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Biochar: Analysis and Economic Potential with a Focus on European Producers

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Abstract

The present work aims to assess the current market situation of biochar, with a particular focus on the European environment. Biochar is the product of pyrolysis, a combustion process made in absence of oxygen, and it is widely recognised as a valid carbon sequestration technology. Moreover, its porosity and high surface area make it suitable for agricultural employment and for a variety of beneficial applications. Seen material’s benefit, biochar has been adopted and produced at a growing scale as the price of the final product is still high and the carbon credits issued for carbon sequestration performed are still limited.

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1. Introduction

Climate change is one of the most dramatic challenges that the global community has to face in the near future. The devastating and uncontrollable increase of the temperatures is a real menace not only for human beings, but also for many different ecosystems that populate the planet and find their life in risks seen new and difficult climate conditions. Indeed, after the industrial revolution the average global temperatures have started to rise with a rapidity never seen in million years and have recently recorded values never recorded before (IPCC, 2023).

The scientific community commonly agrees that the causes of this rapid climate changes are anthropogenic and are directly connected to the increase of greenhouse gas (GHG) emissions verified in last two centuries and that in last period have reached the highest historical levels. In particular, the bound between CO_2 emissions and increase in temperatures has become clear and their role in climate change demonstrated. Even if some other gasses have a higher Global warming potential, CO_2 has a very high level of permanence in the atmosphere, as it requires years to be totally expelled. This makes the increase in CO_2 emissions dangerous for global ecosystems, as CO_2 in 2022 has reached a level of 441 ppm, a level never experienced in last 800.000 years (Lindsey, 2023).

In order to reduce the quantities of CO_2 in the atmosphere the global community has found many solutions based on environmental policies and regulations (Green Deal e.g.) trying to reach NET zero objectives in 2050 and to slow down the effects of global warming. The EU has introduced an Emission Trading System that forces many companies to respect an emission CAP or buy emission credits, in order to stay under the threshold with their net emissions. Every year, the cap is lowered by some percentage points, provoking a slow increase in the price of carbon credits and spurring companies to adopt concrete actions to reduce in a direct way carbon emissions.

Moreover, a general concern on climate change and its consequences is moving companies to implement strategies to become Carbon Neutral, pledging net zero targets to be reached in the next years. Of course, for the majority of companies, it is impossible to reduce their emissions to 0, even more if Scope 3 emissions are considered in the balance. Indeed, Scope 3 emissions are the emissions occurring in the whole supply chain and consider, for instance, also the production of the materials employed in the making of the final product and the use phase, that must be added to the direct emissions caused by the company operations (Scope 1) and the indirect emissions caused by the production of the energy bought by the organization (Scope 2).

Therefore, in order to succeed in reaching their pledges of carbon neutrality, companies are involved in a Voluntary Market of Carbon offset credits. Carbon Offsets are a group of technologies that allow a reduction of GHG emissions, usually capturing carbon and storing it in other forms. This carbon reduction can be certified through some particular methodologies by governments or independent organizations that can issue some carbon credits that represent the benefit to the environment measured by the reduction of emission of one metric tonne of CO_2 or CO_2 equivalent (CO_2e). These credits can be traded and sold in the Voluntary Carbon Market and the purchasers can decide to retire the credit, claiming the Carbon Emission Reduction and offsetting their production of CO_2 or other GHG. In this way, companies can reach their goals towards carbon neutrality.

However, Cabon Offsetting practices have their drawbacks. Indeed, many authors (Dalsgaard, 2022; Lohmann, 2008; Swinfield et al., 2023) consider the offsets market as a medieval market of indulgences, as many companies claim carbon compensation just by buying and retiring Credits and not implementing real and strong actions to reduce their emissions. Moreover, the real impact of offsetting projects is risk of being over-estimated and it is not clearly verified. These risks and “grey zones” are fuelling the scientific debate, and have moved many countries, such as the states of the European Union, not to include Carbon Credits in the ETS, as a means to compensate the emissions to reach the carbon cap. However, in other zones, such as California and China, the credits can compensate a quota of the threshold, opening the door of their introduction where it is now not allowed (ICAP, 2023).

Among the many different technologies that populate the market of offsets, biochar is one of the most promising (Lehman and Joseph, 2009; Santin et al., 2017; Woolf et al., 2010). Biochar is the product of pyrolysis, a slow heating process carried out under a limited supply of oxygen and that transform biomasses into a product similar to charcoal, but which owns a good carbon storage stability, allowing a soil storage capability of over 100 years (Bressard et al., 2016). But the most promising quality of biochar is that, apart from its role in climate change mitigation, it is a product with many different beneficial properties and that can be employed in many different applications. First of all, biochar is an effective soil enhancer, capable to increase drastically soil productivity while performing its function of carbon sink (Allohverdi et al. 2021). Moreover, in this thesis will be covered many of the applications of biochar that go beyond the sole carbon storage and soil amendment. For instance, it can be used for waste disposal practices or for the treatment of wastewater (Parmar et al., 2014); it can be employed in the construction industry (Legan et al., 2022), in the field of material reinforcement (Bartoli et al., 2022) or to produce biosensors (Torrinha et al., 2022).

These different possible applications have increased the interest in biochar and many different entities have started to produce certifications that could guarantee the feasibility of this product for carbon storage and to issue carbon credits that are exchanged in the voluntary market (Puro, 2022; EBC, 2021). Moreover, biochar production has increased rapidly over the years, seeing the gradual interest that has been generated on the material and its different application (EBI, 2023). Anyway, the market is still new and in exploration and in many cases the low production scale provokes high costs and low margin for biochar producers (Campion et al., 2023). In other cases, local manufacturing and low production scale can be beneficial for small producers, that can employ biochar to enhance personal soil productivity, can sell it in local market and can also obtain extra revenues by the trading of carbon credits (Nsamba et al., 2015; Azzi et al., 2021). In general, there are many different feasible optimizations that can be applied to the supply chain of biochar and many different challenges that must be considered when studying its market.

This thesis explores the market of biochar, giving a general overview of the current European situation, with a focus on the production scale, the main regulations and the price of the final product. Moreover, it has been tried to find some possible optimizations that can occur to the final supply chain, that goes from the feedstocks' procurement to the final production process involved in the biochar making. This analysis wants to allow a deeper comprehension of biochar potential, finding critical points, challenges and making clear its potential benefits.

After that, a research part of the thesis was developed, with a collection of secondary firm-level data about European biochar producers. This section wants to give an updated panoramic of the biochar market in Europe, exploring in a first passage the geographic distribution of biochar producers all over the continent and trying to understand in which areas biochar technologies are more spread and developed. Then, the analysis provides insights of the status of the biochar certifications' environment, highlighting which certifications are adopted by European producers and what kind of those are the most widespread. Another analysis has been made on the issuance of carbon credits in Europe. In fact, the study wants to give a focus on the main types of credits issued by biochar producers, on the voluntary market where these credits are sold and also the price at which these credits are sold. In this way, it is possible to study the maturity of biochar as a carbon credit and to compare it to other carbon offsetting technologies. To conclude the research, this thesis wants to give an overview of the range of prices applied to biochar by the producers mapped before. In this way, a clearer view of the market is provided.

This thesis explores the European situation of biochar production, seeing that the current status of the research gives few deep analyses on the theme, being the biochar a technology still in exploration but with a high potential that is recognised unanimously by the scientific community, and which could become an important material employed in many different areas of applications.

2. Technological Overview of Biochar

Biochar is one of the most promising new frontiers in the field of carbon dioxide offsetting strategies, but it finds many different applications in different sustainable themes. Explaining it in a few words, Biochar is one of the products of the process called pyrolysis when it is applied to organic matter. Simply speaking, pyrolysis is a slow heating process carried out under a limited supply of oxygen (Lehemann and Joseph, 2009), which is similar to the one also followed for producing charcoal and other similar materials. Even if biochar can appear similar to these last products, it is produced through a different process, from different feedstocks and for different scopes that will be covered in detail throughout this thesis. Unlike traditional charcoal, biochar is usually produced in controlled conditions during a slow-burning process and in the absence of oxygen, making it more stable and more suitable as a carbon sink (Santin et al., 2017). Indeed, biochar has great carbon storage stability, and it is recognised as one of the most promising carbon offsetting technologies and, applied to the soil, it appears to enhance soil fertility, remaining also able to store carbon dioxide under the soil for more than 100 years. In this chapter biochar technology will be covered in detail and its beneficial environmental effects will be assessed.

Figure 1: Biochar after production, in a large pile. Source: Wikipedia. URL: https://en.wikipedia.org/wiki/Biochar#/media/File:Biochar_pile.jpg

2.1. Production Technologies

Biochar production is mainly obtained through a heating process called pyrolysis, which consists of the conversion of organic matter into bioproducts. The biomass converted consists of three main polymeric compounds that are then converted into biochar: hemicelluloses, cellulose, and lignin which are decomposed at different temperatures leaving space for the carbon materials and many different byproducts according to the different pyrolysis methods used. Moreover, there are some other biochar production methods that must be taken into account, such as gasification and torrefaction (Senthil et Lee, 2021; Safarian, 2023).

Below it is provided a brief analysis of all the biochar production methods.

Figure 2: Beston Biochar Pyrolysis Plant. Source: Beston Machinery. URL: https://bestonmachinery.com/biochar-pyrolysis-equipment/#:~:text=Biochar%20pyrolysis%20equipment%20refers%20to,end%20product%20is%20biomass%20biochar.

2.1.1. Slow Pyrolysis

Slow pyrolysis is a process with biomass heated at a moderate temperature (between 350°C and 500°C on average) and almost in lack of oxygen. Pyrolysis follows three main steps: a first stage of dehydration is followed by primary decomposition and then by secondary reactions. The heating rate is "slow" and allows the formation of secondary cracks formed by the vapour produced by the process (Liao et al., 2018). The quality of biochar is mostly connected to its carbon content, and it is improved when the process happens at a low heating rate. Many different kinds of feedstocks can be used for the process, both organic and non-organic: a good selection of the biomass involved will affect biochar's quality. Depending on all the different factors, it is estimated a char yield range between 20 and 50% (Fawzy et al., 2021). Apart from biochar, vapours released by pyrolysis leave space for the main byproducts of the process: the condensable part of the vapours is collected as bio-oil, the non-condensable can be used as gas.

2.1.2. Fast Pyrolysis

Fast pyrolysis is a process that follows the same phases of slow pyrolysis, but differently from this one occurs at very high heating rates (around 1000°C/min) and moderately high temperatures (around 500°C) (Choi et al., 2017). The biomass experiences a very rapid decomposition that generates as the main product some particular vapours that can be converted into bio-oil. As a matter of fact, biochar is a secondary product of the process. Indeed, the high heating rate reduces the amount of carbon depositions, as the vapours rapidly leave the pyrolysis reactor. The biochar yield in this case is between 5-20%.

2.1.3. Gasification

Gasification is a process that is carried out between 700-1000°C and that has syngas as main product. Also, here biochar is a byproduct, and it is usually measured with a yield of 5%, this is why gasification is more useful for the scope of energy production than biochar generation. Indeed, the yield of oil and syngas reported by the literature are much higher, respectively 10 and 85%. A part of energy production, the process is suitable for the production of the chemical that can be synthesized from syngas.

2.1.4. Torrefaction

In this process biomass is heated at a relatively low temperature (between 200 and 300°C), in absence of air, with a heating rate lower than 50°C/min and a long residence time (between 20 and 120 minutes). A big part of the biomass compound is transformed into a torrefied vapour that participates in the creation of the biochar compound that is the main product of the process, with a yield of 60%-80% and that is discovered to have a very high energy density. Syngas is a by-product of this process, and it has a yield that stays in the range of 20%-40%.

PRODUCTION METHOD	MAIN PROPERTIES
Slow pyrolysis	Process with biomass heated at a moderate temperature (between 350°C and 500°C on average) and almost in lack of oxygen. Biochar is the main product, but the process releases some byproducts of the process: the condensable part of the vapours is collected as bio-oil, the non-condensable can be used as gas
Fast pyrolysis	Occurs at very high heating rates (around 1000°C/min) and moderately high temperatures (around 500°C). Bio-oil is the main product. Biochar is a by-product and its yield is between 5-20%
Gasification	The process is carried out between 700-1000°C and has syngas as main product. Biochar is a byproduct and it is usually measured with a yield of 5%. Yields of oil and syngas reported by the literature are respectively 10 and 85%
Torrefaction	Relatively low temperature (between 200 and 300°C), absence of air, a heating rate lower than 50°C/min and a long residence

	time. Biochar as main product, with a 60%-80% yield. Syngas is a by-product, with 20%-40%.

Table 1: Main Examples of Biochar Production Methods

2.2. Chemical and Physical Overview of Biochar

Biochar chemical composition is a fundamental matter of study as it really affects its properties and its main applications. Biochar is mainly composed of carbon and the presence of other elements depends on the amount and typology of feedstock that is used to produce it. Examples of other components are "hydrogen, nitrogen, sulphur and oxygen as well as inorganic minerals such as potassium, phosphorus, calcium, magnesium, iron, silicon and sodium" (Banik, 2018). Surface chemistry is crucial in determining biochar characteristics and in defining the interactions of biochar with the surrounding environment (Chen et al., 2019). For instance, the presence of specific functional groups determines biochar sorption performance, its pH buffering potential or its polarity, important properties that determine the precise utilisation of biochar. (Usevičiūtė and Baltrėnaitė-Gedienė, 2020). First of all, it is important to underline that the chemical structure of biochar depends mainly on the production process and the feedstock employed (Fawzy et al., 2021). For instance, biochar porosity and surface area are important physiochemical properties that deeply affect biochar applications and are closely related to the typology of feedstock used and to the temperature at which the material is produced. For instance, according to Tomczyk et al. (2022), the use of wood as feedstock generates a biochar with a higher surface area, demonstrating a better water holding capacity and a higher carbon sequestration. However, biochar from waste residuals usually has a higher CEC (cation exchange capacity), a property that is usually positively linked to a higher potential in nutrient source and inorganic sorbent. This explains how pyrolysis conditions influence the properties and the potential of biochar.

2.3. Biochar Main Applications

Apart from its advantages regarding climate change, biochar is also identified as a promising technology able to increase soil fertility, perform water treatment and to fight waste management. As specified by the literature, these objectives are complementary and all connected to the theme of environmental management. In the following sections, all of these streams of Biochar benefits will be carefully analysed to provide the reader with a general overview of the potential of this bioproduct.

Soil fertility:

- ability to retain nutrients of the soil
- water holding capacity
- positive effects on microbial polulation
- soil detoxification

Animal Feeding:

- biochar with is properties have an important tole in animal digestion
- improve health and productivity

Climate change Mitigation:

- CO_2 stored in a recalcitrant form that is highly persistent, with a mean residence time (MRT) above 100 years
- action of mitigation of climate change also includes the effect on the emission of N_2O and CH_4 in the atmosphere

Water treatment:

- biochar chemical properties allow it to remove carcinogenic pollutants such as heavy metals, organic contaminants and nitrogen and phosphorous

Waste management:

- reduces the GHG emissions associated with traditional waste management strategies
- it doesn't produce methane like landfilling
- presents better capabilities to lock up carbon

Produce Energy:

- pyrolysis used to produce energy
- biochar used as bio-fuel
- biochar co-products used as bio-fuels

Material Reinforcement:

- employment as a filler in polymer-based composites, to substitute the classic carbon-based materials used as fillers

Building Materials:

- indirect benefit of biochar is the reduction of emissions due to the replacement to other raw materials employed in the construction industry
- direct carbon footprint reduction achieved by the direct capture and absorption of CO_2 by building materials

Bio-sensors:

- properties as a carrier, catalyst and absorber make biochar a good choice for the production of bio-sensors

Table 2: Main Applications

2.3.1. Biochar to Increase Soil Fertility

Nowadays undernourishment is still a great issue that hits a huge part of the world's population. According to the 2022 Statistical Yearbook redacted by the Food and Agriculture Organization, the Global level of undernourishment has been increasing sharply during the last years, reaching a level of nearly 10% in 2021 (FAO, 2022)

The most alarming numbers come from the African continent, where 20.2% of the population is undernourished, but the Asian continent counts the highest number of hungry people, hosting 55% of the world's hungry people. It is important to underline that during the period between 2000 and 2019, a drastic decrease in hungry people was monitored in Asia, followed by a bounce back during the COVID-19 years. Instead, In Africa the situation has become more and more dramatic in the last 20 years, experiencing a total increase of 42% between 2000 and 2021, reaching a total number of 278 million people.

According to the GRFC 2022 MID-YEAR report (GFRC, 2022) undernourishment has many drivers that can be grouped into three main categories: unstable economic conditions, conflicts and political instability and inadequate food supply provoked by difficult climate conditions and climate change.

This study on biochar applications can be helpful to give focus on its usage for soil amendment and the properties that make it an eligible solution to fight desertification and reduce undernourishment.

Desertification represents a great threat to biodiversity and the socio-economic global environment (Becerril Piña and Mastachi Loza, 2021). There is not only one clear cause for desertification but more concurrent ones. The literature identifies many drivers, such as deforestation, overgrazing, exaggerated water usage and climate change impact. The process regards drylands, areas that cover more than 40% of global soil and where "annual potential evapotranspiration (P) exceeds annual precipitation". The inhabitants of these zones have always been able to adapt to difficult weather conditions, frequent drought and water scarcity, but climate change could worsen the situation in these areas and make these environments unliveable for these populations. This is why progressive desertification is strictly linked to massive emigrations and neat socio-economic sequences not only for the people of arid zones but for the entire world. That's why in 1994 was instituted the United Nations Convention to Combat Desertification (UNCCD), to discuss and find feasible solutions for the issues faced by the drylands. Among the solutions found to fight desertification, biochar has been found to be a good choice, thanks to its chemical properties that make it a feasible solution for soil amendment. The first use of biochar for this scope can be brought back to the utilization of Tierra Preta by the indigenous populations of the Amazon Rainforest (Glaser and Birk, 2012). Already in this context, people had understood the benefit of some kind of materials to improve soil fertility in nasty lands like the Amazonian ones. Biochar can improve soil fertility in many ways and through many of its properties (Allohverdi et al. 2021).

The first advantage of biochar is its ability to retain and provide nutrients to the soil, that are necessary for fast plant growth. Indeed, biochar improves microbial population diversity, allowing it to propagate through its pores. Moreover, it can directly provide some nutrients, such as potassium that are fundamental for plant uptake. It is important to underline that also pH levels are influenced by the use of biochar, depending on its characteristics and formation processes.

Another important property of biochar, that makes it a valid solution to fight desertification, is its water-holding capacity. On average, through the application of biochar soil water retention increases by 18% but this measure varies a lot with biochar properties, type of soil, quantity of biochar applied in the soil. For instance, biochar with high porosity and large specific surface area tends to have a higher water retention (Ndede et al., 2021). Also, the quantity of biochar that optimizes Water Retention depends on the type of soil in which it is applied. For instance, when analysing sandy soil, it is suggested to apply biochar below 10% (v/v).

Moreover, biochar application affects microbial populations in many ways, for instance giving them refuges through its pores and detoxifying soil from toxic substances, such as heavy metals. (Ding et al., 2017). The presence of microbial populations is vital for the health of the soil and the growth of vegetation.

An application of these properties of biochar has been studied in the soil of sub-Saharan Africa (Gwenzi et al., 2015). Here the lands are naturally sandy and infertile, but fast population growth, followed by increased demand for food has even worsened enhanced soil degradation. As a result, Sub-Saharan soils have limited water retention, low soil fertility and low acid ph. This environment is also hit by carbon depletion and environmental pollution. The challenges presented by this environment create a perfect field for biochar exploitation. Here biochar production is mainly carried out by small farmers, using cheap and easy-to-use batch reactors for pyrolysis and manure and firewood as the main feedstock. The use of these pyrolysis systems and this feedstock doesn’t guarantee the best efficiency, but the local farmers' knowledge and economic and technical limitations make these solutions the most widespread in the zone. In any case, the use of biochar and pyrolysis has guaranteed an improved quality of the soil, thanks to nutrient release and water retention properties and its capabilities to neutralize the acidity and toxicity of the soil.

2.3.2. Biochar in Animal Feeding

Biochar has been progressively introduced after 2010 as a feed supplement for animals (Schmidt at al., 2017). Indeed, it has been demonstrated that biochar can improve animal health when added to animal feed, improving nutrient intake efficiency and absorbing toxins. Indeed, this biochar property has been well-known for decades. For instance, Steinegger & Menzi (1955) already suggested biochar use to prevent digestive problems of animals by adding it to chick feed. Anyway, its use as a regular feed additive for animals has been investigated after 2010, and it has been demonstrated its potential in this sense.

The mechanism of feed digestion is based mainly on biochar absorption capacity. Indeed, it is able to absorb different kind of dangerous toxins, such as plant toxins and pesticides. Moreover, another function of biochar that has a positive impact in animal feeding field is its role in redox activity, improving the efficiency of many reactions that are fundamental in the digestion process.

In general, these properties make the biochar a good alternative to improve animal health and productivity while reducing GHG emissions and increasing sole fertility.

2.3.3. Biochar for Waste Management

Waste production is another severe challenge that often leads to water and land pollution, not considering all the logistic and economic issues. Considering biomass residues, landfill is the most chosen solution for waste management (Parmar et al., 2014), but is connected with many environmental problems, producing Methane NH4 and CO_2. With organic waste increasing in number day by day, organic waste management can be considered a real environmental problem. Indeed, there are many strategies for organic waste recovery (Kharola et al., 2022). One of these is to recycle organic waste by feeding animals, but this solution can be dangerous for the animals themselves and requires the creation of specific laws and controls. Another solution consists of compost creation. Compost is the result of an aerobic process called composting, which transforms organic waste into a product that can be used as soil conditioner and fertilizer. Compost has been used for a long time as a soil amendment solution, but the drawback is the huge quantities of methane and nitrous oxide produced by the process, greenhouse gasses that are even worse than CO_2 as GHGs (Sik Ok et al., 2017).

As a consequence, biochar appears as a good solution for sustainable waste management. Indeed, it reduces GHG emissions, which are often associated with traditional waste management strategies. For instance, it doesn't produce methane, like landfilling or composting methods and presents better capabilities to lock up carbon. In general, pyrolysis often appears as a better solution for waste management (Gwenzi et al., 2015):

- is a Carbon-Neutral (or carbon-negative) process and reduces the emissions of GHG in the atmosphere;
- it reduces water and air pollution and odours connected with landfills and dumps;
- its byproducts, biochar, bio-oil and biogas have many different applications in environmental challenges and energy-production strategies.

There are some main categories of wastes that must be kept in consideration: Agricultural residues, Food processing industry residues and municipal solid wastes. Municipal solid wastes (MSW), for instance, are a big global challenge, as they have been sharply increasing in number (up to 2.2 billion tonnes in 2025) and are currently mainly handled by traditional ways such as landfilling, incineration and composting, with all of the environmental problems of these solutions. Pyrolysis of these wastes has the clear advantage of producing value-added products, that can be used to solve environmental problems and for energy-production purposes (Gunarathne et al., 2019).

2.3.4. Biochar for Energy Production

World energy requirements have constantly increased in the last years (Waqas et al., 2018). In 1990 the global energy demand was around 100,000 TWh, and in 2022 has reached the peak of almost 180,000 TWh in 2022. Around three quarters of the global energy production comes from fossil fuels, but to reduce the impact of energy making and the quantity of CO_2 emitted in the atmosphere governments are taking measures to cut the use of fossil fuels and incentivize other forms of energy production sources. Indeed, according to IEA (2022) energy consumption is going to increase more and more and the Planet can't bear a steep increase in carbon dioxide production. The awareness on this issue has started to interest many countries, that are pushing industries to look to low carbon fuel solutions. In the last few years, the growth rate of the energy produced by fossil fuels has gradually slowed down. In particular, even if the demand for oil and natural gas is still growing, coal has started to be abandoned in many countries because of its very high environmental impact. On the other hand, energy production from low-carbon sources, including nuclear and renewable sources, has rapidly increased in the last years, reaching 18% of total energy production in 2022, pushed by the rise of renewable sources, which have doubled in the last 30 years.

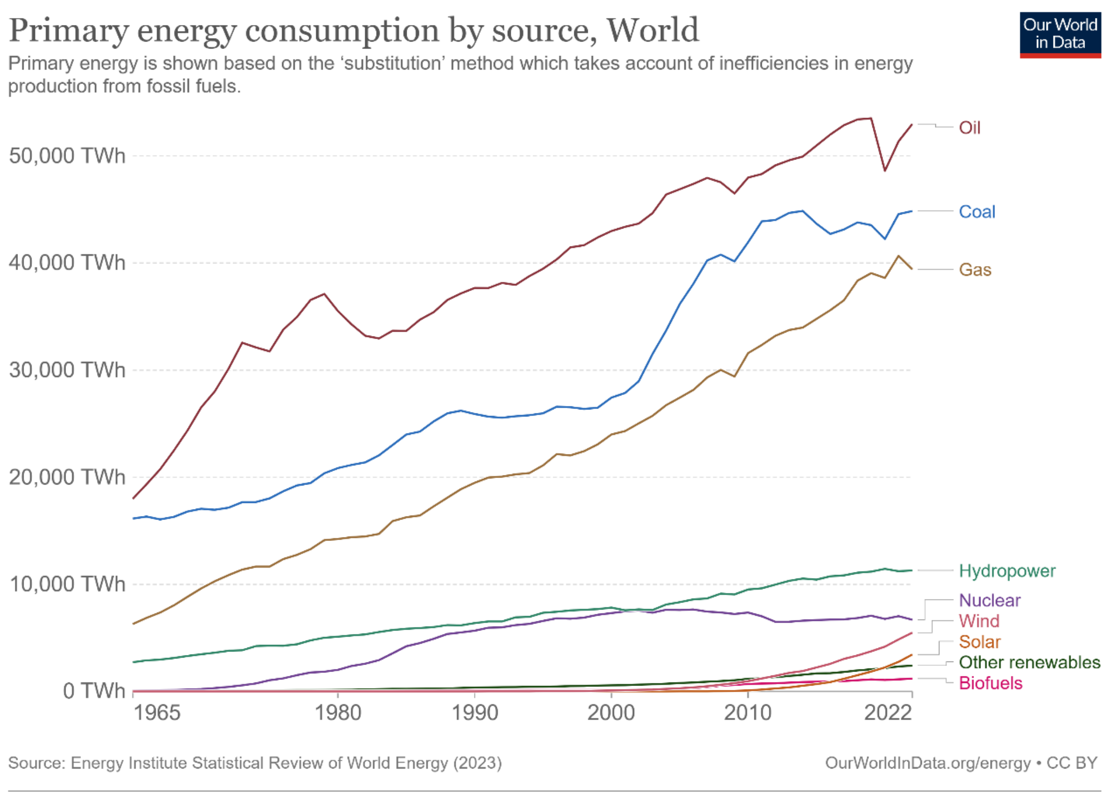

Figure 3: trends of energy generation; Source: Our World In Data. URL: https://ourworldindata.org/energy-mix

In this context, biochar has a crucial role in energy production. Indeed, biochar and biochar production processes offer many different solutions for bioenergy production. Pyrolysis itself produces collectable amounts of energy and biochar itself can be used as fuel (Lehman et al., 2009). However, biochar applied in soil amendment is more beneficial for both agriculture and GHG emissions in the atmosphere. Therefore, the addition of biochar in soil or its use in other applications appears to be more beneficial for the offsetting of global emissions than in its application as fuel as a substitute of fossil fuels. Anyway, it is possible to apply biochar in energy production processes. For instance, biochar can be co-combusted in coal-fired power plants (Roy and Dias., 2017) being a more sustainable replacement for coal or can be used in combined heat and power plants for clean heat and power production.

Therefore, biochar production and, in general, pyrolysis has an important role in bioenergy generation. Indeed, the process itself can generate energy, and the products of it, besides biochar, can be used for energy generation. Indeed, depending on the type of pyrolysis, a great part of the biomass is converted into bio-oil and syngas, which are important inputs for energy production.

According to Roy and Dias (2017) bio-oil has many different applications in the energy production field. For instance, it can be used in industrial or residential boilers, for power or heat making, co-fired in natural gas plants or converted into fuels such as diesel and ethanol. Even if bio-oil appears as a good substitute for heavy fuels, it is important to consider its characteristics to employ it with the best efficiency. Indeed, as explained by Hoang et al. (2021), bio-oil is a complex substance, thermally and chemically very reactive. That’s why it is usually required to be upgraded to become compatible with combustion devices.

Han et al. (2013) have performed a Life Cycle Analysis of biofuels produced from biomass through fast pyrolysis. In their study, bio-oil is produced with fast pyrolysis, and it is then stabilized and upgraded to make it feasible as fuel. During the process, other co-products such as Biochar and Fuel Gas are produced. Biochar, in particular, can be employed for additional heat and electricity production, if a combined heat and power system is installed, or its environmental benefit in GHG reduction can be accounted for in the Life Cycle Assessment. The results of the analysis show that GHG emissions for pyrolysis-based fuel are lower than the GHG emissions from fossil fuels, thanks to the Biogenic CO_2 that is absorbed during biomass production.

2.3.5. Biochar for Water Treatment

Water pollution occurs when toxic and harmful substances contaminate a body of water, degrading its quality and making it toxic. Nowadays, it is becoming more and more an issue that risks devastating entire NRDC, 2023 and putting in danger many human lives. Indeed, the UN estimates that every year more deaths are more the deaths caused by water pollution than the ones caused by all forms of violence, including war (UN, 2013). Indeed, the world's total resources of fresh water are approximately 2.5% of the total water covering the earth, and among the total reservoirs of fresh water, 1% is easily accessible. (Nunez, 2010). These already scarce resources are increasingly threatened by water pollution, a concurrent factor of other menaces such as drought and overpopulation, putting in danger natural ecosystems and populations.

There are many causes of water pollution, including industrial waste disposal, toxic waste disposal into the rivers, pollution caused by drilling activities, pesticides, herbicides and fertilizers, households' chemicals (dishwashing waste, laundry waste) and many more (Khatun, 2017). The adverse effects of water pollution are many and do not only directly hit men, animals and plants but also affect agriculture and soil fertility. Water pollution is the cause of the spread of many diseases and affects some other health aspects of water quality, the health of body organs such as heart and kidneys and the quality of water nutrients. Moreover, it causes direct harm to animals and in general to all living organisms.

In this framework, it is clear the importance of water and wastewater treatment to eliminate pollutants and among these treatments, biochar can be used as absorbent for these pollutants (Xiang et al., 2020). In particular, biochar chemical properties allow it to remove carcinogenic pollutants such as heavy metals, organic contaminants (such as pesticides, herbicides, and antibiotics) and nitrogen and phosphorous. Focusing on wastewater treatment, biochar finds many applications in eliminating water pollution. Some of the main applications are industrial, municipal, and agricultural wastewater. For instance, taking in of analysis Industrial wastewater treatment, we find out how the substance, mixed with chitosan, and casted into membranes, can be used to filter heavy metals such as copper, lead, arsenic, cadmium and other organic pollutants produced in industrial processes.

2.3.6. Biochar for Climate Change Mitigation

Probably the most interesting implication of biochar is its use as carbon offsetting technology and generally for its application in the field of GHG reduction and climate change mitigation. The key to the benefit of CO_2 retention stays in the pyrolysis properties: the slow combustion process allows biochar to retain 50% of its carbon content. This CO_2 is stored in the soil in a very stable form and then it is decomposed and released in the atmosphere after a long period of stability, which is estimated between 100 and 4000 years, depending on the feedstocks implied (Bressard et al., 2016).

So, the process can slow down the rate at which the carbon produced in photosynthesis comes back to the atmosphere, as normally the organic matter is decomposed in five years releasing all the carbon that has been stored.

The literature provides much research about the biochar total capacity of CO_2 offsetting, as it mainly depends on the feedstocks used for its production and the pyrolytic process that has been followed. According to Woolf et al. (2010), the net removal of CO_2 can be set in the order of 1.0e1.8 Mt CO_2-equivalent year $^{(-1)}$. Life cycle assessments (LCAs) have indicated that the net mitigation impact of biochar systems commonly ranges from –0.6 to +1.75 Mg CO_2e $Mg^{(-1)}$ feedstock (–0.3 to +1.3 Mg C $Mg^{(-1)}$ feedstock-C) (Cowie et al. 2015). The big constraint is imposed by the feedstock, whose availability is essential for the production of biochar. The CO_2 is stored in a recalcitrant form that is highly persistent, with a mean residence time (MRT) above 100 years.

But it is important to underline that the persistent action of mitigation of climate change is not only limited to CO_2 emission balance but also includes the effect on the emission of N_2O and CH_4 in the atmosphere.

Methane (CH_4) is one of the most important GHGs, having a global warming potential of 25. The agricultural sector is one of the main ones responsible for CH_4 production, with around 50% of the world's gas emissions. As reported by Lehmann et al. (2009) aerobic well-drained soils are usually a sink for methane, having a high rate of CH_4 diffusion and a "subsequent oxidation by methanotrophic microorganisms", whereas in contrast emissions are usual in aerobic conditions bounded with warm temperatures and presence of soluble C. As been studied before, one of Biochar's main uses is in soil amendment, so the production and reduction of CH_4 emissions in the agricultural implications of biochar is an interesting matter of study (Bressard et al., 2016). It is important to point out that it is difficult to find a general correlation between the use of biochar and a reduction of methane release in the atmosphere, as it really changes depending on soil type, biochar type and feedstock used to produce it. Bressard et al (2016) have studied the literature that analyses the connection between CH_4 emissions and biochar amendment of the soil, taking into consideration 27 different studies. In a major part of the cases (17 times), no significant difference implied by the application of biochar has been reported, whereas only 5 studies have reported a significant decrease in CH_4 emissions, with the remaining 5 eventualities reporting an increase of methane after biochar amendment.

Nitrous Oxide (N_2O) is considered the third most important GHG (Woolf et al. 2018) with a global warming potential of 298 (IPCC, 2007). Also, in this case, soil management is the main driver for N_2O emissions in the atmosphere. In this case, biochar is considered, with clear evidence, as a possible solution capable of reducing N_2O release in the atmosphere. The biochar liming effect is the leading property of the material that impacts directly N_2O production. (P. Brassard et al., 2016). A liming material can "ameliorate soil acidity through both direct and indirect effects" (N. Bolan et al., 2023). Soil acidity reduction appears to be of crucial importance in reducing the release of N_2O in the air, as it favours the "nitrate reduction to N_2 or the adsorption of ammonium that prevents nitrification and denitrification" (Sohi et al., 2010).

2.3.7. Biochar as Building Material

The building and construction industry is one of the most polluting ones and, despite the increase in energy efficiency investments, CO_2 production and energy consumption remain at very high levels. According to the 2022 Global Status Report for Buildings and Construction, the sector has accounted for 37% of energy demand and 34% of CO_2 emissions in 2021 (UNEP, 2022). According to the report, the building sector represents 40% of the total European Emissions and the 80% of the emissions come from fossil fuels. In order to be compliant with the zero emissions target for 2050, it is crucial to intervene immediately to reduce the impact of such a polluting sector.

The biggest part of the emissions is caused by the employment of concrete. Indeed, cement is one of the most polluting materials on earth, the production process is estimated to release 0.8 tonnes of CO_2 per tonne produced and cement is the main ingredient for the production of concrete. Cement huge emissions are caused by the high energy intensive production process (Mehta, 2021) which is responsible for the 5% to 7% of the global CO_2 emissions from the energy used industrially. Moreover, there are many other concurrent causes of the emissions of the cement supply chain. For instance, it must be considered the environmental impact caused by the intensive extraction of the raw materials involved in cement and concrete production, such as sand gravel and crushed rock. The mining process and the transportation of the materials involve an incredibly high amount of energy and CO_2 emissions. The environmental damage of the processes doesn't regard only atmospheric pollution, but also the water footprint of the process is very high, with an annual requirement of water of almost 1 trillion L per year.

Biochar is among the most innovative alternatives introduced to pave the way for more sustainable building materials. The reduction in carbon footprint brought by biochar can be either direct or indirect (Legan et al., 2022). One indirect benefit of biochar is the reduction of emissions due to the replacement of biochar to other raw materials employed in the construction industry. For instance, the study carried out by Praneeth et al. (2021) has given evidence of a massive reduction of CO_2 emissions achieved with the replacement of sand with different dosages of biochar in the process of cement production. Anyway, even if the result proved a 20% reduction of net CO_2 emissions, the results also showed that cement with a 40% dosage of biochar causes a general deterioration of the mechanical properties, making questionable its suitability as a building material. In any case, the substitution of sand or cement with biochar could have an important impact on GHG emissions reduction of cement production and fight the risk of raw materials' shortages in building industries. At these indirect benefits, must be added also a direct carbon footprint reduction achieved by the direct capture and absorption of CO_2 by building materials. Moreover, thanks to its low conductivity and incredibly outstanding water absorption capacity, biochar has an important role in building insulation and humidity regulation (Schmidt and Wilson, 2023). In general, there are many benefits in the application of biochar in the building industry, but the consequences of its effect on their mechanical properties should be carefully analysed and taken into consideration.

2.3.8. Biochar for Industrial Material Reinforcement

One of the most recent applications of biochar is its employment as a filler in polymer-based composites, to substitute the classic carbon-based materials used as fillers. Indeed, unlike these last carbonaceous materials, biochar comes from sustainable biomass resources and demonstrates some useful properties, such as thermal stability, high surface area and good chemical stability (Bartoli et al., 2022). However, these biochar-based materials have not reached the same level of performance as traditional fillers, which show great properties but are extremely expensive compared to biochar, which also held the advantage to be obtained to sustainable biomass.

There are many biochar-based composites that are currently studied and that show different properties and characteristics. One example is the employment of biochar as a filler for polyethylene (PE) to improve its mechanical properties. The study of Zhang et al. (2020) has studied the effects obtained by reinforcing high-density polyethylene (HDPE) with biochar as a filler, demonstrating a general improvement of the material characteristics. For instance, tensile properties, elasticity, creep resistance and flexural properties have been improved by the addition of biochar. But even more importantly, biochar-added composites have shown good thermal and flame-retardant properties. Indeed, PE is very flammable and the improvement of its thermal properties could be crucial in many different applications. Indeed, biochar application also had some negative effects, for instance on the water-resistance of the composites. In general, the employment of biochar as a filler appears to have a positive effect on the properties of the material, being also a green solution that permits the conversion of waste biomass into a useful application.

2.3.9. Biochar for the Manufacturing of Sensors

Biochar has recently caught the attention for its applicability in the world of electrochemical sensors and biosensors. Indeed, its properties as a carrier, catalyst and absorber make it a good choice for the production of these. Indeed, in the making of electrochemical sensors and biosensors carbon-based materials have always played an important role. For instance, materials such as graphene have been crucial in the environment of the fabrication of electrochemical sensing platforms (Li et al., 2022). Biochar appears to have similar properties to graphene, which has always been used as a carrier, a catalyst or a conductive basement.

The need to look for both cost-effective and stable electrodes has pushed the research to investigate new solutions and these biochar-based applications. All of this is pushed by the increased necessity of biosensors in many different applications. For instance, biosensors have recently acquired an increasing importance in the monitoring of water pollutants substances, such as pharmaceutical pollutants that are harmful to waters and aquatic species, that must be detected with sensitive, portable and low-cost devices (Torrinha et al., 2022). Moreover, these sensors find many other applications in other environmental monitoring applications, but also in the field of clinical diagnosis and food analysis, along with agricultural detection (Zhang and Chen, 2019).

Biochar's outstanding properties, particularly the ones connected with its surface area and surface charge have permitted its use in these applications. Indeed, its "highly reactive, surface functionalized spherical and porous structures" make it effective for contaminants absorption (Spanu et al., 2020), along with the presence of negatively and positively charged sites, that make it well-suited for electrochemical applications (Kalinke et al., 2021). Spanu et al. (2020) have analysed in detail the fabrication of biochar-derived electrodes. After the production of biochar through the usual pyrolysis, where biomass is often mixed with some activation substances, the surface of the product is modified by the introduction of some catalytic species, such as metal oxides or enzymes, and finally the immobilization of biochar on a conductor. In particular, feedstock choice, the pyrolysis process decided, the activation substances applied on biomass and the additives that modify the surface are important determinants of the performances of the final product.

Li et al. (2022) describes in detail some of the main applications of electrochemical sensors and biosensors based on biochar that optimally spurs their properties for different detection processers. One possible application of these technologies is the detection of heavy metals in many different kinds of substances, but they can be employed successfully in the detection of pesticide and veterinary drugs residues, environmental estrogen and organic pollutants. However, though the positive sides of the biochar-based sensors, there are still some challenges connected with these technologies. For instance, the precision of these sensors must be improved, along with their sensitivity and stability.

2.4. Other Carbon Offsetting Technologies: A General Overview

Now that biochar technology, its main applications and its use as carbon capture technology have been detailing assessed, it is important to make a brief overview of the other main solutions available for carbon offsetting. In this chapter will be provided a general overview of these solutions, with their main pros and cons.

2.4.1. Avoided Deforestation, Reforestation and Afforestation

The importance of forests in climate change mitigation has been largely assessed by the most important climate conferences (e.g. Kyoto Protocol and United Nations Framework Convention on Climate Change) which have spurred all parties to understand this role and to engage to safeguard it (FAO, 2007). According to Bonan (2008) the existing forests store almost 45% of the organic carbon on land and it is estimated an absorption rate of almost 2 gigatonnes of carbon (GtC) annually (Pugh et al., 2019). These figures help to understand the importance of forests as carbon sinks, and with this the fundamental role that has been led by forest protection and safeguard from human footprint.

Consequently, the first solution for avoiding carbon emissions from forests is Avoided Deforestation, the practice of protecting forests that would have been cleared. This method clearly avoids carbon release and protects the biodiversity of these environments, but from the other side it is difficult to estimate the number of emissions avoided with the projects, as it is difficult to create a precise counterfactual. Moreover, the avoided deforestation of an area could mean the effective deforestation of another one, provoking the risk of leakage, as will be explained in the further chapter.

Moreover, as pointed out by Waring et al. (2020) the practice of planting trees has a clear additional importance. Indeed, Bastin et al. (2019) estimated that planting trees on 0.9 billion hectares would lead to an additional capture of 205 GtC. In this context, it is easy to understand the importance of the practices of Reforestation and Afforestation.

Reforestation consists of the practice of the re-establishment of a forest in an area where there was one once in the past. In the long term, this solution will lead to net negative emissions, but the short-term effect could be an increase in GHG emissions. Indeed, the planted trees would take approximately 100 years to reach the maximum storage potential (Bonan, 2008) and would emit meanwhile volatile organic compounds (VOCs) which could form ozone in the atmosphere.

Indeed, Afforestation consists of the conversion to the forest of land that was used for other purposes in the past. This system has the same long-time advantages of reforestation, but also its disadvantages, to which must be added the risk of negative impacts on biodiversity and ecosystems if the practice is not well executed.

All of these solutions must be sided with well-planned and optimized Forest Management, also studying monitoring programs that can reduce external risks, such as wildfires or storms, that often devastate entire ecosystems and menace high carbon emissions. (Waring et al., 2020) being forest highly vulnerable and having a low persistence rate of CO_2.

2.4.2. Oceans Fertilization

Oceans Fertilization is a carbon offsetting practice that consists of adding special nutrients, in particular iron, to the oceans, in order to enhance the growth of phytoplankton, photosynthetic microorganisms, that have the capacity to absorb CO_2. This technique is of relatively recent development and its real impact on GHG reductions is still not entirely understood yet. Moreover, there are some risks that can be a consequence of this solution. In particular, in Santos et al. (2019) it is pointed out how many experts are aware of the large-scale alteration of primary production that can be caused by ocean iron fertilization. This effect could affect negatively ocean ecosystems, which are mutually interconnected and often unforecastable. Seen that, it is clear that the technology requires more studies and deeper analysis.

2.4.3. Soil Management

Soils are an important carbon pool as it is estimated that approximately more than 2500 Pg of organic carbon (Lal, 2004). Intensive land use causes every year a huge quantity of carbon emissions, as soil depletion provokes a massive release of carbon stored inside lands. That's why the soil carbon sequestration process acquires a clear importance. Soil carbon sequestration includes many different processes that aim to increase the carbon content of soil through land management practices. This practice, as reported by Paustian et al. (2019) is divided into two broad categories by the National Academies report (NASEM, 2019). The first category includes known conservation management systems, which are adopted by more conservative farmers and are referred to the Best Management Practices for increasing carbon storage. The second category includes practices known as "frontier technology", which includes practices that require significant technological investments. Among BMP can be found management practices such as cover crops, improved crop rotations, manure and compost addition, no-tillage and other conservation tillage, rewetting of organic soils and improved land management. Instead, management practices based on "Frontier Technologies" include the deployment of perennial grain crops, Annual Crops Bred to Develop Deeper and Larger Root Systems and, of course, biochar additions in soils.

It is difficult to provide an estimate of the sequestration potential of the soil sequestration techniques, as their effectiveness depends on many distinct factors that are hardly assessable. However, according to Paustian et al. (2019) there is an alignment among global measurements that estimates the sequestration potential among 2-5 Gt CO_2 per year regarding the solutions belonging to the BMP categories. Regarding "frontier technologies" Pustian et al. (2016) estimate a sequestration of ~3 Gt CO_2/y. Of course, this last estimation is difficult to be confirmed, as these last technologies are still in a phase of research and development.

2.4.4. Enhanced Weathering

Enhanced Weathering includes a set of theoretical proposals that target to remove CO_2 by "spreading large quantities of selected and finely ground rock material onto extensive land areas, beaches or the sea surface" as stated by the Geoengineering Technology Briefing (2021). The Carbon Dioxide Removal (CDR) technology theoretically imitates and accelerates the natural weathering processes of silicate and carbonate rocks, a natural process that is calculated to consume one billion tonnes of CO_2 from the atmosphere every year. The process is still totally hypothetical, and many studies have pointed out the drawbacks of this technology: first of all, the great expenses associated with it, but also the high energy consumption and the huge environmental impact that the mining of the materials would have.

2.4.5. Bioenergy with Carbon Capture and Storage (BEECS)

According to the tracking report of IEA (2022), Bioenergy with Carbon Capture and Storage (BEECS) is the only carbon dioxide technology that is eventually able to provide energy. BEECS involves many different solutions where CO_2 is captured from biogenic sources, and it is permanently stored or used as a feedstock for many distinct products (noting that CO_2 removal can only be achieved through permanent storage). Nowadays, just 2 Mt CO_2 are captured through these technologies, and among these over 90% is done in bioethanol facilities. Indeed, the high concentration of CO_2 in the process gas stream is extremely high, allowing to maintain low prices for the process. Considering the actual forecasted stage of projects' deployment and expected future developments, it is estimated a total carbon removal via BECCS will reach ~40 Mt CO_2/yr by 2030, a result that appears to be far from the target of 250 Mt/yr that were expected to be removed in the Net Zero Emissions by 2050 scenario. Indeed, the technology is still very expensive and difficult to be scaled up.

2.4.6. Direct Air Capture (DAC)

Direct Air Capture (DAC) solutions extract CO_2 directly from the atmosphere (IEA, 2022). This technology has a high storage permanence when it is associated with geological storage and requires limited use of land and water, limiting their footprints. Moreover, captured CO_2 can be exploited for food processing and synthetic fuel production. Nowadays technology is still in an early stage of life. Indeed, it counts a total of 18 facilities that can capture almost 0.01 MtCO_2. However, a large-scale air capture plant with an estimated capture capacity of 1 MtCO_2/year is going to open in the mid-2020s in the United States, and many other projects are in the stage of development. According to the current estimates and the planned projects, DAC deployment will reach almost 5.5 MtCO_2 by 2030, even if in the Net Zero Emissions by 2050 Scenario the technology should be able to capture 60 MtCO_2. The DAC solution involves two different technological approaches: a solid and a liquid one. Anyway, both approaches are now very energy-demanding and extremely expensive, explaining the importance of technological developments in the growth of the technology to obtain energetic and economic efficiency.

OFFSETTING TECHNOLOGY	MAIN PROPERTIES
AVOIDED DEFORESTATION, REFORESTATION AND AFFORESTATION	Spurring forest potential in carbon storage in many ways: protecting forests that would have been cleared, re-establishing forest in an area where there was one once in the past, converting to forest of land that was used for other purposes in the past
OCEANS FERTILIZATION	Addition of special nutrients, in particular iron, to the oceans, in order to enhance the growth of phytoplankton, photosynthetic microorganisms
SOIL MANAGEMENT	Includes many different processes that aim to increase the carbon content of soil through land management practices. Divided into two broad categories by the National Academies report (NASEM, 2019). The first category includes known conservation management systems, which are adopted by more conservative farmers The second category includes practices known as "frontier technology", which includes practices that require significant technological investments
ENHANCED WEATHERING	Set of theoretical proposals that target to remove CO_2 by "spreading large quantities of selected and finely ground rock material

BIOENERGY WITH CARBON CAPTURE AND STORAGE (BEECS)	CO_2 is captured from biogenic sources, and it is permanently stored or used as a feedstock for many different products
DIRECT AIR CAPTURE (DAC)	Solutions that extract CO_2 directly from the atmosphere

Table 3: Offsetting Technologies

2.5. Risks of Carbon Offsetting and Biochar

Carbon offsetting solutions can be a powerful strategy able to reduce carbon emissions and store CO_2 in the soil or eventually reuse it for other applications (Cambridge Zero Policy Forum, 2021). However, there are many risks associated with carbon credits that must be considered when assessing their real impact on atmospheric CO_2 reduction. This chapter will cover the main parameters that must be considered in this sense.

2.5.1. Carbon Leakage

The Offset Guide (2023) describes carbon leakage as “Unintended increases in GHG emissions caused by a project outside of its boundaries”. An example of this phenomenon can be found in avoided deforestation projects. The avoided deforestation of a certain area could lead to the deforestation of another zone, eventually causing even more severe damage to ecosystems. Leakage connected to avoided deforestation is a critical issue and one of the main controversial sides of REDD+ projects. REED+ framework has been established for forest protection and the acronym stands for “Reducing emissions from deforestation and forest degradation in developing countries” (UNCC) Indeed, if companies find restrictions on land exploitation in one zone, could easily move to another one without such limitations. A clear example is the Soy Moratorium created to protect against deforestation of the Amazonian Forest (WWF, 2021) but a general increase in deforestation in the nearby zone of Cerrado. Policymakers have to mitigate the risk of leakage through appropriate mechanisms, in order to reduce the economic and environmental risks associated with this issue. An example of these policies is the EU’s Carbon Border Adjustment Mechanism (CBAM) “a tool to put a fair price on the carbon emitted during the production of carbon-intensive goods that are entering the EU and to encourage cleaner industrial production in non-EU countries" (European Commission, 2023). In practice, the tool consists of a system of trade fares applied to carbon-intensive producers which export some categories of goods in the EU.

2.5.2. Additionality

Additionality is one of the key features that must be held by an offsetting project that realistically contributes to climate change mitigation. Indeed, the carbon offset must be additional to any other reductions that would have occurred without the project (Cambridge Zero Policy Forum, 2021). It is important to assess the risk of additionality, as it has emerged that many certified programs do not take into consideration carbon additionality in attributing carbon offsets credits. For example, West et al. (2020) have studied the background of REDD+ projects in the Brazilian Amazon Forest, noticing that the reduction of deforestation is mainly correlated to National Policies and not to the REDD+ projects and demonstrating that in this kind of situation a better national-level carbon accounting is required.

2.5.3. Permanence

Permanence is one of the main challenges that affect the carbon sequestration technique. Indeed, the risk of leakage of the carbon stored with the offsetting strategies is always high and the reversion of CO_2 captured in the atmosphere in the atmosphere is likely to happen. For instance, a classic example of the risk is represented when in forestry projects, where carbon is stored in trees and soils. If a fire devastates the forest, burning down the trees, the carbon stored in them is instantly re-emitted (Offset Guide, 2023) As underlined by the Carbon Offset Guide, usually, carbon has to be stored for 100 years to be considered permanent. It is important to recognise that nowadays the risk of carbon releases into the atmosphere is always higher and higher, as happened in the 2021 fires that devastated part of the offset project in California and Oregon (NewYork Times, 2021).

2.5.4. Double Counting

According to Gold Standard, double counting is defined as the benefit of one emission reduction being used on various occasions. For instance, the situation can be verified if an emission reduction is accounted for in a certain nationally regulated system and also certified by a third-party organization. (Gold Standard, 2015)

RISK OF CARBON OFFSETS	KEY FEATURES
CARBON LEAKAGE	Unintended increases in GHG emissions caused by a project outside of its boundaries
ADDITIONALITY	Carbon Offset must be additional to any other reductions that would have occurred without the project
PERMANENCE	Carbon has to be stored for an extended period of time, usually 100 years or 40 years for some projects based in forest management, to be considered permanent
DOUBLE COUNTING	Benefit of one emission reduction being used on various occasions

Table 4: Main Risks of Carbon Offsets

Biochar is less susceptible to the risks above, that affect the whole field of carbon markets, but there are specific issues that are associated specifically with biochar. Indeed, soil application of biochar can provoke the release of dangerous components that can affect negatively the environment (Xiang et al., 2021). For instance, biochar can directly introduce in soil some harmful components, such as heavy metals when biochar is generated from a biomass rich of heavy metals, or can absorb external pollutants, releasing them into the soil. Moreover, according to other findings, excessive doses of biochar in clay soils can increase the danger of erosion or decrease the level of water content (Brtnicky et al., 2021).

Therefore, it is important to be completely aware of the risks associated with biochar and, more in general, other offsetting technologies, and it is crucial to apply standard methodologies that can assure a high level of control on the feedstocks used to generate biochar and on the way it is applied into the soil.

2.6. Standards and Certifications for Biochar

Carbon offsetting projects risk being a grey environment, with initiatives without a real and clear positive environmental impact; and with this background, a market based on carbon offsetting risks to fall into the greenwashing category. This is why many independent organizations have tried to create standards to evaluate objectively the environmental benefit brought by the offsetting projects (WWF, 2008). In the last years dozens of certifications have been released and some of them are recognized as trustworthy standards that can assess the impact of the biochar projects. In the next part of the paperwork, an overview of these certifications and standards will be provided.

2.6.1. European Biochar Certificate (EBC)

The European Biochar Certificate has been developed with the precise goal to "limit the risks of biochar usage to the best of our scientific knowledge and to help the users and producers of biochar to prevent or at least to reduce any hazard for the health and for the environment while producing and using biochar" (EBC, 2023). All of this trying to incentivize a methodical control of biochar quality and production process. Precisely, the EBC introduces a standard of requirements that biochar producers have to respect to obtain the certification. In particular, the Standard assesses the kind of feedstock used for the production of biochar, requiring the use of particular raw materials, the production technology used and the properties that the biochar has to respect once produced, all of these respecting precise health and safety regulations (EBC, 2023). The certificatory provides a complete service of consultancy, analysis and monitoring and the certified company has to pay a fee to be able to use the label of BCI for its products.

2.6.2. C-Sink

EBC has released in 2020 a specific methodology to certify the exact Carbon sink potential of the biochar produced (EBC, 2021). The C-sink standard gives a method to certify the carbon sinks that are based on biochar. The EBC certifies the carbon sequestration potential of biochar produced by the certified company, tracking down also all the carbon emissions produced by the company during the manufacturing phase, taking into consideration also activities such as transportation and transformation of feedstocks. Once the biochar is mixed with agricultural substrate or is employed in other durable material, the C-sink potential is certified and the certification released can be traded by the certified company. The EBC once a year audits the companies and guarantees the persistency of their credited projects. An important concept underlined in the guidelines of the certification methodology is the accounting method used by EBC to determine the magnitude of Carbon sequestered. Indeed, EBC performs specific controls during the production stage with the support of some state-accredited control bodies, that track down the carbon expenditures performed during the process and subtract the carbon content of the biochar. The result gives the value of the C-sink of biochar at the “factory gate”, that doesn’t correspond to the final value of the C-sink. Indeed, at this value must be added all the emissions occurring from the leaving of biochar from factory to the final application of the material, which must be tracked by the certification broker. Once considered these emissions, EBC emits the certification that can be traded by the broker in the voluntary carbon markets. Even if the methodology is detailed and gives clear guidelines on carbon sink determination, the guidelines still have some missing parts that have to be addressed. For instance, in the last update of the guidelines are still missing a section addressing the topic of additionality. This is why Carbon Standards has provided an integration document which describes the pathway to assess in a precise way the additionality of EBC C-sink certified projects.

2.6.3. International Biochar Initiative (IBI)

The International Biochar Initiative (IBI) provides a meeting point where biochar buyers and producers can remain updated on biochar technology, finding good practices and environmental standards to support biochar systems. In particular, IBI proposes a Certification Program that has been developed to allow biochar producers to verify and demonstrate that their product respects the criteria set in the standards of the IBI Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil (IBI, 2023). The IBI Standard follows a precise methodology to assess biochar feedstock material and production system, and it has, in particular, a section dedicated to the assessment of the toxicity of the product and another one focusing on the soil enhancement properties of the substances. The methodology provides quality assurance and in some parts of the assessment requires a third-party certification that has the task to verify the information provided, of the input employed and the processes developed. For instance, biochar feedstocks have to be certified by specific bodies approved by IBI. The certified company is granted to use the IBI Certified™ biochar seal for the period of 1 year and then has to renew the subscription.

2.6.4. VERRA Biochar Methodology and Verified Carbon Standard (VCS)

Verra is a non-profit organization created with the goal to set the standards for clear sustainable development. The more famous program of Verra is the Verified Carbon Standard Crediting Program, one of the most famous and widely recognised crediting programs (VERRA, 2023). Projects that are compliant with a VCS are rewarded with carbon credits that can be exchanged in the voluntary carbon market. Verra continuously publishes many different methodologies to assess the real impact of carbon offsetting projects. The compliance of the projects with the relative methodology allows them to be VCS certified. VERRA has recently published the VCS Biochar Methodology (VERRA, 2022) that defines the procedures for a precise quantification of CO_2 emissions reduction obtained with the production and the soil application of biochar. The methodology assesses in particular the impact of biochar in three main phases of its supply chain:

- feedstock sourcing;
- biochar production;
- nutrient retention.

The methodology gives a standardized approach for the demonstration of the additionality of the project and a monitoring and accounting framework for GHG impacts in the three stages mentioned before. The methodology is really detailed and takes into consideration many different parameters influencing biochar quality and quantity of emissions produced.

For instance, taking into consideration the emissions assessment for the production stage, the methodology takes into consideration how in the balance between the carbon retained in the biochar after pyrolysis and the CO_2 emitted in the atmosphere, the different parameters are influenced by the level of technology applied in the process. The Guide takes into consideration two scenarios: a High Technology Production Facility and a Low Technology one. In the two different scenarios, different parameters are set determining the degree of efficiency of the processes, having the High technology one employing feedstock more efficiently, creating fewer emissions and a more stable form of biochar.

As for the other projects of carbon offsetting, once assessed the compliance with the methodology, biochar initiatives are VCS Certified and are eligible to be issued Verified Carbon Units (VCUs) that represent "one metric tonne of carbon dioxide reduced or removed from the atmosphere" (VERRA, 2023) and can be monetized in the voluntary carbon market.

2.6.5. PURO standard Biochar

PURO Standard Biochar has been one of the first methodologies developed for carbon removal in the market. In 2019 it was released the first standard for carbon removal that was applied to "verify biochar projects and issuing CO_2 removal certificates to be sold in the carbon credit voluntary market". The methodology provides a framework to permit the calculation of the Carbon Sequestration over 100 years (CORCs) which is calculated as the difference between the carbon sequestrated over a 100-year time horizon by the biochar amount produced in that period of time and the sum between the life cycle greenhouse emissions of the biomass used for the production of biochar, the lifecycle GHG emissions arising from the production of biochar and the lifecycle GHG emissions arising from the use of it, including the GHG emissions occurred in the transportation from the producing facility to the use point (Puro, 2022).

$$CORCs = Estored - Ebiomass - Eproduction - Euse$$

Estored: carbon sequestrated over a 100-year time horizon by the biochar amount produced in that period of time

Ebiomass: life cycle greenhouse emissions from the biomass used for the production of biochar

Eproduction: life cycle greenhouse emissions from the production of biochar

Euse: lifecycle greenhouse emissions arising from the use of biochar

Equation 1: CORCs balance

To obtain the Puro Certification the net balance of GHG emissions must be under a certain threshold and the production process has to some other conditions, such as the lack of methane production during the process, the sustainability of the biomass source, and a year over year update of the data provided.

The last update of the methodology was performed in 2022 and has widened the perimeter of the biomass sources and the technologies that can be employed in the biochar production process.

Certification / Standard	Features	Last Update	Feedstock Employed	Technology Considered
European Biochar Certificate (EBC)	Standard of requirements that biochar producers have to respect to obtain the certification. The Standard assesses the kind of feedstock used for the production of biochar, requiring the use of particular raw materials, the production technology used and the properties that the biochar has to respect once produced.	05/04/2023	Agriculture, forestry and wood-processing, landscape management, recycling economy, kitchen and canteen waste, food processing residues on vegetable basis, water maintenance & vegetal marine biomass, textiles, anaerobic digestion, sludges from wastewater treatment, animal by-products	Pyrolysis and Gasification
C-Sink	EBC certifies the carbon sequestration potential of biochar produced by the certified company, tracking down also all the carbon emissions produced by the company during the manufacturing phase, taking into consideration also activities such as transportation and transformation of feedstocks.	01/02/2021	Agricultural biomasses, organic residues from food processing, wood from landscape conservation, short rotation plantations, arable forestry, forest gardens, field margins, and urban areas, biomass from forest management, wood waste, other biogenic residues.	Pyrolysis and Gasification

International Biochar Initiative (IBI)	It follows a precise methodology to assess biochar feedstock material and production system, and it has a section dedicated to the assessment of the toxicity of the product and another one focusing on the soil enhancement properties of the substances	01/11/2015	For certification approval, the IBI Feedstock Chain of Custody Form must be downloaded and completed, in order to track down feedstock origins and movements	Pyrolysis and Gasification
VERRA Biochar Methodology and Verified Carbon Standard (VCS)	Defines the procedures for a precise quantification of CO_2 emissions reduction obtained with the production and the soil application of biochar, giving standardized approach for the demonstration of the additionality of the project	05/07/2023	Agricultural waste biomass, food processing residues, forestry and other wood processing, recycling economy, aquaculture plants, animal manure, high-carbon fly ash from biomass	High and Low Technology Production Facility
PURO standard Biochar	Carbon sequestration is calculated as the difference between the quantity of carbon sequestered and stored in biochar and the quantity emitted during all the phases of biochar production	26/01/2022	Agriculture, forestry and wood-processing, landscape management, recycling economy, kitchen and canteen waste, food processing residues on vegetable basis, water maintenance & vegetal marine biomass, textiles, anaerobic digestion, sludges from wastewater treatment, animal by-products	Pyrolysis and Gasification

Table 5: Main Biochar Certification and Standards

3. The Market Potential of Biochar

Biochar's different applications and wide range of advantages have allowed its market to expand rapidly in the recent times. In the European Biochar Industry Consortium Market Report 2022/2023 it is provided a European market analysis of biochar production facilities (EBI, 2023) The report has tracked down 28 production plants that were installed and commissioned in 2022, and the number is expected to grow in 2023. Also, the production capacity of biochar has experienced a drastic growth of 52% in 2022, reaching 53.000 t Biochar produced. In particular, the 3-year Compound Average Growth Rate (CAGR) of production capacity has been equal to the 56% in the period between 2019 and 2022. For 2023 the capacity is expected to grow over 90.000 t, with an annual growth rate above 80% and a 3y CAGR of 68% for the period between 2020 and 2023.

Moreover, the European Biochar Initiative has estimated a total actual biochar production of 33.500t in 2022 a number that is expected to grow reaching the 50.000 tonnes produced in 2023. The report has also analysed the distribution of production facilities, highlighting Germany, Austria and Nordic countries as the main producers. One of the key elements for the biochar production feasibility and scale opportunity is feedstock availability, with an increasing relevance of non-woody ones.

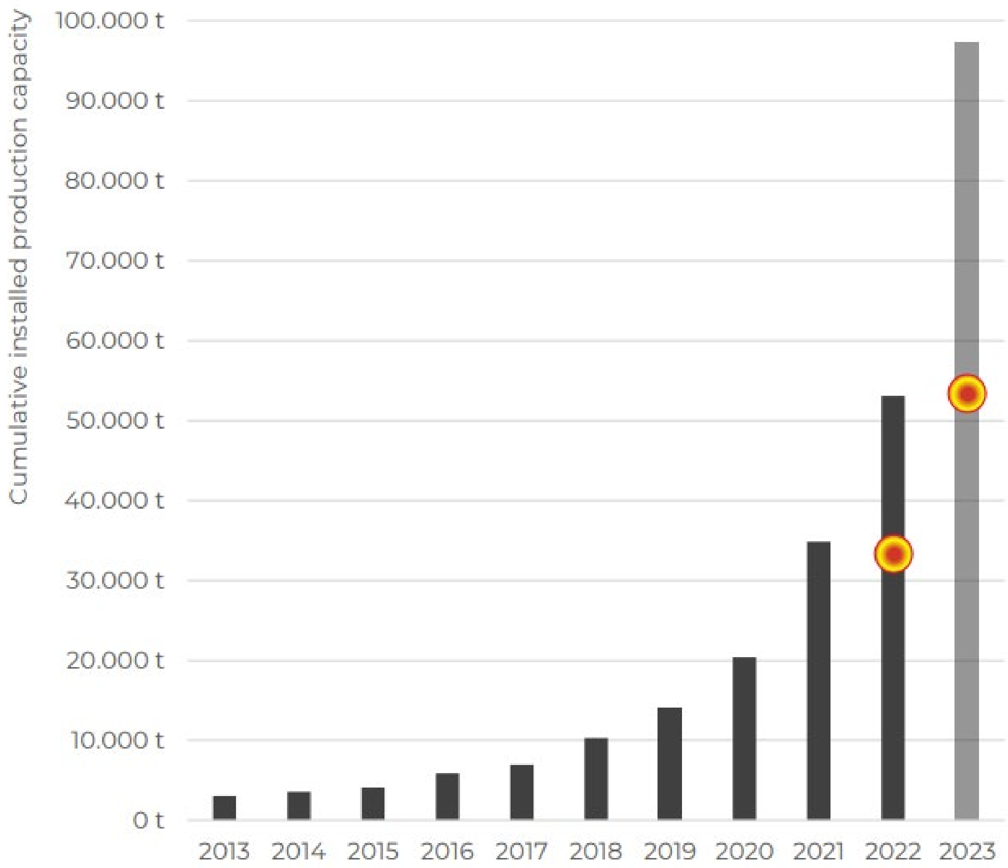

Figure 4: Quantity of biochar produced 2013-2023. Source: European Biochar Industry. URL: https://www.biochar-industry.com/market-overview/.

Considering a global point of view, according to Garcia et al. (2022) China is the country that is yearly producing the greatest quantity of biochar, followed by the USA and the European zone. Anyway, as seen before, the growth rate of EU biochar production is rapidly increasing.

This increase in the global interest in biochar and its expected growth of it is connected to its many different benefits and its important contribution to circular bioeconomy, an integration of the concepts of bioeconomy, a field that includes the production of renewable biological resources and the conversion of the waste coming from them into value-added products, and circular economy (Carus and Dammer, 2018). Indeed, the traditional linear economic has been redesigned, with a global propension toward the Circular Economy.

For instance, some disposal solutions that are typical of the linear economic system, such as landfill or waste incineration appear to be convenient from an economic point of view but hide some relevant social costs that have to be considered and that are pushing the governments (Neamatian et al., 2021) to create specific regulations to follow circular solutions. In Europe, the EU has adopted in 2020 the Circular Economy Action Plan, to support the development of new and innovative Circular Economy Solutions, in order to reduce the quantity of fossil fuels employed and wastes produced, but also to demonstrate the economic sustainability of the solutions adopted. Indeed, according to the report, if a sustainable framework is created, the application of circular economy principles could lead to an increase in EU GDP of an additional 0.5% by 2030 creating 700,000 new jobs.

3.1. Biochar Cost Determinants

As can be imagined, biochar well fits in this contest, as it can be employed in many different applications, and it is generated mainly by biomass and biological waste. For instance, biochar that is produced from forest biomass is then used in agricultural soil amendment (Oni et al., 2019). Anyway, it is important to assess the economic feasibility of the biochar supply chain, as biochar solutions are difficult to be adopted without a clear economic return and the prospect of scale. Nowadays, there are many economic challenges that biochar producers have to face and considerations that must be taken into account in the economic analysis of each stage of the lifecycle.

3.1.1. Feedstock Choice

First of all, the choice of the feedstock employed in the production of biochar inevitably affects the cost of the material. Indeed, as reported by the International Biochar Initiative there are many costs connected to feedstock, in particular due to collection, transport and storage. This is why biochar producers are incentivized to seek more economic feedstock solutions, such as waste or crop residues.

At this production costs must be added the transportation's ones. Indeed, if biomass used in pyrolysis is locally available, the logistics costs of transport are cut down. As a matter of fact, if the biomass is found far away from the pyrolizer plant, the costs of transport could be very high, as could rise the need to chip or palletize the feedstocks. Another factor to be taken into consideration in the economic assessment of feedstock logistics are their storage and preprocessing. Indeed, many feedstocks need to be stored and dried, and this preprocessing phase can be a great expense that the producers have to take into consideration. A clear estimation of the impact of the different choices of feedstocks is difficult to be carried out. However, many authors have studied and compared different feedstock applications.

For instance, the study by Sessions et al. (2019) offers a detailed analysis of how feedstock supply impacts on the cost of biochar production. The authors analyse the possibility of exploiting low-value trees cut by mechanical thinning to reduce the risk of wildfires in the US. Indeed, these trees have low economic value and the conversion to biochar is a valuable option. In this case, the feedstock supply chain has an important impact on the total economic cost. Even if the thinned wild trees are waste materials, for a correct analysis the cost of harvesting and pre-treatment must be carefully considered.

Moreover, the delivery costs of feedstock must be assessed, as the distance from the forest to the production plant and the transportation employed have an important economic impact. Another study that compares the differences in GHG mitigation and economic returns for different kind of feedstocks is the one by Field et al. (2013). Among many different analyses, the authors assess the differences in GHG balance and profitability of pine and spent grains in fast pyrolysis. The comparison of the two different feedstocks resulted in a lower net GHG-mitigation value for spent grains, but better economic performance than pine. Indeed, the opportunity cost of using spent grains for biochar production instead of animal feed is lower than the expense of waste wood collection, even if the use of wood instead of heavy fuels assures a net environmental external benefit, thanks to the avoided air pollution.

Kung et al. (2015) have given clear evidence of the differences among the different kinds of feedstocks used. In particular, the authors have studied the different economic returns held by biochar produced by different kinds of feedstock and through different kinds of processes. Focusing on feedstocks, the paper studies biochar produced from Poplar, Corn Stover, Rice Straw, Orchard Waste, Animal Waste and Open pasture waste in China. Almost all the feedstocks appear desirable, in particular Poplar, Corn Stover and Animal Waste. The authors take into consideration many different parameters that are influenced by feedstock’s choice. In this case, the cost of feedstock collection and hauling and pyrolysis are not particularly impactful in the net margin of the biochar, differently from the value of biochar and the energy produced and sold after pyrolysis. Another aspect that is highlighted in the study is how the economic yield of different feedstocks is influenced by different production processes. For instance, the net return of rice straw pyrolysis is much higher when processed under fast pyrolysis than slow pyrolysis.

These studies explain how difficult it is to assess in a unique way the correlation between feedstocks employed and biochar price, as it is closely connected to many different considerations, such as the distance of the feedstock basin, the transportation costs to the plant, the production process applied to the feedstock and if this process is the best suited for the feedstock chosen. To conclude, the choice of feedstock has to be a trade-off of these different variables that have to be carefully analysed to maximise the economic return and minimise the environmental impact.

3.1.2. Biochar Production

The production process used for biochar generation is another important parameter that must be carefully considered in the economic assessment of biochar and its profitability (Campion et al., 2023). In particular, the difference in economic returns can be given by the pyrolysis technology adopted, as stated by Sessions et al. (2019). Many authors distinguish the differences between fast and slow pyrolysis. For instance, Kung et al. (2015) compares the costs, the energy produced, and the carbon yield of biochar obtained from different raw materials processed with slow and fast pyrolysis.

The results of the studied evidence a clear difference in the economic return of the different biochar types. For instance, in the system studied by Kung et al. (2015), Rice Straw is studied as feedstock obtained after both slow and fast pyrolysis processes. The result obtained for the biochar obtained with slow pyrolysis is a negative net margin, differently from the one obtained with fast pyrolysis that is neatly positive. Indeed, even if the biochar value of the slow pyrolysis product is higher, the energy obtained during the fast pyrolysis process has very high economic value. As stated by Roy et al. (2017), fast pyrolysis produces as the main product bio-oil, increasing the value of energy produced during the process. On the other hand, slow pyrolysis produces biochar as main product, permitting higher carbon capture and environmental benefits. Therefore, even if the economic benefit of fast pyrolysis is higher in general, the environmental one could lead slow pyrolysis to be the preferred, protected and incentivized by policy regulations.

Snyder (2019) provides another comparison between different biochar production processes, particularly studying differences and similarities between slow, fast pyrolysis and gasification. Also in this case, fast pyrolysis shows a higher economic yield than slow pyrolysis, even if both production processes are suitable as good solutions for atmospheric CO_2 reduction. Instead, gasification is in general more costly and has a net present value that is lower than other solutions (Snyder, 2019). However, also in this case the difference in economic return is due to the higher value of bio-oil compared to biochar, that could change in the future.

Other studies compare the difference in the economic performance of the same process performed in different conditions. For instance, slow pyrolysis performed at different temperatures gives different economic results. Salgado et al. (2018) have compared the biochar yield, the energy efficiency and the economic return of pyrolysis processes carried out at 450°C and 550°C. The authors have analysed the economic returns generated by the transformation of residual biomass generated during quinoa and lupin threshing, in a wider circular analysis of these pseudo cereals. Both the residuals of quinoa and lupin have been subjected to 2 different pyrolysis processes carried out at 2 different temperatures (450°C and 550°C). The results showed better overall performance from the biochar produced through the 450°C process. Indeed, in both cases, the biochar yield and the energy efficiency have been better in the pyrolysis performed at the lower temperature. Moreover, also the economic performances are inversely related to the temperature. Indeed, for all the economic value considered in the paper (Cashflow, Operating Income, Earning Before Taxes and Depreciation (EBTD), Free Cash Flow) the biochar obtained after 450°C pyrolysis has gained better performances.

Using the same logic, Campbell et al. (2018) compared economic return of biochar obtained with slow pyrolysis performed at different temperatures. In this case, high-temperature pyrolysis gives better results than lower-temperature ones, different from the study conducted by Heredia Salgado et al. (2018). Therefore, there is no unique correlation between the temperature of the pyrolysis process and the economic return of the products. Indeed, even if the quality of biochar is generally higher when lower temperature and pyrolysis processes are applied, the economy behind the production processes accounts many different factors (Maroušek and Trakal, 2022) such as the economic return of the byproducts produced in the selected process, along with the energy produced and required by the machinery and all the set of considerations about the costs connected with the production plant.

The costs associated with pyrolysis plants are extremely variable and difficult to be precisely stated. Beston Company, one of the best-known producers of pyrolysis plants, provides a punctual analysis of all the costs of production, maintenance and management. The price range for the pyrolizer stands between the $45,000 and $700,000. This wide price range is affected by many different features that could be held by the machines and requested by the biochar producer. For instance, the capacity of the plant and the features of the reactor have a crucial impact on the price, which in this case varies from $29,000 to $75.000, and the performance of the machine. Moreover, the machinery costs are inflated by the costs of auxiliary equipment that could be necessary for the plant, such as an Oil Distillation Plant, and by particular customization that can be requested by the customers. At these costs, must be obviously added some delivery, installation and maintenance expenses, and all the costs that are necessary faced to run the plant.

Some authors have tried to estimate the costs related to the biochar production plants, but the costs are obviously variable and connected with the assumption made in the process. Nematian et al. (2021) deployed a punctual techno-economic analysis of biochar production from orchard biomass. In this study, the authors tried to estimate all the costs related to biochar production and among them, obviously, the expenses related to the technology employed. The authors divide fixed and variable costs and include all the expenses related to the plant and the logistics connected. In this study, a major part of the costs is due to the pyrolysis unit chosen to perform the biomass transformation, the machinery necessary for biomass pre-treatment and transportation means needed for biomass and bio-products.

3.2. Optimizations in Biochar Supply Chain

There are many different ways to seek optimizations in the biochar supply chain, involving different phases of biochar production and distribution. Indeed, various kinds of technology can be applied in the processes involving biochar and co-products production and some logistic and entrepreneurial decisions can drastically improve the economic management.

One of the most economically and environmentally impacting stages of the supply chain is the transportation of biomass from the source to the production plants. To reduce the impact of this stage many different solutions can be adopted. There are many technologically viable options that could help in this view. One possible solution is to carefully study the position and the dimensions of the plant.

Nematian et al. (2021) focus on the use of small plants located directly to the feedstock sources, in order to produce biochar locally in rural locations. To do that they assume to use a portable pyrolysis unit instead of a centralized facility. In this way, the costs related to the feedstock transportation and all the logistic issues connected are reduced and the supply chain is drastically simplified. Moreover, the costs of the mobile plant are obviously lower than the ones of a bigger centralized plant and through this mobilized system it is possible to move toward different feedstock sources, covering a very large geographic area without installing many different plants or one plant requiring high transportation costs (Hoang et al., 2021).

However, this solution is not always applicable and cannot be always chosen as the optimized one. Indeed, in the case studied upward the quantity of biomass to be processed was not as much as in other cases and the logistic costs required for biomass handling and transportation would have been a huge burden. Moreover, the feedstock basins were dispersed and could be covered effectively only through the mobile solution. Anyway, as suggested by Hoang et al. (2021), moving the production site near the biomass sources can be an important saving in transportation expenses, but it is crucial to take into consideration all the costs related to the distribution of biochar and its co-products. For instance, Braimakis et al. (2014) have evaluated the cost impact of a decentralized pyrolysis approach for the production of bio-oil. According to their analysis, placing the bio-oil production plant directly into the feedstock source is more convenient till the distance between the pyrolizer and the central bio-refinery stays between 100 and 500 km, as the transportation cost of bio-oil is cheaper than biomass'. In general, biochar and pyrolysis products are easier and cheaper to be transported than raw biomass, which is why using mobile pyrolysis systems or building plants close to the basins generally are good and optimized choices (Roy and Dias, 2017).

In other cases, a higher profitability of biochar plants can be found by increasing the scale of production, as the increase of the fixed and variable costs is covered by the larger scale of production and the longer lifespan of the plant, allowing a better amortization of the costs. The efficiency of the scale of production varies drastically depending on the technology adopted in the biomass transformation process (Kochanek et al., 2022). For example, Kuppens et al. (2015) evidence how gasification becomes more profitable than fast pyrolysis when the plant's scale becomes larger. Indeed, the capital cost of gasification is much higher than fast pyrolysis' when the scale of production is small but becomes more convenient when large scales are taken into consideration, thanks to economies of scale. Also, the pyrolysis reactor choice depends on the scale of production that is wanted to be obtained and not only on the product that is needed. Indeed, some particular reactors, are suitable for higher production levels, such as the Rotating Cone and the Spouted Bed (Hoang et al., 2021). Moreover, large-scale plants have the additional benefit of producing some other high-value products, such as Hydrogen, that increase the profitability of the process.

Moreover, biochar technologies can create many opportunities for small-scale producers. Farm-scale biochar production could be a profitable action for small farmers, who can employ many economic small-scale technologies (Nsamba et al., 2015). For instance, simple batch kilns are economical and easy-to-use solutions that are typical for small-scale production. They can be loaded with many different varieties of feedstocks and, even if do not assure the possibility of large-scale production, their biochar yield is very high. A simple kiln can be created with simple and locally available materials, and although it is not cost-effective for commercial use, it can be perfect for a smart and optimized reuse of waste products and for the production of small biochar quantities that can be employed to increase soil fertility or in the creation of a local, niche market.

A study on small-scale biochar production has been carried out by Azzi et al. (2021) in an analysis of a case study in Sweden. The biochar produced in the process and applied in soil has generated a benefit due to carbon sequestration, but also an increase in other environmental emissions. This is why it is important to consider all the co-benefits connected to biochar generation. An element that could incentivise investments in small-scale production solutions is their enablement as a technology in carbon markets (Sörman, 2023). Indeed, the possibility to obtain carbon credits from biochar production and to trade them in the carbon voluntary market can be a strong incentive for local production.

However, local farmers could not be interested in these technologies, seeing that the biochar quantity produced is relatively small and the carbon credits would be few and too expensive to be obtained. Therefore, the income coming from carbon credits could become interesting if sided to a good support policy and a strong collaboration between similar small local farmers.

Another benefit of small-scale production of biochar can be found in the case of its beneficial application in developing countries, where it could be used as a precious resource to fight many local problems. This is the case in Sub-Saharan Africa, where the “black gold” has gained more and more importance in the fight against soil degradation, food insecurity, environmental pollution and lack of energy. For instance, in Zimbabwe the feedstock eligible for biochar production has been estimated to be around 9.9 Mt/yr, 88% of them derived from manure. Therefore, biochar production could be an innovative solution to perform effective waste management, generating at the same time many other environmental benefits.

In a major part of these zones, in Zimbabwe for instance, there is a high presence of small farmers with low technical skills. That is why the employment of simple, low-cost pyrolizers. Low-cost metal drum batch reactors are fabricated with locally available materials, but a more attractive solution is represented by the introduction of pyrolytic cookstoves that permit biochar production but can also be used for cooking purposes and heat production. For places with a dramatic lack of energy, coupling biochar production, with all of its beneficial effects, and energy generation is an incredibly attractive solution. Gwenzi et al. (2015) have estimated that using the feedstock available in Zimbabwe, it is possible to produce 3.5 Mt/yr of biochar, which if applied in soil could sequester a total of 2.2 Mt/yr of Carbon. With this positive environmental impact, it is important to add all the other potential benefits, connected to the improvement of health conditions, heat and energy generation and waste management (Gwenzi et al. 2015).

OPTIMIZATIONS IN THE SUPPLY CHAIN	MAIN FEATURES
SMART POSITIONING OF THE PLANT	One of the most economically and environmentally impacting stages of the supply chain is the transportation of biomass from the source to the production

	plants. In some cases, choosing to position a smaller production plant directly close to the feedstock source can help in the reduction of the costs and the environmental impact of feedstock transportation.
INCREASE THE SCALE OF PRODUCTION	In some cases, a higher profitability of biochar plants can be found by increasing the scale of production, as the increase of the fixed and variable costs is covered by the larger scale of production and the longer lifespan of the plant, allowing a better amortization of the costs
USE OF SMALL-SCALE PRODUCTION FACILITIES	Farm-scale biochar production could be a profitable action for small farmers, that can employ many economic small-scale technologies. Biochar produced locally can be employed for direct agricultural use or can be traded in the local market. Moreover, small producers can take advantage of the carbon credits obtained for the sequestration of CO_2

Table 6: Possible Optimizations in Biochar Supply Chain

3.3. Biochar Market Analysis

A precise assessment of the market value of biochar is a difficult task. Indeed, as it has been seen, biochar production cost is affected by many different variables, and it is sold for many different applications. For any of the applications, the economic benefit of biochar changes and the price of it is closely related to many different variables. In general, the price is closely dependent on the biomass feedstocks employed in the production process (Sessions et al., 2019), the technology used for that (Kung et al., 2015), the quality of the biochar produced and the application at which it is dedicated (Campion et al., 2023).

Campion et al. (2023) provide a comprehensive analysis of many studies on biochar pricing and biochar profitability. In general, it is shown that biochar profitability is difficult to be reached by biochar producers. Indeed, even if there is a high variability of the price applied, in general, it remains much higher than the average willingness to pay of a potential buyer. In particular, the most general case is the application of biochar in agriculture for soil amendment. For instance, according to Sessions et al. (2019), the maximum affordable price for farmers stands around 3,27 USD/Mg biochar, when, in Campion et al. (2023) analysis the median price is 400 USD/Mg biochar. Even if the price range is very wide, going from around 17 USD/Mg biochar to more than 2,700 USD/Mg biochar, there is still a huge difference between the price and the willingness to pay. Of course, these high prices negatively affect the desirability and profitability of the material, as farmers or other buyers are not incentivized to acquire it (Galinato et al. 2011). Anyway, some other factors are important to take into consideration when analysing parameters that affect biochar profitability. Some examples of these factors are the positive and negative externalities associated with biochar production and government policies and interventions in the field.

3.3.1. Externalities influence

As shown during this analysis, biochar has many external effects that it is important to take into consideration when assessing its net environmental and economic benefit. It is important to underline that biochar has both external benefits and external costs that affect the final results (Campion et al., 2023).

The main external benefit that has a fundamental impact is the reduction of GHG emissions in the atmosphere through carbon sequestration, application in soil, substitution of fossil fuels for energy production and many other methods that are connected to the reduction of carbon dioxide in the atmosphere. Considering direct carbon sequestration obtained by storing biochar in soil, in the study of Campion et al., (2023) the range of carbon sequestration stays between 0.896 Mg CO_2/Mg biochar to 10.55 Mg CO_2/Mg biochar, with a median of 2.93 Mg CO_2/Mg biochar. Field et al. (2013) analyses the beneficial effect of biochar on the reduction of soil GHG emissions, considering the avoided emissions not only of CO_2 but also of N_2O and CH_4, which, as stated upward in this thesis, can be even more dangerous than Carbon Dioxide. Moreover, CH_4 emissions would be produced also with alternative treatments of biomass, such as landfill, which are avoided thanks to biochar (Parmar et al., 2014). Thus, biochar, but mainly other pyrolysis products such as bio-oil, have been demonstrated to be valid substitutes for fossil fuels but generate a lower environmental impact (Kung et al, 2015). Part of the benefits connected to the reduction of emissions, another positive externality is given by the application of biochar for soil amendment and the consequent improvement of fertility and water-holding capacity, reducing the need for fertilizers and improving crop productivity.

Understood the positive externalities of biochar, it is crucial to find the correct way to account for them with a monetary value that could affect its economic value and the willingness to pay of the buyers. The fastest way to assess the benefits of carbon removal is by using prices from the voluntary carbon markets (Pandit et al., 2018). Anyway, estimating with precision a price for carbon credits is very difficult, as voluntary market is not regulated, and the prices change according to different technologies used for credit production. In general, Southpole in its 2023 Voluntary Carbon Market report has estimated a 40% increase, mainly connected to an increase in demand over supply over the last year. At the same time, the number of issuances of credits has gradually increased over the last years, and it is destined to follow the trend.

Focusing on biochar, credit markets are still in a stage of development. The credited projects are not so much and the prices for carbon reduction are still high. For instance, in the Puro Earth marketplace are listed biochar carbon removal credits suppliers and the prices at which they are selling the CORCs (CO_2 Removal Certificates). In the case of biochar, the prices range between 110 €/CORC and 535€/CORC. In Europe, the cheapest project is valued at 150 €/CORC. Another value that could be taken into consideration is the social cost of carbon (SCC) that in the review analysed by Campion et al. (2023) is estimated between 23 USD/Mg CO_2 and 42 USD/Mg CO_2. However, SCC is difficult to estimate with precision. Until the economies of scale had not encouraged a wide adoption of biochar technologies, market and innovation development were supported by policies and economic government support policies (Nematian et al., 2021). The current state of biochar regulation and its effect will be covered in the next part of this review, but it is important to understand their influence on biochar desirability.

However, it is important to underline that biochar does not generate only external benefits. Indeed, external costs have to be included in the assessment of externalities (Campion et al., 2023). The first external costs to be accounted for are the GHG emissions occurred from operations connected to biochar production. For example, as analysed before, in the LCA performed by Field et al. (2013) and Kung et al. (2015) all the negative emissions of activities such as feedstock production and handling, operation of the pyrolysis plant or transport of the final product are taken into consideration. Moreover, it has to be added the effect of GHG emissions of the soil connected with biochar application, even if they are normally less than those generated by other products dedicated to soil amendment.

EXTERNALITY	TYPE OF IMPACT
GHG SEQUESTRATION	Positive impact
FOSSIL FUEL SUBSTITUTION: POSITIVE	Positive impact
INCREASE IN SOIL FERTILITY: POSITIVE	Positive impact
GHG PRODUCTION DURING PRODUCTION STAGE	Negative impact
SOIL EMISSIONS FOR BIOCHAR APPLICATION	Negative impact

Table 7: Main Externalities Affecting Bbiochar Market

The inclusion of externalities has a clear impact on biochar profitability and desirability. (Campion et al., 2023). The internalization of the externalities, through economic instruments such as taxes and subsidies permit an increase in the profitability of biochar projects, that without a supportive policy framework are often not convenient. (Verde and Chiaramonti, 2021). The introduction of financial rewards would notably incentivize the diffusion of biochar systems and would improve the economy of scale that would lead to a progressive adoption of the technology (Nematian et al., 2021).

3.4. Biochar Regulatory System and Policy Framework

The beneficial potential of biochar has been deeply assessed in this review, a potential not limited to environmental benefit held by the technology, but that covers all the applications that have been analysed, from its applications as efficient fertilizer to its employment in modern biosensors. Anyway, the technology needs to be supported by a solid policy framework that can effectively support its development and the generation of a scale economy model that would make its application more and more affordable (Verde and Chiaramonti, 2021). In this sense, many governments have started introducing policies that incentivise the adoption of biochar-based technologies.

For instance, Nematian et al. (2021) have spotted a total of 35 policy programs in the U.S. that provide different measures to help the development of biochar projects. Among them, there were included some financial incentives, such as loans and funds dedicated to research and development, but also non-financial policy support. For instance, the Biomass Crop Assistance Program (BCAP) promotes the cultivation of biomass for bioenergy production. Indeed, through this assistance program, farmers receive special funding that covers some of the costs experienced by growing biomass for bioenergy production. Moreover, in some states, such as California, farmers are supplied with "financial and technical help" for employing biochar in soil cultivation. Moreover, in 2021 has been introduced the Biochar Act, a Bill that establishes two programs that have the goal to "encourage research, development, and commercialization of biochar". Indeed, the Department of Agriculture (USDA) and the Department of Energy have to provide funds for biochar demonstration projects, in particular the ones with the best carbon sequestration potential and the ones that create positive economic benefit and new job opportunities. Moreover, the USDA has to finance colleges and universities' research on the environmental and economic benefits of biochar (Congress, 2021).

Verde and Chiaramonti (2021) have evidenced how in the past the diffusion of biochar in the European Union has not been supported by a strong supportive policy framework, something necessary to realise the potential of biochar at scale. According to the authors, many important developments with a positive influence in this sense have occurred at the EU level., all spurred by the introduction of the European Green Deal (European Commission, 2019) and its targets for Carbon emissions reduction. Among the many actions introduced by the EU in recent years, the most important are: 1) The introduction of a new Fertilising Product Regulation, published in 2019 and with the most recent update in 2022. In an update of 2021, the Regulation has included biochar in the list of fertilising products (European Commission, 2022) 2) The introduction of the reform of the common agricultural policy (CAP). The agreement was reached at the end of 2021 and entered into force on 1 January 2023 (European Commission, 2023). 3) Adoption of the new Circular Economy Action Plan, that has been recently updated in May 2023 (European Commission, 2023) 4) The proposal of a Carbon Removal Certification framework prepared by the European Commission, that creates a framework to certify carbon removals generated in Europe. The proposal is now in the course of evaluation by the European Parliament and the Council (European Commission, 2023) 5) The introduction in 2019 of the Green Deal, with the related targets of climate neutrality by 2050 and 55% reduction of the emissions by 2030. After COVID-19, it has been introduced the NextGenerationEU, a funding instrument was introduced to support the post-pandemic recovery. The EU has allocated for this purpose a budget of €800 billion that will be also employed to sustain the green transition and the targets established in the Green Deal (European Commission, 2021). 6) A more precise consideration of the GHG emissions produced in the Land Use, Land Use Change and Forestry (LULUCF) sector, in order to achieve the target, set in the Green Deal (European Council, data).

POLICY INTRODUCED	STATUS
FERTILISING PRODUCT REGULATION	New Fertilising Product Regulation, published in 2019 and with the most recent update in 2022. In an update of 2021, the Regulation has included biochar in the list of fertilising products.
INTRODUCTION OF THE REFORM OF THE COMMON AGRICULTURAL POLICY (CAP)	The agreement was reached at the end of 2021 and entered into force on 1 January 2023.
ADOPTION OF THE NEW CIRCULAR ECONOMY ACTION PLAN	Adoption of the new Circular Economy Action Plan, that has been recently updated in May 2023.
PROPOSAL OF A CARBON REMOVAL CERTIFICATION FRAMEWORK	Proposal for a Carbon Removal Certification framework prepared by the European Commission, that creates a framework to certify carbon removals generated in Europe, now during evaluation by the European Parliament and the Council.

GREEN DEAL	Introduction in 2019, updated after Covid-19 in the context of NextGeneration EU.
PRECISE CONSIDERATION OF THE GHG EMISSIONS PRODUCED IN THE LAND USE, LAND USE CHANGE AND FORESTRY (LULUCF)	Consideration in course of evaluation in 2023

Table 8: Policies Introduced to Support Biochar Market

According to Campion et al. (2023), it is crucial to include subsidies, taxes and tradable permits to assess the correct economic value of biochar and the willingness to pay of buyers. Clare et al. (2015) in their study have accounted for an improved Net Present Value of biochar production considering the positive impact of subsidies obtained by avoiding the burning of straw and the generation of energy from biomass. Also, Kuppens et al. (2015) state that providing a calculation of the economic return of pyrolysis projects without taking into consideration eventual policies and subsidies would lead to a misleading result. In general, the internalization of externalities increases a lot the net profit of biochar projects, sometimes leading them to a positive Net Present Value, as in the case of Campbell et al., (2018). Moreover, the impact of the externality's inclusion and the connected increase in profitability affects also the desirability of biochar's use (Campion et al., 2023). Indeed, the willingness to pay of biochar users changes and becomes higher including the positive benefit of the externalities. According to Galinato et al., 2011, the willingness to pay of farmers increases from 9.19 USD/Mg to almost 100 USD/Mg when carbon price is included in the calculations. This augmented willingness to pay is crucial in the progressive adoption of biochar by potential buyers and of its production technology, even if this number is still lower compared to the average market price of biochar. However, the precise market value of biochar is difficult to assess. According to Ciolkosz (2023), the price of biochar would be estimated at around 350 USD/ton, whereas Campion et al. (2023) assess a range of prices with the median of around 400 USD/Mg biochar.

According to Verde and Chiaramonti (2021), there are some powerful instruments that should be used to incentivise the diffusion of biochar systems, rewarding GHG removals. A first option, the most capable of incentivising in a fast way biochar production, would be to grant funds to farmers under the Common Agricultural Policy. A second one could be the creation of an obligatory market for certificates of GHG removals. And, finally, the third option, the most widely discussed one, would be the introduction of a quota of the emission removals performed as offset in the European Union Emissions Trading System (ETS). The European Community has been discussing the third point for many years. In fact, the introduction of Offsets in Emission Trading Systems can have many different positive and negative sides. The choice to include Offsets as a compliance instrument in ETS guarantees a further option to reach the ETS cap, allowing a further diffusion of the beneficial technologies that stay at the base of the Offsetting practices, building capacity and scale, incentivising entities to adopt NET projects. Moreover, by considering Offsetting Credits as eligible for ETS, policymakers can further reduce the ETS cap. Strong of these benefits, many countries such as California and China use offset technologies in ETS jurisdictions (ICAP, 2023). However, the inclusion of Carbon Offsets in ETS has some potential drawbacks. First, the reliance on this kind of Carbon Credits would disincentivise many companies to take up investments in emissions mitigation and low-carbon projects. Moreover, the price of Offsets is unstable, and, at this moment, it is hard to assess the integrity of the projects. Indeed, as analysed before in the Review, additionality and permanence of offsets are not always precisely estimated. In California, companies can use offset credits to cover only a small part of their compliance obligations. For instance, In the period 2021-2025, covered entities can offset 4% of their total obligations (CA Gov, 2022).

BENEFITS	DRAWBACKS
Further diffusion of the beneficial technologies that stay at the base of the Offsetting practices	Reliance on this kind of Carbon Credits would disincentivise many companies to take up investments in emissions mitigation and low-carbon projects
Policymakers can further reduce the ETS cap	Price of Offsets is unstable
option to reach the ETS cap	Hard to assess the integrity of the projects

Table 9: Benefits and Drawbacks of Offsetting Inclusion in ETS

4. Methodology for Market Assessment of Biochar Producers

The analyses developed in the next chapter are based on an ad hoc created dataset that collects the information about almost 100 European biochar producers. The collection of these companies has been developed with data research supported by many official and reliable different databases and websites collecting information about biochar production. Among these, the most important have been:

- the European Industry Consortium (EBI) and the list of its members;
- the European Biochar Certification (EBC) list of certified companies;
- Puro.earth, one of the most famous and used crediting platforms for carbon removal projects;
- Carbonfuture, one of the most affirmed platforms for trading in carbon credits;
- Biochar Zero, a platform that collects information about many European biochar producers

First of all, the reliability of the data from these sources has been assessed and cross-checked using all the databases available. Therefore, the information needed for the analysis has been collected, using mainly secondary data obtained through the official websites of the companies selected and the databases quoted upward. Sometimes, it has been necessary to contact directly the companies directly in order to obtain some data that would have been impossible to be collected in other ways.

In particular, the information obtained was:

- the name of the company, with its official website and official contact information;
- the price that the company applies to biochar, if given;
- the certifications that the company holds;
- if the companies issuing carbon credits, and the issuing partners;
- the price of carbon credits, if given.

After many rounds of data collection, the first draft of the companies of the list has been analysed and some of them have been excluded being out of scope for the research. Then, all the data have been organized in database for the analyses performed in the second phase.

5. Results

An assessment of the market situation of biochar producers in Europe has been developed through the creation and the analysis of a dataset collecting crucial information about companies that are performing biochar production in Europe. The database has been created collecting information from the main European certificators and associations of biochar.

Therefore, the information obtained has been enriched with further research looking for other companies not contained in the databases employed. The result obtained has been the creation of a collection of a total European 95 biochar producers, that are spread all over the continent. Thanks to the data collected, it has been possible to produce many different analyses that give a precise idea of the situation of the development of the market of biochar in the European zone. In particular, the analyses carried out have been a geographic analysis, a producer capacity analysis, a biochar price analysis, a certification analysis and a carbon credits analysis.

5.1. Geographic Analysis

The first analysis provided is a geographic analysis and wants to give a panoramic of the position of the biochar producers found and their concentration across Europe.

The first view gives an overview of the collocation of the companies across the countries with the help of a heatmap that evidence the countries with the higher number of production companies. The darker the colour, the higher the number of companies in the country.

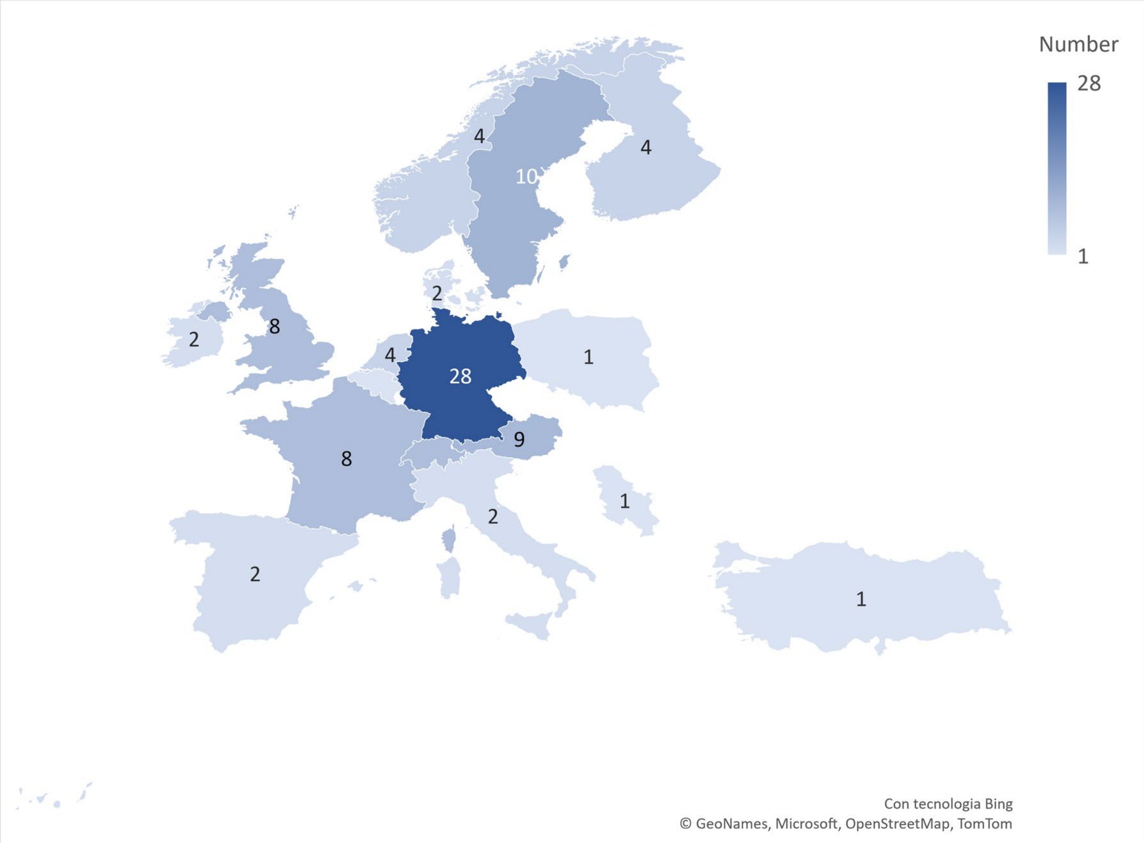

Figure 5: Geographic Presence of Biochar Producers in Europe

From the heatmap Figure 4 can be seen that in Germany can be found most biochar producers. In general, the in Western Europe is found most of the companies in the list, that are particularly spread in the central and northern part of Western Europe. The data are visualized in a more numeric way in Table 10. Here, it is even clearer how the distribution of the companies is unbalanced towards northern Europe. Indeed, in Germany is placed a total of 28 biochar producers, almost the 30% of the total collected on the producer list. The second in the list is Sweden, with a total of 10 companies (10% of the total) and the third one is Austria, with 9 companies spread across the country. At the 4th place in the list, can be found France, Switzerland and UK, all with 8 companies each. It is interesting to see that Nordic Countries, Norway, Finland and Sweden, are all inside the top 10 by number of biochar producers.

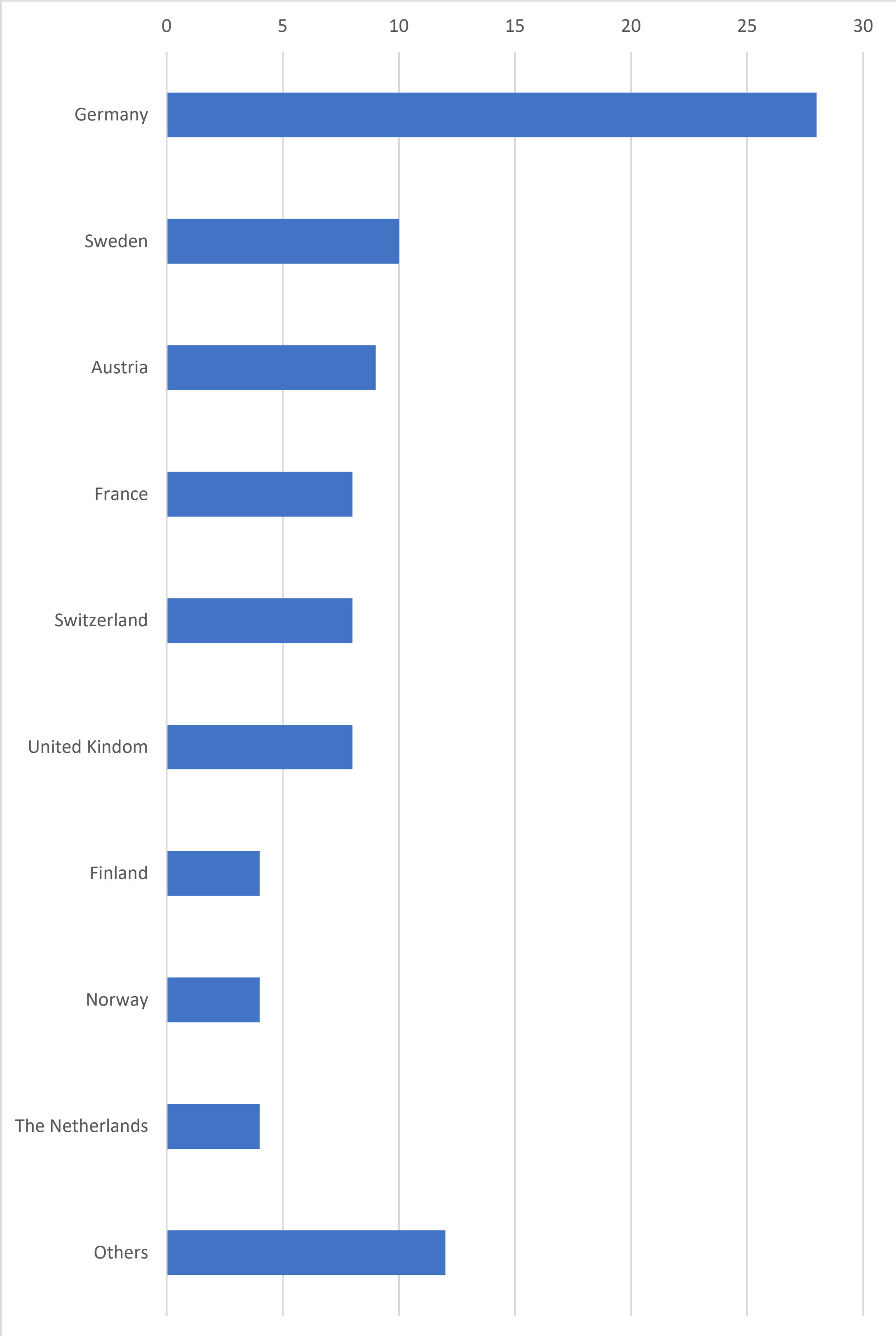

Table 10: Number of Producers per Country

5.2. Analysis of Producers' Capacity

The production capacity of each producer has been assessed and the data set has been divided into three categories:

- small size producers: producing below the 200 tonnes of biochar per year;
- medium size producers: producing between 200 and 2000 tonnes of biochar per year;
- large size producers: producing more than 5000 tonnes of biochar per year.

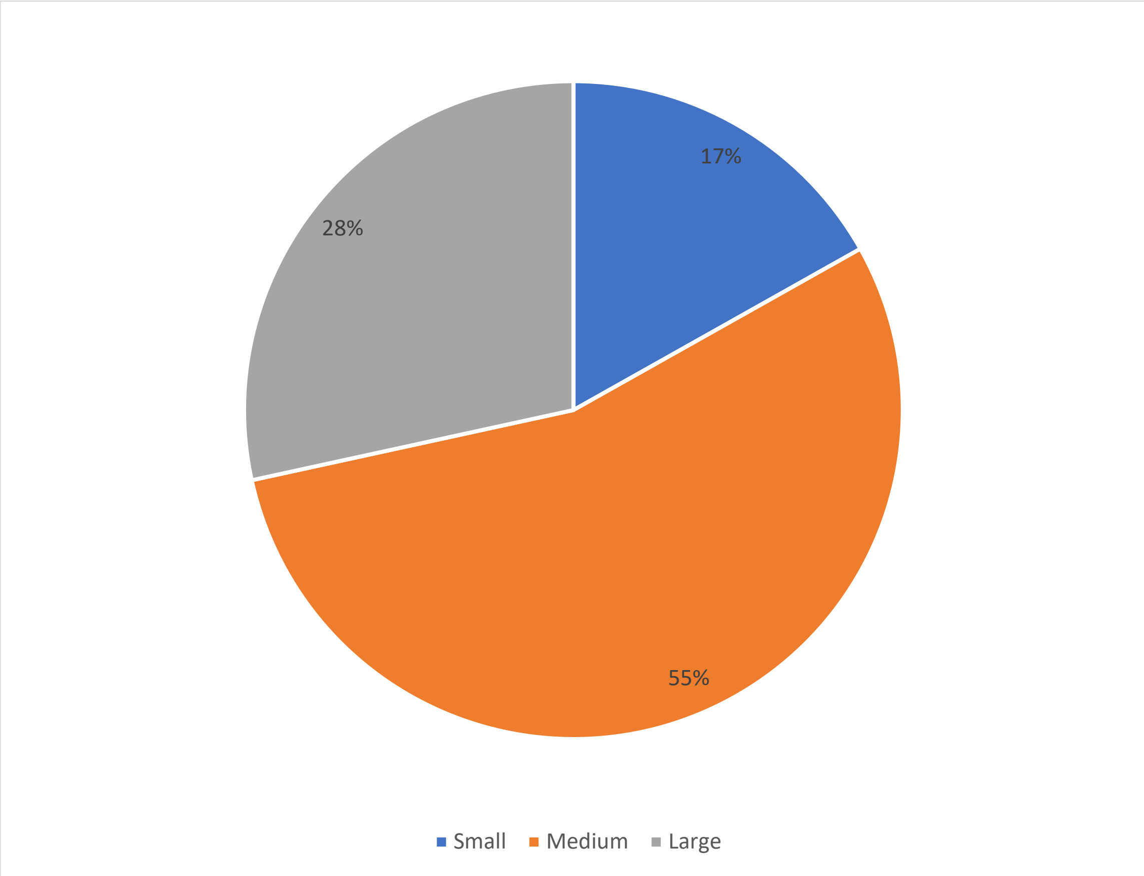

Table 11: Production Capacity

Most of the producers found in the research, the 55%, have medium sized production facilities, whereas large and small producers are respectively 28% and 17% of the market. These results are coherent with the 2023 EBI report, that states that most producers have medium sized production facilities, that have a production capacity between 200 and 2000 tonnes of biochar per year.

5.3. Analysis of Prices

In the research it was possible to find the biochar prices of a total of 24 companies, more than 25% percent of the companies collected in the database. It is important to underline that companies apply very different prices according to the quality of biochar they are selling, the size of the bag they are commercializing, the percentage of carbon stored in biochar, the feedstocks used in biochar production and the field of application of the product. Indeed, some sellers commercialize biochar for feeding purposes, or biochar enriched with nutrients or with compost. In this research, biochar price refers to the price of biochar sold in bulk quantities, usually big bags. Here is provided the list of companies whose prices have been assessed, with their plant size, pack size of biochar commercialized and biomass used for biochar production.

NAME	COUNTRY	PLANT SIZE	CERTIFICATION	PRICE OF BIOCHAR (€)	Pack Type and Size (m^3)	Biomass
Biocarbo	Italy	Small (under 200t)		209,5	2	Wood
Bioenergie Frauenfeld AG	Switzerland	Large (2000-5000t)	EBC, GMP+	236,8	2,2	Woodchips
Bionero	Germany	Medium (200-2000t)	EBC, FIBL	419,0	1	Wood chips
Carbex	France	Medium (200-2000t)	EBC, GMP+, FIBL	400,0	1	Woodchips, Spelt husks, Straw pellets, Mixed pits and shells
Carbon Gold Ltd	UK	Large (2000-5000t)		522,0	1	Woodchips, Green waste
CarboVerte GmbH	Germany	Medium (200-2000t)	GMP+, FIBL	500,0	1	Wood chips
Carbuna	Germany	Large (2000-5000t)	EBC, GMP+, FIBL	460,0	1,5	Wood chips
CharLine	Austria	Medium (200-2000t)	EBC, GMP+	320,0	2	Woodchips, Spelt husks
E4F	Germany	Medium (200-2000t)	EBC	520,0	0,02	Green waste
Grassroots	Sweden	Medium (200-2000t)	EBC	500,0	1	Wood chips
Grossenbacher Grüngut	Switzerland	Small (under 200t)	EBC	313,3	1,5	Green waste
INKOH	Switzerland	Medium (200-2000t)	EBC, FIBL	350,0	1,2	Wood chips
Klimafarmer	Germany	Medium (200-2000t)	EBC, FIBL	530,0	1	Woodchips, Green waste
Kompostbau Wagner	Germany	Small (under 200t)		940,0	0,87	Wood chips
Moola	Germany	Large (2000-5000t)	EBC, FIBL	250,0	2	Wood chips
Oxford Charcoal Biochar	UK	Medium (200-2000t)	EBC	817,9	1,8	Wood chips
Phoenix Terra	Belgio	Small (under 200t)	EBC	490,6	1,8	Wood chips
ProE Bioenergie	Germany	Medium (200-2000t)	GMP+, FIBL	490,0	1,3	Wood chips
Skånefrö	Sweden	Medium (200-2000t)	EBC	493,0	1	Wood chips
SONNENERDE	Austria	Large (2000-5000t)	EBC	320,0	2	Spelt husks, Cellulose fibre
Swiss Biochar	Switzerland	Medium (200-2000t)	EBC	470,0	1	Wood chips
Terra Fertilis	France	Small (under 200t)	EBC	700,0	0,05	Wood chips
Verora AG	Switzerland	Medium (200-2000t)	EBC, FIBL	405,0	1,2	Green waste
Wundergarten	Germany	Medium (200-2000t)		475,0	2	Cocoa shells

Table 12: Price of Biochar Producers

The range of price goes from 209 to 970 €/ m^3. The average is 464 €/ m^3 and the median price 473 €/ m^3. As can be seen in Table 13, most of the producers stand in the range 451-500 €/ m^3, followed by the range 301-350 €/ m^3.

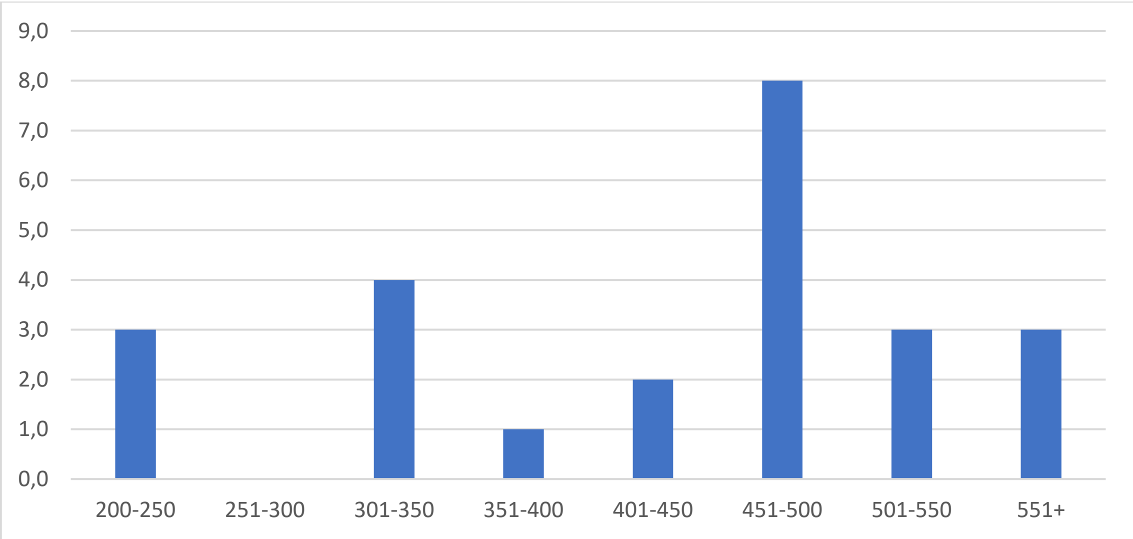

Table 13: Distribution by Price Range

As can be deducted from Table 14, one important determinant of biochar price is the size of its bag. Indeed, biochar is usually sold in a big bag format, but the size of the big bag changes, along with the price of the product. Bigger size usually means a lower price for biochar. An exception can be found when special biomasses are employed in biochar production. Indeed, the biochar produced by Wundergarten is sold in big bags sized 2 m^3, but its price is far above the average price of the size (475 €/m^3 when the average price is 315 €/m^3 for the 2 m^3 big bags) as its biochar is made from cocoa shells.

Another impact on the price is given by the geographic position of the producer. Indeed, biochar produced in Austria and Switzerland has average prices that stand below the European average price. Indeed, producers from Austria have a price of 320 €/m^3 and the ones from Switzerland 355 €/m^3. Indeed, Austria and Switzerland are small countries with a developed biochar market, the third biggest market after Germany and Nordics. This is why competition is high in these markets and biochar prices are generally lower, also taking into consideration the high feedstock availability of these countries. For instance, almost 50% of the Austrian land is covered by forest (World Bank, 2023).

In biochar supply chain, indeed, distance from feedstock source is an important determinant of the price, as well as the distance between the final user and the producer. Indeed, local availability of feedstock allows producers to apply a low final price, seen the high cost of biomass and biochar transportation. Moreover, final consumers have a high demand for biochar produced near their location, in order to avoid high costs of transport, enhancing local price competition on country markets. This is why in the small Austrian-Swiss market prices are generally lower than other markets'.

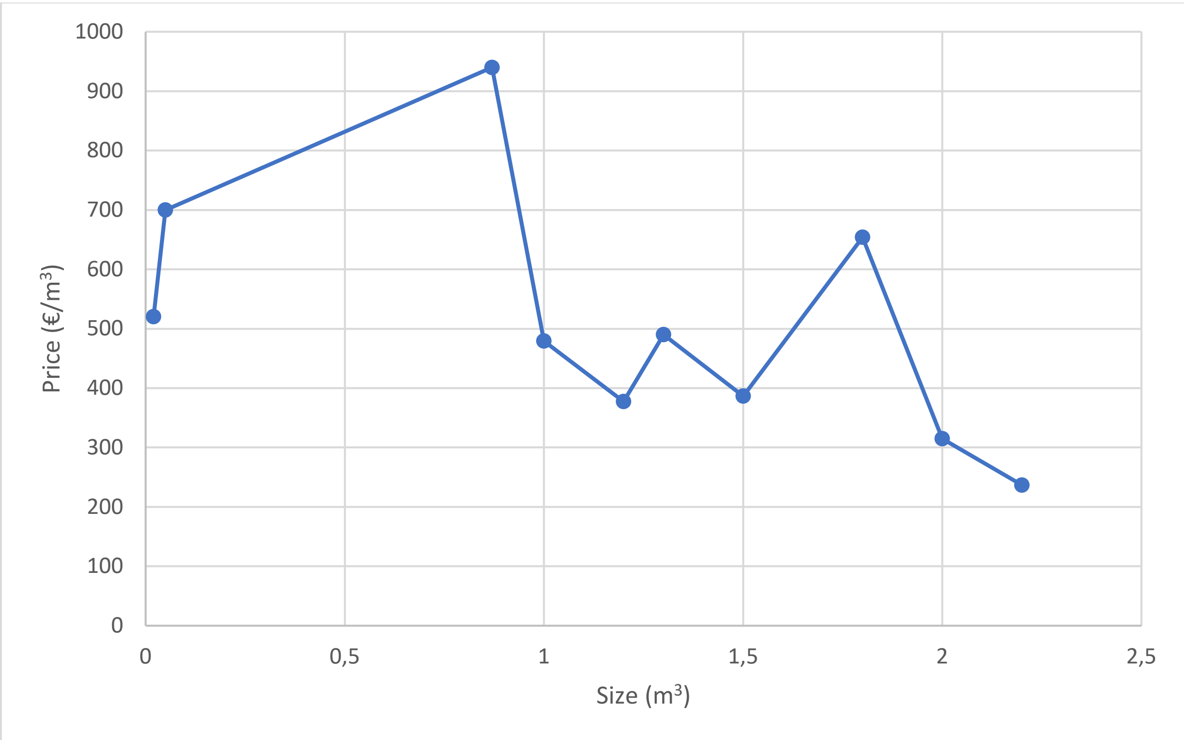

Table 14: Price per Size of Bag

Another important price determinant is given by the plant production capacity. Indeed, in the sample considered, the plant capacity is indirectly proportional to the final cost of biochar. Indeed, biochar produced in small production plants (under 200 t of biochar produced yearly) has an average price of 530 €/m^3, higher than biochar produced in medium size plants (478 €/m^3) and large size plants (358 €/m^3). Indeed, higher production capacity allows higher scale of production and the possibility of lower final prices.

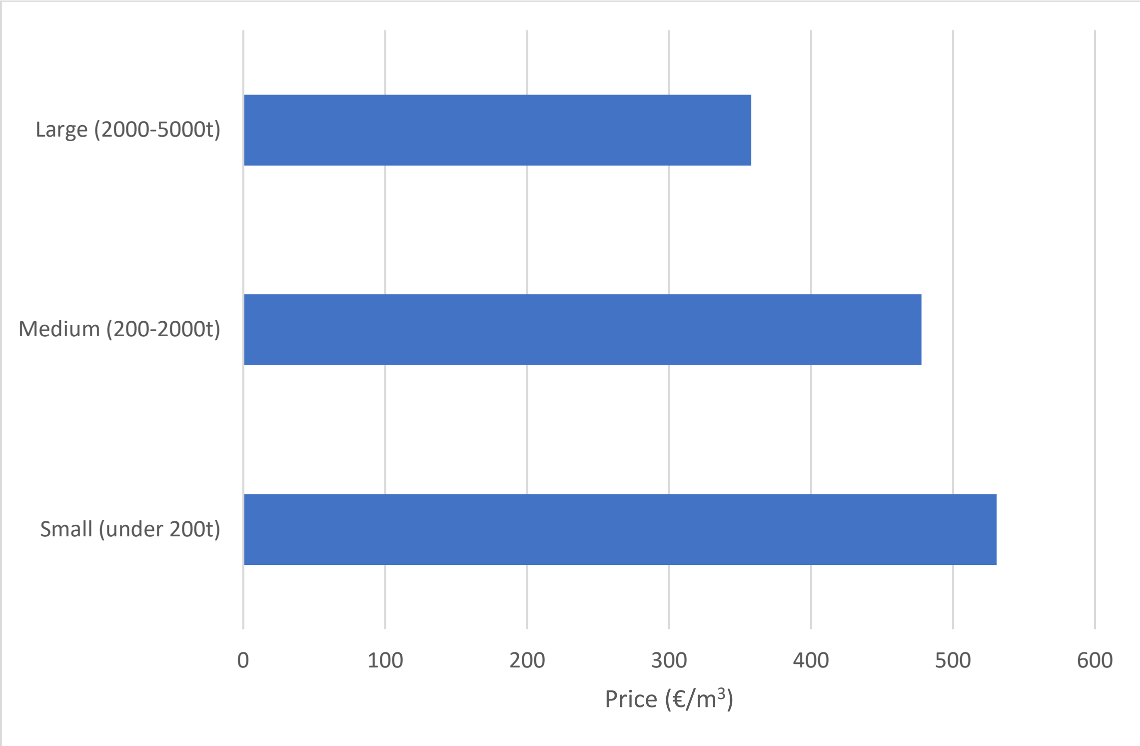

Table 15: Price of Biochar per Capacity of Production Plant

5.4. Analysis of Certifications

Certifications are an important requirement that assures not only a good quality of biochar but guarantee also for the methodology applied for its production, the feedstock involved and the application of the final product in the right way. The most important certification held by a major part of biochar and that is considered in this research is the European Biochar Certification. Moreover, in the following analyses has been assessed the compliance of the producers to other two certifications: the GMP+ and the FiBL. GMP+ (Good Manufacturing Process) certifies that the food safety risk of the company stands in the highest industry standards and, in the case of biochar, assures the best quality for animal feeding applications. Instead, FiBL (Forschungsinstitut für biologischen Landbau) certifies that the product created and commercialized can be employed in Organic Agriculture practices.

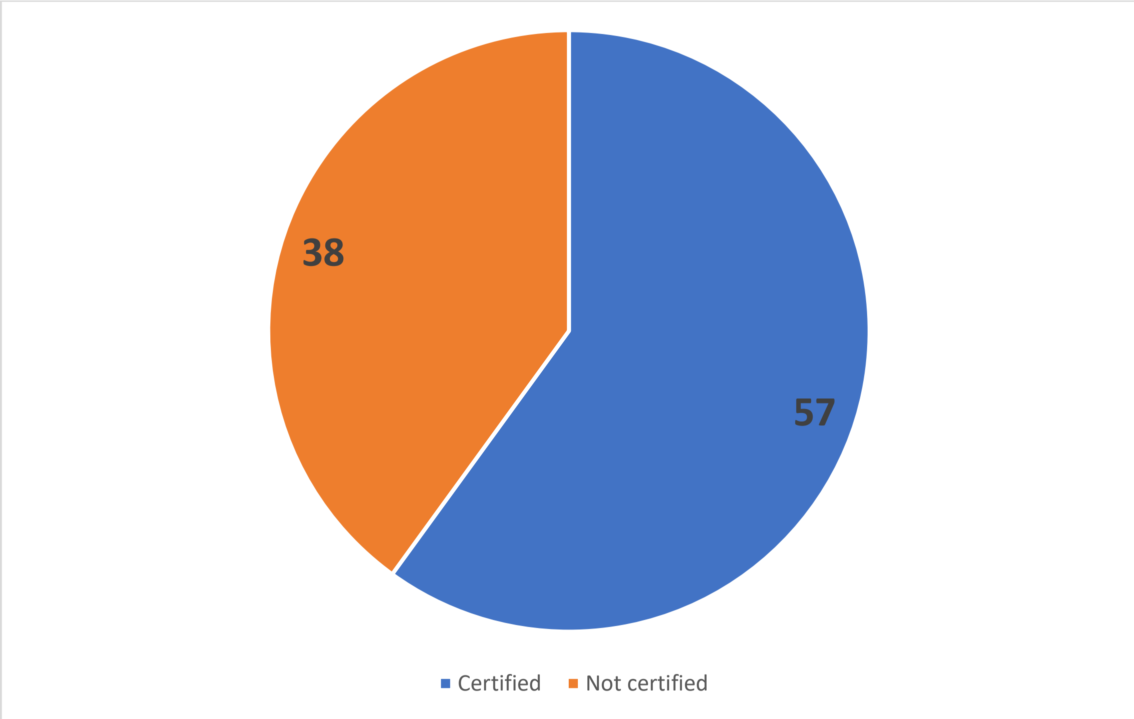

Table 16: Number of Biochar Producers Certified

As shown in Table 16, from this study results that 57 of the companies analysed own at least one of the certifications taken into consideration. This means that the 60% of the producers have certified their biochar, with the remaining 40% that have not adopted the certifications considered in this study.

Among the 57 certified producers, almost all of them have at least certified their biochar following the EBC standard. In fact, it is shown in Table 17 that a total of 54 producers are at least EBC-certified, meaning that only 3 of them have adopted only other certifications. Instead, a total of 14 companies hold FiBL certification and only 10 the GMP+ as it is employed in companies selling biochar for feeding proposes.

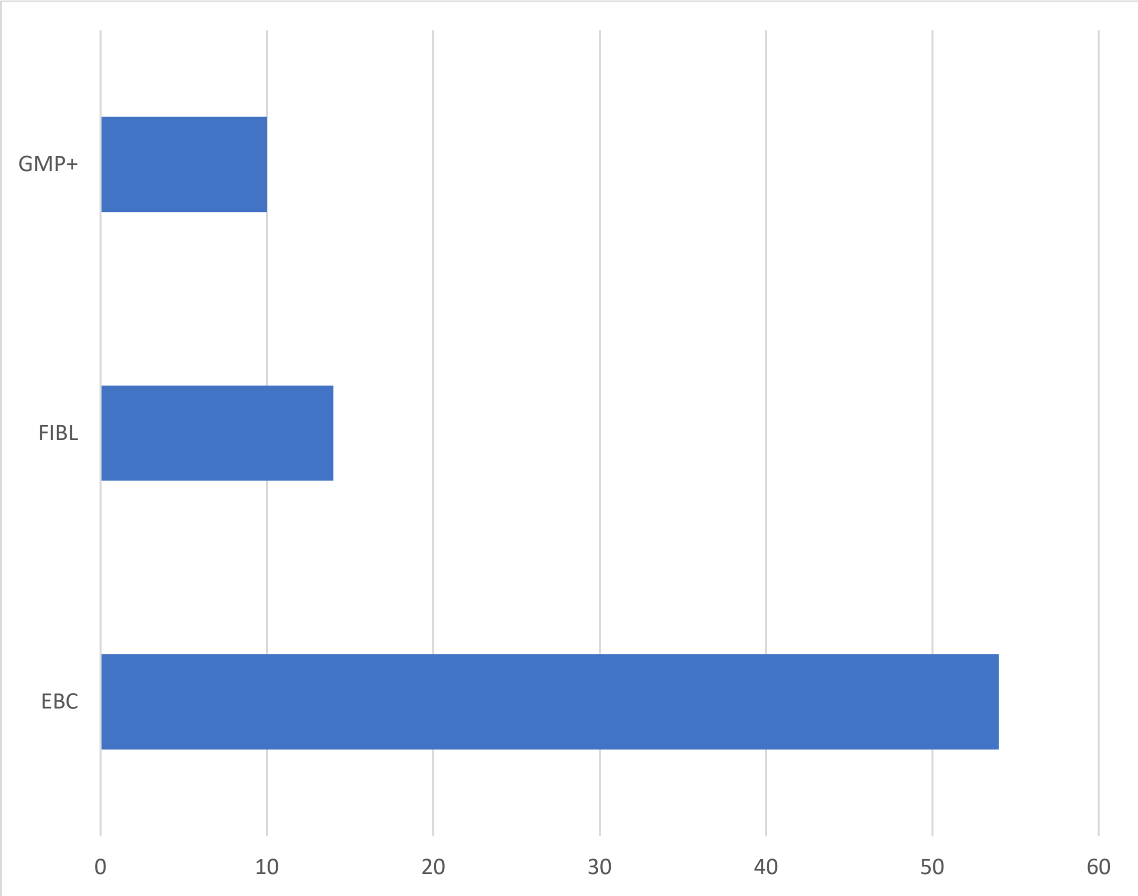

Table 17: Certification Held

Moreover, out of the 57 certified producers, a majority of them (39) owns only EBC certification. Moreover, EBC is also adopted by the companies which detain more than one certification. This makes clear the importance of EBC certification for most of the companies involved in biochar production. Indeed, as it is shown in Table 18, 7 companies detain both EBC and FiBL, 4 companies EBC and GMP+, and other 4 EBC, GMP+ and FiBL. Finally, the of the remaining 3 companies not certified EBC, 2 of them have both GMP+ and FiBL, and only one the sole FiBL.

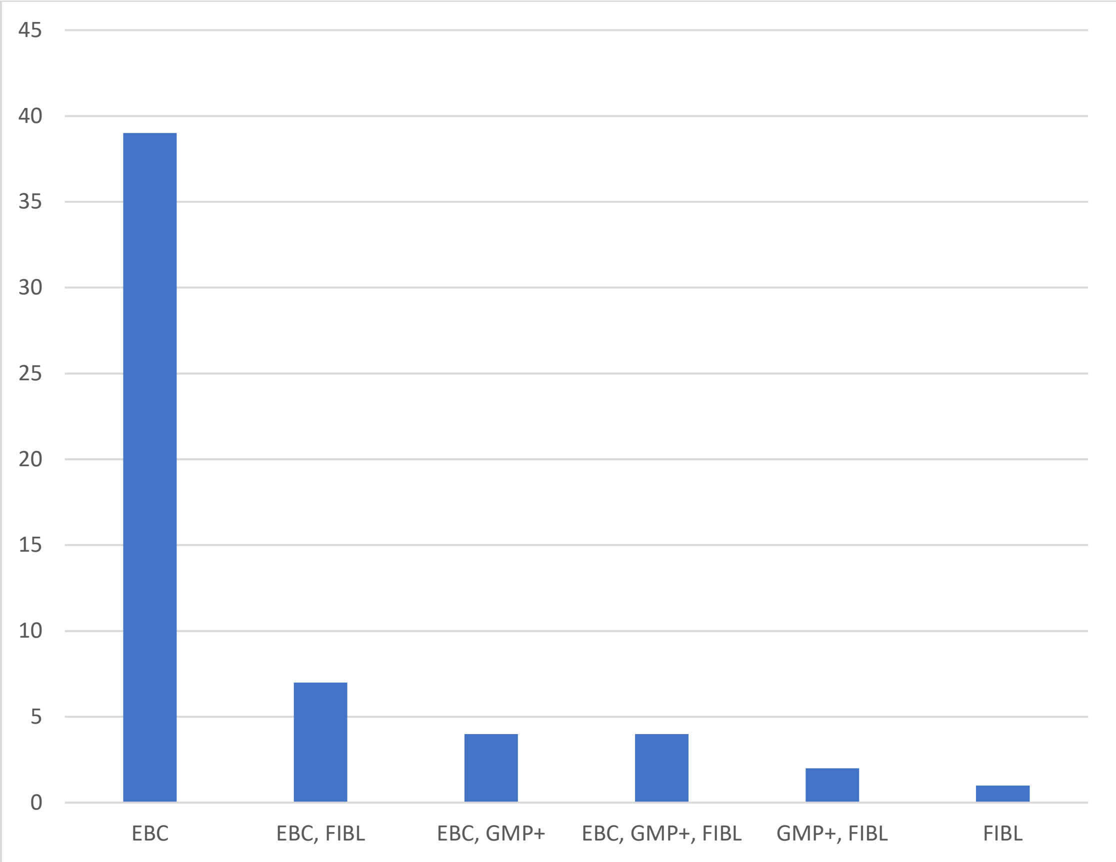

Table 18: Certification Mix

5.5. Analysis of Carbon Credits

This part wants to give an overview of the Carbon Credits issued by biochar producers, understanding how many companies are currently issuing Credits and what the pricing situation is. Analysing the database companies, from the research done has resulted that the almost 31% of European biochar producers considered is currently issuing Carbon Credits. That means that 29 companies on a total of 95 are trading Carbon Credits, with 66 companies that are not currently involved in the market of Carbon Offsets. In this study, the carbon credits taken into consideration are the ones issued following the guidelines dictated by the C-Sink and the Puro.earth standards. These methodologies permit a precise assessment of the carbon removal potential of the offsetting projects, certifying the total GHG sequestration performed and the quality of it in terms of storage period. The C-Sink Certification guidelines have been established in relatively recent years, as the first version was published in 2020. The C-Sink certificates are mainly traded in Carbonfuture, one of the most famous Carbon trading platforms.

Among the 29 certified projects, the majority are CORCs and are issued following the Puro.earth standard. Indeed, 17 biochar producers have accredited their projects following the Puro.earth standard and 11 companies are EBC accredited. In this analysis has resulted one company that has issued Carbon Credits independently, following the ISO sustainability standards.

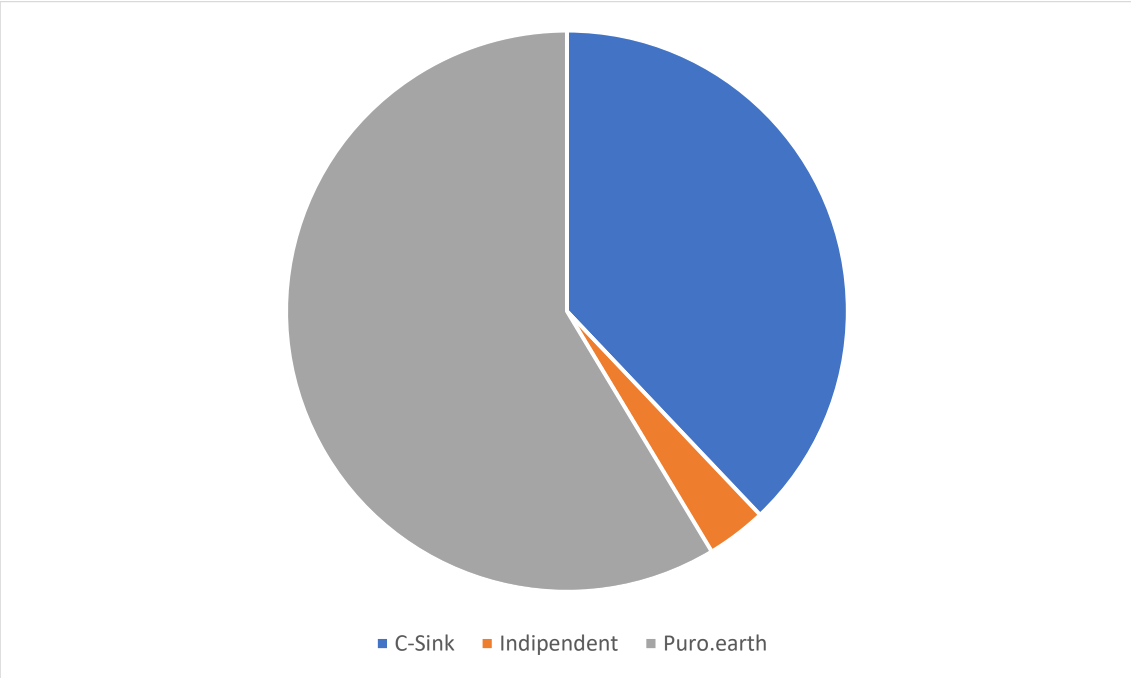

Table 19: Credits Issued by Category

Moreover, it has been possible to assess the price at which the majority of these carbon credits are currently sold in the Voluntary Carbon market. Even if some of the companies do not declare the price of their credits if there is not a concrete interest in its acquisition, it has been possible to assess the value of more of the 60% of certified projects. The price range of these issued carbon credits stays between 150 and 550 €/ton CO_2. The range is quite wide, but the average price is 288 €/ton CO_2, and the median price is 220 €/ton CO_2, showing already how prices are unbalanced towards the lower part of the range. However, most of the projects produce credits with a price that stands around the median price. Indeed, more than 72% of credits have a price between 150 and 270 €/ton CO_2. However, some producers issue credits at a much higher price. In general, these high prices of carbon removal are justified by the use of premium or particular kind of feedstocks that increase the circularity of biochar projects and product stability. For instance, as can be seen in Table 20, Sonnenerde applies a high price to its carbon credits, but this price can be justified by the employment of biogenic wastes for biochar production such as grain husks, sunflower pods and pulp mud, improving the circularity of the project.

NAME	CREDITS	PRICE (€/Ton of CO_2e)
Biochar - ECOERA Millennium 1 - Sweden	Puro.earth	535
Biochar GmbH & Co. KG	Independent	159
Biokol	Puro.earth	275
Bussme Biochar - Sweden	Puro.earth	150
Carbo Culture	Puro.earth	500
Carbofex	Puro.earth	270
Carbon cycle, Germany. Premium quality biochar	Puro.earth	220
Carbon Hill	Puro.earth	220
CharLine	Puro.earth	550
DarkBlack	Puro.earth	250
Energiewerk Ilg	C-Sink	200
Mash Makes	C-Sink	212
Nordgau Carbon. Biochar, SE Germany	Puro.earth	220
Novocarbo	C-Sink	220
OBIO-biochar from sustainable Norwegian forests	Puro.earth	220
Premier Forest, Wales.	Puro.earth	220
SONNENERDE Biochar - Austria	Puro.earth	550
Terra Fertilis	Puro.earth	220

Table 20: Credit Price per Producer

6. Conclusions

In this thesis, the various benefits of biochar technology have been assessed. Indeed, in a world that is progressively going towards the adoption of solutions that are able to fight effectively climate change's causes, biochar appears as a valid alternative.

Indeed, biochar has not only a good carbon sequestration technology, able to store carbon in soil for over 100 years but can be also applied in many different applications. The most famous one is the employment of biochar for soil amendment, but the material, thanks to its beneficial physical and chemical properties, has started to be used in many other different fields, from water purification to biosensors manufacturing. These aspects of the material have made it a very interesting matter of study and many different companies have begun to show interest in its applications.

Biochar seems to respect all of the properties that must be held by a good carbon offset, but only when its entire supply chain and its production processes respect the guidelines of the main methodologies that are published by the most recognized organizations in the field of carbon removal practices. Indeed, biochar production pyrolysis is a combustion process and all the emissions that occur in this production stage and in the transportation, practices must be taken into consideration when assessing the potential of biochar as carbon storage technology. In particular, a special focus must be given to the recently released Verra Carbon Standard, the most detailed and authoritative methodology in the field, which has seen a recent update in 2023. A good assessment provided by certificators guarantees also the quality of carbon removal credits and their role in the carbon trading market.

Analysed all the advantages of biochar, a market review of the situation of the European market has been made. Biochar market has experienced a rapid growth in recent years, growing with a GAGR of the 63% in the period between 2020-2023 and this rapid market development is expected to increase even more in next year, strong of the many new applications of the material that have been recently introduced. However, the profitability of biochar production depends on many different variables that have to be considered when assessing the increase of the adoption rate of the technology. The first variable that drastically affects biochar profitability is the kind of the feedstock and the kind of plant that is employed in the process. In fact, these aspects impact drastically on the production costs of biochar, on the final price and on marginality.

Moreover, there are some supply chain considerations that have to be evaluated in biochar making process. For instance, the evaluation of the distance between feedstock basins and production sites has a crucial impact on feedstock transportation costs. In some cases, it could be an advantage to employ smaller pyrolysis plants and produce biochar directly in the site where feedstocks are collected. In other circumstances, it is more convenient to take advantage of production scale, producing biochar directly in a bigger plant. Moreover, biochar production offers good opportunities for very small producers, such as local farmers, that can use small and simple pyrolysis technologies to convert waste in valuable product, that can apply for their own soil improvement or can trade them in local markets.

However, biochar cannot yet be considered a scaled-up technology and its price is still far above the average willingness to pay of the potential buyers even if all the positive externalities connected with social and environmental benefits are taken into consideration in the assessment of biochar economic value.

Being the situation of the research in biochar economy still in a late state of development, this research wants to give a useful instrument able to give a wide panoramic of the European market situation of biochar and that can be employed also in further research and assessment in the future. Indeed, the main output of this thesis is a database of 95 European biochar producers, with their website and contact information. Moreover, some other useful information has been found, inserted in the dataset and then analysed.

The first analysis made has been a geographic analysis. From that resulted that countries from Northern and Central Europe have a higher concentration of biochar production plants. The results obtained are aligned with the EBI 2023 Biochar Market report. Indeed, in the study it is stated that three quarters of biochar producers is distributed among Germany, Nordic regions, Austria and Switzerland, and in the research has resulted that about the 70% if the facilities can be found in these zones. In both the studies Germany is the country which hosts more producers (about the 30% according to this research and the 32% according to EBI) followed by Nordics (about 22% in this research and 25% according to EBI) and the zone formed by Austria and Switzerland (18% according to both this research and EBI). The high presence in these zones could be connected to a major greater availability of feedstocks than in the Easter and Southern areas, seen that in the production supply chain plant proximity is an important discriminant; or could be related to some other social and cultural factors that makes the implementation of these technologies easier and widely diffused. These aspects could be investigated in some further research on the theme.

Another dimension analysed has been the size of the productive plant. From the research it has resulted that the most of producers employ medium size plants, with a production capacity that stands between 200 and 2000 tonnes of biochar produced every year. Indeed, the costs of the production plant are generally high and the implementation of large production plant can be very expensive. Medium-sized plants guarantee good production capacity, limiting capital expenses.

Another analysis provided has been the one on the certifications held by biochar producers. The results show that the majority of the companies are certified and that the EBC is the most adopted certification in Europe. Instead, only 29 companies over the 95 analysed are currently issuing Carbon Credits. These Credits are issued following Puro.earth and the EBC-sink guidelines, but in future it would be interesting to monitor the evolution of the adoption of VCS by European companies in order to obtain carbon credits certified by VERRA. Indeed, VCS is one of the most famous recognized carbon standards, and in the year many companies have issued credits following its methodologies. Over the years the VCS projects have increased rapidly, reaching an equivalent of 300 Mln tCO_2e in 2021, six times the quantity issued in 2018 (Climate Focus, 2023). However, in the last years the quantity of issued credits has decreased dramatically, also because of a scandal about the effective carbon removal potential of the projects. Indeed, the Guardian has affirmed in an article published in 2023 that 90% of rainforest carbon offsets are worthless (The Guardian, 2023). Verra, in response, has made significant changes to methodology of forest-based carbon offsets and, despites the scandal, remains one of the central players in offsets certifications (S&P, 2023). The VCS for biochar is a recent methodology, and even if now is adopted by only few projects in India, it is likely that many projects will adopt the certification, also seen the last updates in 2023.

In general, not all the companies are issuing carbon credits as the process of certification of carbon sequestration is expensive and demanding. Indeed, certifiers have to assess carefully the sequestration potential of the biochar employed and companies have to respect strict standards dictated by the methodologies.

Moreover, the prices of Carbon Credits issued analysed in this research range between 150 and 550 €/ton CO_2, but with a median price of 220 €/ton CO_2. The price of these credits is high, justified by the high cost of production of biochar and the high quality of its Carbon Credits. Indeed, as has been seen upward in the text, biochar has a very good carbon stability, guaranteeing carbon storage for over 100 years. An organization that wants to invest in premium carbon certificates can be available to spend more than the average price of carbon credits.

Finally, biochar prices have been assessed in the range between 209 and 940 €/ m^2. The average is 464 €/ m^2 and the median price 473 €/ m^2. In general, in the analyses the prices considered refer to pure biochar sold in bulk, usually in big bags. This choice has been made trying to find uniformity of prices, as in general there is a great variety of products sold in the portfolio of biochar producers. For instance, companies sell premium biochar, enriched with special substances that enhance its properties and make it suitable for many different applications, also at a small scale. Another market covered by many biochar sellers is the one of biochar for feeding purposes, a kind of material that requires even more specific standards and processes. However, even trying to reduce the variability, the price range remains still wide. Indeed, biochar quality, tipology of feedstock employed in its production and quantity sold drastically affect the price of the final product. For future studies it would be interesting to study how biochar quality affects its market value, taking into consideration also the special applications of the material.

In this complex framework, regulatory policies have an important impact. Indeed, if the profitability of biochar systems is not always guaranteed, policies and subsidies can be crucial for the development of production sites. Moreover, all the situation that has been assessed in this research would be totally changed if the European governments decided to introduce carbon credits coming from offsets in the regulatory framework of the Emission Trading Systems. Indeed, biochar would become an even more valuable material, with more and more companies starting to implement biochar production systems. Moreover, more opportunities for carbon insetting would be created for organisations that would employ biochar technology directly inside their supply chain in order to obtain valuable carbon credits. In this view, it would be a matter for future research an assessment of how the environment of biochar producers would change with these introductions.

This research study gives a panoramic view of the European situation of biochar producers. The database shows interesting information that can be used to make for future research, such as biochar producers' contact information. It would be useful to use this information for specific questionnaires and interviews to biochar producers, to assess more precisely the market size and market perspective of biochar on the continent.

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