, where each producers own a small number of plants. Little benefits from economy of scales. - Complicated logistics and requires access to massive land areas. Can be economical to own the entire value chain. Produce locally with short distance from

		feedstock to plant, on to the arable land.

This market differs from biocarbon; since there is no true substitute for biochar as soil improvement remedy. In contrast, biocarbon can easily be replaced by fossil coal. Use of biochar in agriculture reduces the need for fertilizer and irrigation. Biochar can be viewed as a slow working fertilizer and to also improve the soil's ability to keep moisture therefore reducing need of irrigation. Furthermore, there are studies that demonstrate that biochar even increases crop size in certain areas. So, biochar offers economic benefits to its users. In metallurgy using biocarbon instead of fossil coal does not decrease the overall consumption or improve metal quality. However, there may be some reductions in taxes related to CO_2-emissions.

Regarding logistics there are also important differences. Fossil coal is mined from one place over several years or decades and has a fixed infrastructure in place from the beginning. Often there is a railway transporting the coal straight to a harbor so it can be brought onto a large collier that transports it directly out in the world. This is a very cost-effective way of transporting large amounts of coal as one collier transports up to 20 000 tons. Biochar buyers purchase smaller quantities than those buying biocarbon which makes the distribution more complex. Package and delivery costs are higher for biochar too. So having to handle both the feedstock and the biochar volumes imposes a logistical cost-disadvantage for biochar production compared to fossil coal mines. Further the limiting factors (logistics and handling of biproducts) for biochar production do not apply to fossil coal with regards to production capacity.

In the future, buyers of biochar will be farmers who need a given quantity based on the area of arable land they manage. This makes smaller plants spread around more advantageous due to the logistical complexity. The biochar producers take advantage of being closer to the feedstock and closer to the buyers.

The effect of Carbon credits into the economical assessment will be discussed in the next chapter.

5 Discussion

The calculations in Chapter 4 demonstrate that the potential demand is large. With the constraints on available biomass for pyrolysis. The potential supply of biochar and biocarbon will be insufficient to meet the future demands from the agriculture and the metallurgical industry. The key limiting factor is available area to produce the biomass feedstock needed. Biomass waste can also be used but the amounts are probably still insufficient. Regarding the potential size of future plants, the main limiting factor is the logistics and transportation. As the production capacity keeps growing, eventually the production costs will grow faster than the revenues as the law of diminishing returns states. The economy of scales will eventually turn into diseconomies of scales. Again, this is due to the costs related to logistics of collecting feedstocks and handling of biproducts.

The consumption of met coal in Europe in 2021 was 53.4 million tons. The IEA expects this number to increase based on a predicted growth in activity level. Replacing met coal with biocarbon would according to the analysis in chapter 4.2 require an area six times the size of France, 67.5 million hectares, dedicated to biocarbon production. In the EU the utilized agricultural area covered 157.4 million hectares of land in 2020. This is 38.4% of the land area (European Union , 2022). Dedicating another 67 million hectares, 16% of EU's land area, to biocarbon production is obviously not possible as EU's land is already employed in high value uses.

Even if biocarbon cannot fully replace fossil coal in the metallurgical industry it can still compete with fossil coal. The following factors influence the competitiveness of biocarbon:

- Lower price. If the products are substitutes of equal quality, then the cheaper option will naturally be preferred.
- Lower environmental footprint.

External pressure can also force biocarbon to be the preferred option due to:

- Legislative directives, forcing the metallurgical industry to choose biocarbon.
- "Green investors"- owners with influence voting through green initiatives and sustainability goals for the metallurgical company.

On the other hand, the IEA's forecast for European demand for met coal might be wrong. The demand can decrease due to stronger focus on circular business models involving recycling and re-use of materials. Re-using scrap-metals requires both less met coal and energy. Through the "European Green Deal", the EU is pushing everyone in this direction towards a more sustainable and circular economy. Furthermore, other emerging technologies may prove to be superior, making today's production practice obsolete. A technology being researched for such an application is the use of hydrogen (H) instead of carbon. If this technology turns out to be successful, biocarbon will only have a commercial case for a shorter time, a transition period.

However, these are early-stage developments, and the outcome of these technological innovations are highly uncertain. As a result, it is unlikely that hydrogens will replace fossil coal in the near to medium future. This does not imply that the market is open for biocarbon as a replacement for fossil coal because the market is still immature. Those who want to enter the biocarbon market should consider their strategic position in relation to access to biomass and access to a buyer. Some considerations could be to:

- Enter into a long-term contract with a supplier. Preferably someone who has a "wood waste problem". Then parts of the logistical challenges may be solved as well, for instance if the plant is close to a saw mill the distance from the feedstock source is small.
- Establish a long-term commitment with a customer for the biocarbon.
- Find a solution for the biproducts, can it be sold to anyone?
- Have capital-strong investors that are willing to make the initial investments.
- Find a placement of the plant such that the transportation is optimized with regards to feedstock that constitutes the large volumes and thus the main part of the transportation requirements.

The need for biochar in the EU agriculture are large and the soil needs refill every year. The demand for biochar in the agriculture is even higher than the demand of biocarbon for the metallurgical industry.

In contrast to biocarbon, the requirements to the feedstock content are less strict for biochar than for biocarbon. Where biocarbon is mainly based on wood, biochar can employ all types of biomasses. It includes a wide range of residues and “waste products” from forestry, animal husbandry, agriculture, and sewage. Due to this variety that can be pyrolyzed, the production of biochar does not require as much land area as biocarbon. So, in this matter biochar producers need to identify one or more reliable sources of feedstock within a reasonable distance to put up a plant at a desired location. For example, one can even look to the fish farm industry for biomasses. As fish farms trend towards land-based facilities, so-called recirculating aquaculture systems (RAS), the sludge is collected instead of seeping out into the open waters in the ocean that sinks to the bottom or dilutes into nutrients in the sea (The Economist, 2023). In land-based facilities the sludge accumulates into a waste problem that needs to be handled in some way.

Legislative forces are promoting a more sustainable society with a more environmentally friendly and healthy food chain. EU’s “Farm2Fork” strategy, a part of the European Green Deal, lay down the pathway for a fair food system that is healthy and environmentally friendly. The objectives are to reduce dependency on pesticides and antimicrobials, as well as reduce excess use of fertilization, and to increase the organic farming level up to 25% by 2030 (European Commission, 2019). In this strategy document they are specifically mentioning biochar as a “new green business model”, carbon sequestration by farmers.

Not only in EU are there forces to drive the breakthrough of biochar in the agriculture. The US Biochar Initiative (USBI) is a not-for-profit organization lobbying for increased use of biochar in agriculture in the United States. (USBI, n.d.) Research is also conducted across the world, much of it in Asia. To use Norway as an example, the government gives a subsidy of 15 000 NOK per ton to make the use of biochar attractive to the farmers (Miljødirektoratet, 2023). The government also points out that the value chain of biochar as a climate action remains to be established and would probably need monetary support.

Mixing biochar into the soil means storing carbon in the ground. This is the last part, the Storage, of PyCCS. PyCCS is associated with Carbon Credits, an additional revenue, whose price is expected to continue increasing in the future. Farmers who apply biochar to their lands generate additional revenue because they create Carbon Credits that emitting companies buy. If biochar is to be commercially interesting product at an industrial scale, it needs to generate value for its users. Carbon Credits is one part of this value creation. The other benefits are increased crop size and reduced consumption of fertilizers which are somewhat more difficult to putting a number to because of sparse data and complexity. The productive benefits of biochar application will depend on several factors like type of soil, crops, climate, humidity etc. Thus, these benefits need to be researched and documented further.

The market for biochar for soil improvement and simultaneously PyCCS has the largest potential:

- Large demand potential, with yearly refill demands.
- Feedstock can be many kinds of biomass residues, handling a waste problem at the same time. Thus, the potential supply is not as limited as for biocarbon.
- The producer can establish near the feedstock source and to some extent its consumers. The production plant can be kept at a reasonable scale at the same time as logistics and transportation will be simpler.
- Policy initiatives from the government (both in the EU and US) to become more sustainable, circular, and self-sufficient in line with the Paris Agreement.
- The initial high investment costs will eventually come down as the production plant technologies become more streamlined.
- Carbon Credit price expected to rise in the near to medium future meaning increased revenue to farmers who apply biochar to their crops.

6 Conclusion

To conclude on the market analysis of biochar and to comment on what seems to be the most likely future of biochar:

- The biochar market is currently still immature.
- Biochar plants can increase production capacity beyond the 10 000 tons that are planned today. The most likely maximum size of a biochar plant is approximately 50 000 tons a year. This encourages many new production plants and offers opportunities for new, capital-strong entrants.
- It is not possible for biocarbon to completely replace fossil coal in the metallurgical industry if today's demand level continues. Thus, biocarbon needs to be price competitive towards fossil coal.
- Biochar in the agriculture is the most prominent market; the potential demand is even larger than the metallurgical demand. The requirements to the feedstock are less strict. Logistics prove less complicated.
- Taxes on CO2-emissions and the price of Carbon Credits increase and are expected to keep increasing. This makes biochar as a C-sink more and more economically attractive.

This thesis has investigated the most established applications of biochar and what the future may look like for these. However, there are other possibilities for biochar and the ongoing research investigating new applications can, and probably will, open up new markets.

References

(u.d.). Retrieved from https://www.vowasa.com/

Al Arni, S. (2017, April 5). Comparison of slow and fast pyrolysis for converitng biomass into fuel. *Renewable energy Journal*.

Andreasen, A., & Kotler, P. (1987). *Strategic Marketing for Non-Profit Organizations.* Pearson.

Boslaugh, S. E. (2023, June 1). *Britannica*. Retrieved from Science - Chemistry: https://www.britannica.com/science/pyrolysis

Carbon Credits. (u.d.). Retrieved from Carbon prices today: https://carboncredits.com/carbon-prices-today/?sl=cc-google-ads&gclid=EAIaIQobChMInsGN4p7A_gIVAm0YCh0VVAANEAAYAiAAEgIfK_D_BwE

Danesh, P., Niaparast, P., Ghorbannezhad, P., & Ali, I. (2022, October 16). Biochar production. Recent developments, applications and challenges. *Fuel*.

Debevc, S., Weldekidan, H., Snowdon, M. R., Vivekanandhan, S., Wood, D. F., Misra, M., & Mohanty, A. K. (2022, September 12). Valorization of almond shell biomass to biocarbon materials: Influence of pyrolysis temperature on their physicochemical properties and electrical conductivity. *Carbon Trends*.

Dr. Parikka, M. (2006). Biomass potential in Europe. Stockholm, Sweden: ExCo2006.

EBC. (2022). *European Biochar Certificate - Guidelines for a Sustainable Production of Biochar.* Frick, Switzerland: Carbon Standards International (CSI).

Elkem ASA. (2021). *Annual Report for 2021.* Oslo: Elkem ASA.

ERA. (u.d.). Retrieved from https://www.era.bio/croptimist

European Biochar Industry Consortium. (2021). *European Biochar Market Report 2020.* European Biochar Industry.

European Commision. (u.d.). *European Commission*. Retrieved from Climate Action: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

European Commission. (2019, December 11). *The European Green Deal.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52019DC0640

European Union . (2022). *Key figures on the European food chain, 2022 edition.* Luxembourg: Publications Office at the European Union.

Hadiya, V., Popat, K., Vyas, S., Varjani, S., Vithanage, M., Gupta, V. K., . . . Mohanty, S. S. (2022, May 10). Biochar production with amelioration of microwave-assisted pyrolydid: Current scenario, drawbacks and perspectives. *Bioresource Technology*.

IEA. (2022). *Coal 2022.* Paris: IEA.

Liu, Q., Liu, B., Zhang, Y., Hu, T., Lin, Z., Liu, G., . . . Xie, Z. (2019, February 1). Biochar application as a tool to decrease soil nitrogen losses (NH3 volatilization, N2O emissions and N leaching) from croplands: Options and mitigation strength in a global perspective. *Global Change Biology*.

McConnell, C., Brue, S., Flynn, S., & Grant, R. (2018). *Microeconomics.* New York: McGraw-Hill Education.

Miljødirektoratet. (2023). *Klimatiltak i Norge mot 2030: oppdatert kunnskapsgrunnlag om utslippsreduksjonspotensial, barrierer og mulige virkemidler.*

Oger, A. (2022). *The Fertilizer Transition.* Institute for European Environmental Policy.

Oliveira, F. R., Patel, A. K., Jaisi, D. P., Adhikari, S., & Lu, H. (2017, August 22). Environmental application of biochar: Current status and perspectives. *Bioresource Technology*.

Osborne, D. (2013). *The Coal Handbook: Towards Cleaner Production. Volume 2: Coal utilisation.* Philadelphia, PA: Woodhead Publishing.

Pardo, N., Moya, J., & Vatopoulos, K. (2012). *Prospective Scenarios on Energy Efficiency and CO2 Emissions in the EU Iron & Steel Industry.* Luxembourg: Joint Research Center of the European Commission.

Porter, M. E. (1979). How competitive forces shape strategy. *Harvard Business Review*.

Porter, M. E. (u.d.). The Competitive Advantage: Creating and Sustaining Superior Performance. *NY Free Press*.

Pyreg GmbH. (u.d.). Retrieved from https://pyreg.com/

Safarian, S. (2023, January 13). To what extent could biochar replace coal and coke in steel industries? *Fuel*.

Sandle, D. (2023, March 24). *Digital Journal*. Retrieved from Tech-science: https://www.digitaljournal.com/tech-science/carbon-sequestration-making-biochar-from-cocoa-shells/article

Schmidt, H.-P. (2018, October 19). the Biochar Journal. *Biochar and PyCCS included as a negative emission technology by the IPCC*. Retrieved from Biochar and PyCCS included as a negative emission technology by the IPCC: https://www.biochar-journal.org/en/ct/94

Schmidt, H.-P., Hagemann, N., Draper, K., & Kammann, C. (2019, July 31). The use of biochar in animal feeding. *PeerJ*.

Skinnes, K. (2022, June 23). Norwegian Biochar Activity - R&D. Norsk Biokullnettverk - presentation.

Statista. (2023, May 22). *Statista Research Department*. Retrieved from Statistics: https://www.statista.com/statistics/438967/fertilizer-consumption-globally-by-nutrient/#:~:text=In%201965%2C%20the%20consumption%20of,to%20over%20190%20million%20tons.

Stobierski, T. (2020, December 3). *What is a value chain anaysis? 3 steps*. Retrieved from Insights: https://online.hbs.edu/blog/post/what-is-value-chain-analysis#:~:text=What%20Is%20Value%20Chain%20Analysis,your%20final%20product%20or%20service.

Suarez-Riera, D., Restuccia, L., & Ferro, G. (2020). The use of Biochar to reduce the carbon footprint of cement-based materials. *Elsevier B. V.* .

The Economist. (2023, May 31). Retrieved from https://www.economist.com/science-and-technology/2023/05/31/the-future-of-fish-farming-is-on-land

Tiihonen, A., Siipola, V., Lahtinen, K., Pajari, H., Widsten, P., Tamminen, T., . . . Miettunen, K. (2020, December 7). Biocarbon from brewery residues as a counter electrode catalyst in dye solar cells. *Electrochimica Acta*.

Tisserant, A., & Cherubini, F. (2019, November 23). Potentials, Limitation, Co-Benefits, and Trade-Offs of Biochar Applications to Soils for Climate Change Mitigation. *Land 2019*.

Tveteraas, S. L. (2023, May). Discussions with supervisor.

U.S. Energy Information Administration. (2022, June 2). Retrieved from Energy explained: https://www.eia.gov/energyexplained/biomass/

United Nation FCCC. (u.d.). Retrieved from process and meetings: https://unfccc.int/process-and-meetings/the-paris-agreement

USBI. (u.d.). *US Biochar Initiative*. Retrieved from https://biochar-us.org/

VOW ASA. (u.d.). *VOW ASA*. Retrieved from https://www.vowasa.com/

VOW Green Metals AS. (2022, April 26). *VOW Green Metals AS.* Retrieved from News: https://www.vowgreenmetals.com/blog/Annual%20report%202022/

Wakefield. (u.d.). Retrieved from https://wakefieldbiochar.com/

Walmart. (u.d.). Retrieved from Patio & Garden: https://www.walmart.com/ip/Wakefield-BioChar-1-Cu-Ft-Bag-Premium-Biochar-Garden-Soil-Conditioner/987855036?from=topicPage

Wikipedia. (u.d.). Retrieved from https://en.wikipedia.org/wiki/Charcoal_pile

Wikipedia. (2023, June 1). *Wikipedia*. Retrieved from Fertilizer: https://en.wikipedia.org/wiki/Fertilizer

Zabaniotou, A., Rovas, D., Libutti, A., & Monteleone, M. (2014, December 9). Boosting circular economy and closing the loop in agriculture Case study of a small-scale pyrolydid-biochar based system integrated in an olive farm in symbiosis with an olive mill. *Environmental Development*.