PYROLYSIS FOR HEAT PRODUCTION

Biochar – the primary byproduct

Mattias Gustafsson

2013

Master’s Thesis in Energy Systems
15 credits

Energy Engineering
Examiner: Taghi Karimipanah (University of Gävle)
Supervisor: Lars Hylander (Swedish University of Agricultural Sciences)
Foreword

I would like to start this report to thank Lotta Ek, EcoTopic AB, for giving me the opportunity to write this report and for your feedback. Taghi Karimipanah, University of Gävle, has been a part in the reference group and a good support around the report’s execution. Lotta Niva, Eskilstuna Energy and Environment, contributed with great knowledge and experience of incineration plants and economics. I have gotten invaluable experience of biochar and its many applications from Lars Hylander, Swedish University of Agricultural Sciences. Thank you Olle Sollenberg, The Federation of Swedish Farmers, LRF, for your knowledge about agriculture and thank you Björn Embrén, Stockholm City, who enabled the study visits and for your commitment to biochar. Thanks to Carbon Terra and Pyreg for sharing practical information on pyrolysis plants, pyrolysis process and the European biochar market. Finally, thanks to Jörgen Björnfot, Eskilstuna Energy and Environment, for your interest in the subject and the ability to work flexibly with this report.

Mattias Gustafsson
2013-07-25
Summary

Pyrolysis is the process where biomass is heated in an environment with low oxygen level forming pyrolysis gas and char. Pyrolysis gas can be combusted to produce heat with low emissions and the char has a multitude of uses: soil improvement, animal feed supplements, filter material, carbon storage, energy source, steel production etc. If certain requirements for the fuel and how the char is used the char certified as biochar. The purpose of this report is to determine if the pyrolysis technology is a sustainable, technical and economical alternative to pellet and wood chip combustion for heat production. The goal is to convey pyrolysis technical and economic conditions, both positive and negative. The report is based on a combination of literature reviews, interviews, plant visits and reference group discussions.

Pyrolysis has been used for thousands of years to produce char. Areas, of a total area larger than the Great Britain, with pitch black soils were discovered in the Amazon. This black soil, terra preta, is enriched with carbon, and has thus become much more fertile than the surrounding native soil. In Sweden char was produced to meet the metal industries’ demand for char as material and fuel. Unlike pellet and wood chip combustion, pyrolysis can use a variety of fuels, as long as they meet the requirements of calorific value and moisture content. The market for biochar is growing particularly in Germany but is still small in Sweden. The suppliers of pyrolysis plants visited in this report, Pyreg and Carbon Terra, develop their plants in order to produce biochar. Pyreg has developed a process with a screw reactor and an integrated pyrolysis gas combustor to be able to use sewage sludge as fuel. Carbon Terra’s process is simple and robust, with a focus to produce large quantities of carbon.

The strengths of the pyrolysis technique are the flexibility to use different types of fuels, low emission, low environmental impact and the different uses of the char. Looking at weaknesses, they are market-related; undeveloped Swedish market and lack of knowledge of how to use biochar. In addition, the pyrolysis facilities have static power output that they are less flexible than pellets and wood chip combustors. At a time when finding solutions on climate change are urgent, carbon storage, using biochar as a soil improver and conversion of pyrolysis gas as a vehicle fuel are great opportunities. However, the existing pellet and wood chip combustion is well established as a heating technology, which could pose a threat to the pyrolysis technology entering the market. The lack of regulation due to shortages of knowledge of pyrolysis may also prevent the establishment of pyrolysis plants.
The conclusion of this report is that pyrolysis is a good alternative to conventional pellet and wood chip combustion if you can manage the static power output and that you realize the value of the char. Heat production from pyrolysis produce lower emissions including CO, NOx and smog particles than pellets and wood chip combustion and biochar used for carbon storage has the possibility of significant global climate impact. The strongest influences on the economic calculation are the cost of fuel and the revenue of the char. The strength of being able to choose different types of fuel makes it possible to have a fuel at zero cost if the material is otherwise regarded as waste. The market for biochar in Sweden is undeveloped which increases the uncertainty of the calculations, but if the trend follows that of Germany, the economic prospects are strong.
Sammanfattning

Pyrolys innebär att exempelvis biobränsle hettas upp i syrefattig miljö för att bilda pyrolysgas och kol. Pyrolysgasen kan brännas för att producera värme med låga utsläpp och kolet har en mängd användningsområden; jordförbättringsmedel, fodertillskott, filtermaterial, kolfastläggning, energibärande, ståltillverkning m.m. Om krav på bränsle och användningsområde för kolet uppfylls kan kolet certifieras som biokol. Syftet med den här rapporten är att utreda om pyrolystekniken är ett hållbart, tekniskt och ekonomiskt alternativ till pellets- och flisförbränning för värmeproduktion. Målet är att förmedla pyrolysteknikens tekniska och ekonomiska förutsättningar, såväl positiva som negativa. Rapporten är baserad på en kombination av litteraturstudier, djupintervjuer, besöker anläggningar och referensgruppsamtal.


# Contents

1  Introduction......................................................................................................................... 8

  1.1  Background...................................................................................................................... 8

  1.2  Purpose........................................................................................................................... 9

  1.3  Objective........................................................................................................................ 9

  1.4  Questions......................................................................................................................... 9

  1.5  Limitations....................................................................................................................... 10

  1.6  Method............................................................................................................................. 10

      1.6.1  Reference group...................................................................................................... 12

  1.7  Glossary........................................................................................................................... 12

2  What is pyrolysis?...................................................................................................................... 14

  2.1  History............................................................................................................................. 14

  2.2  Technology...................................................................................................................... 17

      2.2.1  Operating parameters.............................................................................................. 17

      2.2.2  Different types of pyrolysis..................................................................................... 18

3  Pyrolysis process..................................................................................................................... 20

  3.1  Materials.......................................................................................................................... 20

      3.1.1  Wood material........................................................................................................ 22

      3.1.2  GROT...................................................................................................................... 23

      3.1.3  Straw...................................................................................................................... 23

      3.1.4  Manure................................................................................................................... 24

      3.1.5  Material mixes......................................................................................................... 25

      3.1.6  Pre-treatment......................................................................................................... 25

  3.2  Pyrolysis reaction............................................................................................................... 26

      3.2.1  Process start........................................................................................................... 26

      3.2.2  Reactor................................................................................................................... 26

  3.3  Products............................................................................................................................ 29

      3.3.1  Pyrolysis gas........................................................................................................... 29

      3.3.2  Char...................................................................................................................... 31
3.4 Energy balance ................................................................. 36
3.4.1 Comparison with conventional combustion technologies ........ 37
4 Example plants ........................................................................ 38
4.1 Carbon Terra ........................................................................ 38
  4.1.1 Pre-treatment .................................................................... 39
  4.1.2 Process start ..................................................................... 40
  4.1.3 Reactor ............................................................................ 40
4.2 Pyreg .................................................................................... 41
  4.2.1 Pre-treatment .................................................................... 42
  4.2.2 Process start ..................................................................... 42
  4.2.3 Reactor ............................................................................ 43
5 Environment ............................................................................. 45
  5.1 Locally .................................................................................. 45
    5.1.1 Noise ............................................................................ 45
    5.1.2 Odour ............................................................................ 45
    5.1.3 Aesthetics ...................................................................... 46
    5.1.4 Leakage ......................................................................... 46
    5.1.5 Exhaust gas .................................................................... 46
  5.2 Globally ................................................................................ 47
6 Permission and safety aspects .................................................... 49
  6.1 Combustion ......................................................................... 49
  6.2 Gas production ...................................................................... 50
  6.3 Handling biochar ................................................................. 50
7 Economic analysis ..................................................................... 52
  7.1 Investment cost ..................................................................... 52
  7.2 Operating and maintenance costs ......................................... 52
  7.3 Material cost ........................................................................ 53
  7.4 Personnel cost ....................................................................... 54
  7.5 Comparison euros/kWh .......................................................... 54
7.6 Revenues from pyrolysis gas ................................................................. 55
7.7 Revenues from char ........................................................................ 55
8 Analysis ........................................................................................................ 58
8.1 Strengths ................................................................................................. 58
8.2 Weaknesses ............................................................................................. 59
8.3 Opportunities ........................................................................................... 60
8.4 Threats ....................................................................................................... 60
9 Conclusion .................................................................................................... 61
10 References .................................................................................................. 63
Appendix .......................................................................................................... 69
1 Introduction

1.1 Background

In Sweden, 21% of the total energy demand of 614 TWh was used for heating in the year of 2010 (Energimyndigheten, 2012). How the energy is produced and how it is used is central in Sweden’s environmental efforts. Two of Sweden’s 16 national environmental objectives which this report concern read:

- Reduced carbon footprint – “The concentration of greenhouse gas in the atmosphere in accordance with the UN Framework Convention on Climate Change should be stabilized at a level that would prevent anthropogenic interference with the climate system to be dangerous.”
- Fresh air – “The air must be clean to not damage human health, animals, plants and cultural values.”

(Naturvårdsverket, 2013 A)

Combustion is the most common technology for heating buildings from biomass in Sweden. This technology is used in different scales from a wood boiler dimensioned for a house up to district heating plants supplying entire cities with heating. To be able to produce renewable energy through combustion the fuel has to follow certain requirements. To not harm the combustion plant there are also demands on the quality of the fuel. (Svebio, 2013) Combustion of solid materials causes particle emissions to the air. On larger district heating plants filters removing portions of the particles are demanded while the smaller plants are less regulated. (Gulliksson et al., 2005).

Reducing the amount of carbon dioxide emissions is the focus of individuals, businesses, municipalities and countries (Naturvårdsverket, 2013 A). National plans to lower carbon emissions sometimes include CCS-technology, Carbon Capture and Storage, which in short means that carbon dioxide is pumped into underground caves (Vattenfall, 2013). The CCS-technology is expensive, includes big risks for the local environment and it is difficult to scale up from pilot plants (Zettersten, 2011).

The pyrolysis technology involves heating biomass in an environment restricted of oxygen. This technology has been practiced in thousands of years and in modern time used in kilns which supplied the Swedish blast furnaces until the 1950s. (Lindblad, 2013)
The pyrolysis process produces char and pyrolysis gas which can be combusted to produce heat. (Brownsort, 2009)

The pyrolysis process requires less of the supplied fuel than traditional combustion. Thanks to gas being combusted, problems related to solid fuel such as emissions of chlorine, alkali and particles as well as sintering, are avoided. (Brownsort, 2009) This means that it is possible to use materials that are difficult to combust and that itself is seen as a problem today. One of these materials are horse manure which is a burden to many horse owners because according to Swedish law you need large areas for spreading the manure and you are not allowed to give it away to nearby farmers unregulated because of the risk for contamination. Biomass with less energy content such as straw with low quality or reed has also few areas of use, but they can all be pyrolyzed. (Substrathandbok för biogasproduktion, 2009; Pyreg, 2013)

The char produced in the pyrolysis process has many potential areas of use, one of which is soil improver. If the char is loaded with nutrients and spread on farm land there are significant studies made on the effects of the soil’s increased productivity. In addition, the carbon is stored, so called carbon capture, in the soil and it works the same way as carbon capture and storage. (Lehmann & Joseph, 2009)

1.2 Purpose

The purpose of this report is to investigate if the pyrolysis technique is an environmentally, technically and economically sustainable alternative to pellet and wood chip combustion for heat production.

1.3 Objective

The objective is to spread knowledge about the technical and economic conditions of the pyrolysis technology; positive as well as negative.

1.4 Questions

- What type of materials can be used in a pyrolysis process?
- What alternative areas of use are there for the end products in the pyrolysis process?
- How does the pyrolysis technology measure up to the national emission requirements for local heating plants?
• Which regulations and demands exist on pyrolysis plants today?
• What are the costs and income related to a pyrolysis plant?
• Which are the pyrolysis’ strengths and weaknesses compared to pellet and wood chip combustion?

1.5 Limitations

The thesis limits itself to only include technology and materials approved by "Guidelines for biochar production" written by European Biochar Certificate in 2012. Thereby the torrefication technology and HTC (Hydrothermal Carbonization) are not studied in the report. Furthermore only materials not containing environmentally hazardous chemicals can be used, why only a selection of materials possible to pyrolyze are studied.

Aspects on sustainability, technology and economics are evaluated after Swedish conditions but since extensive experience on pyrolysis is lacking in Sweden other countries are sometimes used as a reference. If this is the case it should be clearly stated in the report.

The solid pyrolysis product will be called biochar when the purpose is to use it as soil improver or feed supplement. Otherwise it is called char.

1.6 Method

Working with this thesis started with gathering a reference group where stakeholders and experts with great relevant experiences were chosen. Literary studies on pyrolysis technology, the pyrolysis end products, environmental aspects, laws and regulations followed. To get a feeling of how the pyrolysis technology is used today and what challenges it meets two visits with suppliers of pyrolysis plants in Germany were made.

Relevant facts and information has then created this report with the following structure:

The report starts with an introduction to the phenomenon pyrolysis in the chapter What is pyrolysis? Definitions of pyrolysis and the technology’s development throughout history are described in the first chapter.

In the chapter The pyrolysis process we follow the process from beginning to end. First we characterize the different materials which can be added to
the pyrolysis plant followed by a general description of the technology. The chemical and physical properties as well as the characteristics of the end products from the pyrolysis process are described. In the last part of the chapter there is an energy balance of the two example plants compared with a pellet and one wood chip combustion plant.

The two pyrolysis plants which were visited and studied for the thesis are described in the chapter Example plants.

The environmental aspects for this type of plant are described on a local and a global level in the chapter Environment. Emissions from the example plant Pyreg are compared to the national regulations established for larger plants. Restrictions on emissions from smaller plants are few.

In the chapter Permission and safety aspects possible classification of pyrolysis plants are compared with traditional technology. Also safety requirements are described.

An economical comparison between the pyrolysis technology and the more traditional combustion technology are made in the chapter Economics. The focus is on the economic aspects concerning heat production but also potential markets for the solid product, char.

In the chapter Analysis a SWOT-analysis, including strengths, weaknesses, opportunities and threats, is described.

Conclusion answers the thesis questions which all together also fulfils the thesis purpose.

This thesis will be presented through this written report and in a seminar to spread the information about the pyrolysis technology.
1.6.1 Reference group

Lars Hylander, researcher, Swedish University of Agricultural Science (SLU)
Lotta Ek, CEO, EcoTopic AB
Lotta Niva, project manager department Heat production Eskilstuna Energy and Environment AB
Olle Sollenberg, head of the The Federation of Swedish Farmers (LRF) in Eskilstuna municipality
Taghi Karimipanah, University lecturer, department Energy technology, University of Gävle

1.7 Glossary

Biochar is defined as char produced through pyrolysis of organic material with the purpose to use the char for agricultural and other non-thermal uses in an environmentally sustainable way. (Schmidt, et al 2012).

CO stands for carbon monoxide which is formed during incomplete combustion and it can affect the cardiovascular system and the brain in a negative way. (Naturvårdsverket, 2005)

Dioxins are a generic name for a group of chlorized organic substances which can be formed from combustion of chlorine containing materials in the presence of the catalyst copper (Naturvårdsverket, 2005). Dioxins are a very stable molecule and it easily travels up the food chain. (Naturvårdsverket, 2010)

Chemical name
B – Boron
Ca – Calcium
K – Potassium
Mg – Magnesium
N – Nitrogen
P – Phosphorus
SO$_4$ – Sulphate
Zn - Zinc
**NOx** is a generic name for nitrogen monoxide (NO) and nitrogen dioxide (NO₂). NOx is formed from the nitrogen in the air and in the material. (Naturvårdsverket, 2005)

**PAH** is a generic name for a group of polycyclic aromatic hydrocarbons. These substances are formed from heating of carbon or hydrocarbons in an environment restricted from oxygen. This is the largest group of carcinogenic substances known today. The PAHs concentrate the higher up the food chain they go and when degrading in the host organism the products can be more dangerous than the original substance. (Naturvårdsverket, 2010)

**SOx** are sulphur compounds created from combustion of sulphurous materials like peat. (Naturvårdsverket, 2005)

**Dust particles** are solid particles like ash (oxides from silicon, cadmium and alkali) and sot (incompletely combusted particles). Dust particles are health hazardous since the particles can enter the airways. (Naturvårdsverket, 2005)
2 What is pyrolysis?

The process where organic material is heated in an environment with restricted access to oxygen is called pyrolysis (Zanzi, 2001). Pyrolysis is a thermo chemical process (Brownsort, 2009), where cellulose and lignin are broken down from long to short carbon structures (Bates, 2010). Pyrolysis gas and char are products in the pyrolysis process, see Figure 2-1. The pyrolysis gas contains bio oil and synthetic gas, which itself contains long carbon structures, methane, hydrogen, carbon monoxide and carbon dioxide. The solid product is called char when the purpose is to use it as an energy carrier. If the char fulfils certain standards concerning material and end use it is called biochar. Approved areas of use for biochar are soil improvement, feed supplement, filter material for water treatment and carbon capture (Lehmann & Joseph, 2009). Biochar is defined as char produced through pyrolysis with the purpose of agricultural use (and other non-thermal applications) in an environmentally friendly and sustainable manor. To get a biochar certification there is also restrictions on the type of material you use in the pyrolysis process. (Schmidt, et al 2012)

2.1 History

The earliest and simplest way known to produce char is by using kilns. A kiln was made by filling pits with biomass, usually wood, or piling the biomass. The pits, called pit kilns, or the piles, called mound kilns, were then covered with a layer of dust to restrict
the inlet of air. (Lehmann & Joseph, 2009) A pit kiln and a mound kiln are illustrated in Figure 2-2.

![Diagram of pit and mound kilns](image)

Figure 2-2 Illustration of two types of kilns; pit kiln and mound kiln. (International Biochar Initiative, 2013)

When the biomass is lit, the pyrolysis process is initiated. These traditional methods to produce char has three stages which can be identified by the colour of the smoke; white smoke during drying of the biomass, yellow smoke during pyrolysis and blue smoke when the process is done. (Lehmann & Joseph, 2009) This technique was used from 8000 years ago to produce a light and efficient energy carrier. The char was among other things used for metal extraction. Kilns were used in Sweden to provide the metal industry with char until the 1950s (Lindblad, 2013).

![Image of kiln](image)

Figure 2-3 A ”Värmlandsmila” (typical kiln from the region Värmland in Sweden) in Brunskog (EcoTopic, 2013)

The char has many other areas of use than energy carrier (Lindblad, 2013). The char can also be used for soil improvement to increase the crop yield. In 1963 a Dutch named Wim Sombroek published his thesis on black soil, so called ”terra preta”, from the Amazon. With the work of Wim Sombroeks these nutritional soils where brought to attention in
modern time. Though the Spanish delegation led by Captain Francisco de Orellana wrote reports on how nutritional the black soils of the Amazon were already in the 1500s. The native people of the Amazon mixed the soil with char, which increased their crop yield and made it possible to feed the growing population (Bates, 2010). When the native moved or expanded their territories they brought the terra preta to the new area to spread the essential microorganisms thriving in the black soil (Jansson, 2009).

Analyses on the black soil in the Amazon show that it contains char up to 10 000 years old. By using satellite pictures one has determined the area with terra preta to be larger than Great Britain (Bates, 2010). Multiple reports on the benefits of the char have been written during the last decade. (Lehmann & Joseph, 2009). The biochar’s effect on crop yield and the characteristic colour of terra preta is shown in Figure 2-4. Today char is often used as energy carrier for cocking in large parts of the world (Schmidt el al., (2012).

Figure 2-4 Terra preta, increased crop yield and colour. (International Biochar Initiative, 2013)

Biochar has been used as soil improvement also in Sweden, especially around the old farms given to soldiers hundreds of years ago. The soils were often bad, why char was added. There is also a tradition of using char as a feed supplement to prevent diseases in animals. (Hylander, 2013)
2.2 **Technology**

Char can be produced by very simple means, for example in kilns described earlier, but modern methods give a more effective use of the added material and the possibility to create special characteristics of the end products. (Schmidt et al., 2012)

2.2.1 Operating parameters

To get the right quality of the end products char and pyrolysis gas, the operating parameters can be adjusted. The operating parameters affecting the pyrolysis process are temperature, mass flow, particle size, pressure and moisture content.

2.2.1.1 Temperature

The top temperature has a direct effect on the carbon production and the char characteristics. Higher temperature gives less char in all types of pyrolysis reactions. With a higher temperature you can imagine that more volatile material is forced out of the biomass and therefore the amounts of char decreases. On the other hand the level of carbon in the char increases. The temperature in the reactor affects the heat transfer rate and the gas flow rate, which are both described in the following chapters. (Brownsort, 2009)

2.2.1.2 Mass flow

The mass flow of material input, char and pyrolysis gas output in the pyrolysis process together with the reactor temperature affect the heat transfer rate (Brownsort, 2009). The heat transfer rate means how quickly heat moves through the material and thereby starts the pyrolysis process in every particle. It is one of the most important parameters and depending on its' value you then choose type of material and mass flow. Depending on the heat transfer rate in each particle you identify two different pyrolysis reactions; slow and fast pyrolysis; which are described in chapter 2.2.2. (Garcia-Perez et al., 2011)

The gas flow rate in the reactor is the speed of which the pyrolysis gas flows out of the pyrolysis plant. The gas flow rate affects the char production. Low gas flow rates give a larger char production and it is preferred in slow pyrolysis while high gas flow rates are preferred in fast pyrolysis. (Brownsort, 2009)

2.2.1.3 Particle size

The size of the particles in the material is adjusted depending on what kind of char you want to produce and it also affects the heat transfer rate in the biomass. Larger particles give more char and small particles give more biooil. (Brownsort, 2009)
2.2.1.4 Pressure

High pressure increases the gas flow rate in and on the surface of the particles, which give a secondary carbonization. The effect is most present with pressures under 0.5 Mpa. The pyrolysis processes which have been pressurized can produce more char. (Lehmann & Joseph, 2009). The production of biooil benefits from vacuum in the process which decreases the amount of char. The reaction is exothermic, submits heat, under high pressures and low mass flows. (Brownsort, 2009)

2.2.1.5 Moisture content

The moisture content in the material can have different effects on the production of char and pyrolysis gas depending on the environment in the reactor. Under pressure the process gives more char if the moisture content is low. In fast pyrolysis you generally need dryer material with a maximum of 10 % moisture content to save the amount of energy needed to dry the material before the pyrolysis starts. Slow pyrolysis is more tolerant to moisture content but again the efficiency of the reactor decreases for high moisture content due to the need for drying the material. (Brownsort, 2009)

The moisture content affects the char’s final characteristics. By regulate the moisture content you can produce active carbon which has specific structural characteristics. (Brownsort, 2009)

2.2.2 Different types of pyrolysis

Depending on how the operating parameters are regulated the pyrolysis technology can be divided into different types; slow, fast, batch, semi batch and continuously.

2.2.2.1 Slow pyrolysis

Slow pyrolysis means that the time it takes to heat up the biomass is relatively long. The heat transfer rate is 5-7 °C/min. Slow pyrolysis gives a larger amount of char, 25-35 weight-%, and a relatively small amount of biooil, 30-50 weight-%. Reactors for slow pyrolysis can handle material with a particle size larger than 2 mm in diameter. (Garcia-Perez et al., 2011) In a slow pyrolysis process you want the steam to have a long retention time in the reactor since it increases the production of char. (Brownsort, 2009)

In traditional kilns the slow pyrolysis method is applied since the focus is on char production. This technique is also used today in modern processes. The development of slow pyrolysis for industrial use started to accelerate during the late 1800s and early 1900s, often in combination with batch of continuous pyrolysis described in chapter
2.2.2.3 and 2.2.2.5. In these more sophisticated processes the biooil can be extracted. During the last part of the 1900s slow pyrolysis kept being developed. (Brown sort, 2009)

2.2.2.2 Fast pyrolysis

The heat transfer rate in fast pyrolysis is over 300 °C/min and therefore requires that the material particles are small, < 2 mm in diameter (Garcia-Perez et al., 2011). This type of process is designed to quickly remove the steam in the reactor and thereby decrease the time when the steam and the material are in contact with each other since that inhibits the heat transfer rate. (Brown sort, 2009) Typical for this type of process is that the sought after end product is biooil (Garcia-Perez et al., 2011). In fast pyrolysis fast heating and fast cooling is preferred to decrease the risk of second hand reactions which increases the amount of char at the expense of the biooil. (Brown sort, 2009)

2.2.2.3 Batch process

The batch process is used foremost when focus is on producing char. In this process the pyrolysis plant is heated, the process initiated followed by cooling the plant when the pyrolysis process is finished. Energy required initiating the process, and therefore also the cost for this process, is greater than in a continuous process in which it can be neglected. More on the energy balance in chapter 3.4. It is still of greatest importance that the pyrolysis gas is combusted to avoid emissions of greenhouse gases to the atmosphere. This type of process is often used in small pyrolysis plants. (Garcia-Perez et al., 2011)

2.2.2.4 Semi batch process

This process is of the same type as the batch process but the plant has more than one reactor which allows it to use the emitted heat energy from one reactor to start another. This way the required energy is decreased. (Garcia-Perez et al., 2011)

2.2.2.5 Continuous process

The continuous process is energy efficient and it gives an even production of the products pyrolysis gas and char (Garcia-Perez et al., 2011). The big benefit is that operating the pyrolysis plant takes very little effort. It is easy to produce heat from the pyrolysis gas and the plant does not need to cool down in order to take in more material. Once the process is started there is no further need to add more energy since the process is exothermic, meaning that it emits heat which in turn drives the process. (Carbon Terra, 2013; Pyreg, 2013)
3 Pyrolysis process

In pyrolysis process biomass is required as a fuel. This biomass, that usually is wood material, has absorbed carbon from the atmosphere during its lifetime. When the biomass is added in the pyrolysis plant a start up energy source is used to initiate the process. Inside the reactor it is close to oxygen free and temperatures reach up to 1000 °C (Schmidt et al., 2012). Under these conditions approx. 50 % of the carbon contained in the biomass is gasified and produces the pyrolysis gas. The remaining amount of carbon is contained in the solid product, the char. (Lehmann & Joseph, 2009) The pyrolysis process is illustrated in Figure 3-1.

![Figure 3-1 Snapshot of the pyrolysis process (EcoTopic, 2013)](image)

3.1 Materials

It is important that the fuel in a pyrolysis process meets the purity requirements for attaining the desired quality of the end products (Bates, 2010). This report covers the fuels that meet the requirements for certification of biochar although of course it is possible to pyrolyze all types of organic materials.

Listed below are some of the key requirements the European Biochar Certificate sets on the fuel to be able to classify the produced char as biochar.
Only organic material is allowed to be used for biochar production. All materials that contain inorganic compounds such as e.g. plastics, rubber and metal have to be removed from the fuel before pyrolyzing.

The organic material has to be untreated with e.g. paint and impregnation.

PAH (Polycyclic aromatic hydrocarbons) may contain maximum 12 mg/kg.

PCB (Polychlorinated biphenyls) has to be below 20 ng/kg.

When using agricultural waste as fuel is important so guarantee that this waste has been cultivated in a sustainable manner.

Wood chips from forestry must come from forests that are sustainable produced, e.g. according to certificate organizations; PEFC (Program for the Endorsement of Forest Certification schemes) or FSC, (Forest Stewardship Council).

Traceability of the fuel is important.

The amount of heavy metals in the fuel is also regulated but since the biochar has an ability to bind certain heavy metals the requirements differ greatly. For more detailed requirements see Appendix. (Schmidt et al., 2012)

Generally the biomass is composed of three main groups of natural polymeric materials such as cellulose, hemicellulose and lignin. The biomass also contains some minerals and other minor organic molecules and polymers. The composition of these polymers and minerals varies from different types of biomass and affects the pyrolysis process and its products. The minerals in the biomass, especially alkali metals, can have a catalytic effect on the pyrolysis reaction but increasing the char yield. The composition of different types of biomass varies including due factors such as when and where the biomass is grown, climatic conditions, soil type and cultivation practice. The carbon content may vary in the same type of biomass by as much as 10 % which in turn controls the biomass calorific value. The coal has a calorific value of about 35 MJ/kg. (Brownsort, 2009; Lehmann & Joseph, 2009)

Examples of fuel pyrolyzed successfully and meet the requirements for biochar is among others:

- Garden waste
- Untreated textile
- Paper fibres
- Plant based packaging materials such as cotton or tree fibres
- Bio-manure from biogas plants
- Slaughterhouse waste such as bones, feathers, skins, etc.
- Plants growing in water

(Schmidt et al., 2012)

Solid materials keep its shape when pyrolyzed even in charred condition while materials with higher moisture content will become a fine granulate. In Figure 3-2 an example is visualized with different types of pyrolyzed materials and what bricked char can look like. (Pyreg, 2013) Sewage sludge is not automatically an approved material for biochar production (Schmidt et al., 2012).

![Figure 3-2 Example of different charred materials](EcoTopic, 2013)

The following addresses some types of materials for pyrolysis process.

### 3.1.1 Wood material

According to Swedish standard SS 187106 concerning wood fuel the following definition is given:

"**Wood fuel** biofuel from wood raw material which has not undergone a chemical process. Wood fuel includes all biofuels with trees or parts of trees, such as bark, pine, needles, leaves, wood products industry, e.g. shavings, wood chips, sawdust, etc. Fuel from waste paper and waste liquors is not included" (Strömberg, 2005)
Different types of wood fuels have different moisture content but generally it is approx. 50%. The calorific value varies between 16 MJ/kg and 18 MJ/kg when calculated on dry and ash less material. Ash content is between 0.4 and 0.6 weight-% DS (Dry Substance). (Strömberg, 2005)

To increase the calorific value in sawdust, it is today common to produce pellets. In the manufacture of pellets the material is grinded before it is pressed into pellets. To increase the strength of the pellets steam or other binders such as starch or lignosulphate is used. When using starch as a binder the ash content is increased and sometimes also the sulphur content. (Strömberg, 2005)

3.1.2 GROT

According to Swedish standard SS 187106 more than one definition can be found of GROT:

"fuel from biomass originated from logging activities consisting of branches, tops and small trees from logging where even industrial wood is included cf. logging fuel. Logging fuel can be extracted in both final logging and thinning. The acronym GROT stands for logging fuel from branches and tops (Swedish GRenar Och Toppar). Logging fuel is fuel from the final stages of logging activities. Forrest fuel is tree fuel where the material has not had a previous use. Forrest fuel can for example consist of fuel from logging, from sawmills and from the paper industry. Wood fuel from tearing down houses is not included." (Strömberg, 2005)

The calorific value in GROT is between 19 MJ/kg och 21 MJ/kg in dry and ash less material. The ash content is between 1 och 5 weight-% DS. GROT has normally a moisture contents between 40 och 50 weight-%. Important to note is that GROT is voluminous fuel which can increase the transportation costs with untreated GROT. (Strömberg, 2005)

3.1.3 Straw

Straw has a calorific value of, approx. 19 MJ/kg in dry and ash less material. This leads to a greater transport cost then for a more energy dense material. When storing chopped straw in stack on the farm fields the moisture content will in average be approx. 25%. The ash content is between 4 och 10 weight-% DS. To store straw it is important that the straw is dry while harvesting otherwise there is a risk for auto-ignition. (Strömberg, 2005)
Straw contains high levels of alkali metals and chlorine. When straw is pyrolyzed it is important that most of the alkali and the chlorine remains in the char and not follows the pyrolysis gas to the combustion chamber. If the alkali metals and chlorine is combusted increases the risk for high temperature corrosion. This is a major challenge when straw is used as a fuel in a combustion process. By keeping a low temperature and thus low heating transfer rate the chlorine and alkali metals will be bond in the char. (Bernesson & Nilsson 2005) There are major differences in potassium content between various grains; oat and barley straw contain six times as much potassium as wheat straw. The content of chlorine and potassium can be substantially reduced if the straw is stored outdoors and the same effect can be obtained by washing the straw at 50-60 °C. Co-combustion with other types of materials can also solve some technical combustion problems. (Strömberg, 2005)

In batch pyrolysis processes, as described in chapter Fel! Hittar inte referenskälla., it may be necessary to pack materials with low , such as straw, to pellets och briquettes before the pyrolysis. If the materials with low density not is packed the risk increases that the material is combusted instead of charred. (Kihlberg et al., 2013 C) The visited pyrolysis plant constructors mean that in their continuous processes straw can be used in the pyrolysis process, but it can be advantageously mixed with wood chips, pelletized or the retention time can be increased by increasing the mass flow rate. (Carbon Terra, 2013; Pyreg, 2013)

3.1.4 Manure

With manure usually means animal wastes including litter, which often consists of paper, peat or sawdust. Manure is covered by the ban on landfilling of organic matter, which came into force in 2005 in Sweden. The manure also has to undergo some form of treatment. (Strömberg, 2005) Many farms, especially horse farms, have too little land for spreading their manure on. If the manure is used on more than three farms is has to be hygienized to lower the infection risk, which is a subject in the ABP regulations. (Substrathandbok för biogasproduktion, 2009)

Solid manure as a material in the pyrolysis process can be seen as equal to straw, because straw is one of the most common bedding materials in stables. However, it is important to control the moisture content of the manure. If the moisture content is too high the manure should be dried or mixed with drier material before pyrolyzing. (Carbon Terra, 2013; Pyreg, 2013)
When combusting manure a mix with other types of materials such as wood chips is recommended. Otherwise there is a risk for both sintering and corrosion since the manure often have a high moisture, sulphur and chloride content. Depending on which type of bedding is being used it can also contain high quantities of alkali metals. Manure differs depending on different animal species and also on how the livestock is stabled. Generally, the fresh manure contains high levels of moisture and ash. (Strömberg, 2005)

Depending on which manure fractions that are used and how fresh it is, the moisture content will vary. Usually, horse manure mixed with bedding material has a DS-content of 30-50% (Substrathandbok för biogasproduktion, 2009) and an ash content of 15-42 weight-% DS. Calorific value is between 19 and 21 MJ/kg DS and free of ash. (Strömberg, 2005)

3.1.5 Material mixes

Thanks to the possibility to use different types of materials the biomass properties can be regulated by mixing different fuels. High moisture content can then be regulated by mixing very dry materials etc. (Carbon Terra, 2013; Pyreg, 2013) In Table 3-1 the calorific value is shown in kWh/kg (1 MJ = 0.28 kWh) together with the moisture content and ash content for the above mentioned materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Moisture (wt-%)</th>
<th>Calorific value (kWh/kg)</th>
<th>Ash (wt-% DS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood chips</td>
<td>50</td>
<td>4.5-5.0</td>
<td>0.4-0.6</td>
</tr>
<tr>
<td>GROT</td>
<td>40-50</td>
<td>5.6</td>
<td>1-5</td>
</tr>
<tr>
<td>Straw</td>
<td>25</td>
<td>5.3</td>
<td>4-10</td>
</tr>
<tr>
<td>Manure</td>
<td>4-92</td>
<td>5.6</td>
<td>15-42</td>
</tr>
</tbody>
</table>

Through mixing different types of materials the desired properties and quality of the biomass for the pyrolysis process can be obtained (Carbon Terra, 2013; Pyreg, 2013).

3.1.6 Pre-treatment

To meet the requirements for the biomass on moisture content, particle size and purity it may need to be pre-treated. The most common methods are drying, shredding and sorting.
3.1.6.1 Drying

To increase the efficiency and obtain a better process, drying the material might be necessary. There are different ways of drying a material e.g. let it dry in a stack outdoors or by using heat. If focus is on char production and there is no deposition for the produced heat from the combusted pyrolysis gas then advantageously the heat can be used for drying the materials with to high moisture content. (Carbon Terra, 2013; Pyreg, 2013)

3.1.6.2 Shredding

As previously mentioned the need of pre-treatment depends on which type of process that should be used. The heat transfer rate is strongly affected by the particle size of the material. To get the right particle size at the material and right can shredding or pelleting be necessary. (Carbon Terra, 2013; Pyreg, 2013)

3.1.6.3 Sorting

If the material is polluted with stones, metal or other loose objects they should be removed before the material is fed into the plant to eliminate the risk of damaging the plant and polluting the final products. (Carbon Terra, 2013; Pyreg, 2013)

3.2 Pyrolysis reaction

This section deals with the chemical reactions occurring in the pyrolysis reactor, what requirements this puts on the construction of the plant and which functions that are built in. Initially the start-up of the pyrolysis process is described.

3.2.1 Process start

The process must be started with some form of external energy. Today usually liquefied petroleum gas (LPG) or electricity is used (Carbon Terra, 2013; Pyreg, 2013) although the start energy according to the certification system for biochar, European Biochar Certificate, shall be limited to fossil free fuels (Schmidt et al., 2012). Once the process is started there is no further need to add more energy since the process is exothermic, meaning that it emits heat which in turn drives the process. This means that the process generates heat and continues as long as new material is added. (Brownsort, 2009)

3.2.2 Reactor

The reactor is the heart of the pyrolysis process. This is where the reaction takes place, where biomass is pyrolyzed to pyrolysis gas and char.
3.2.2.1 Function

In the reactor there are high temperatures, up to 1000 °C. The temperature must not fluctuate more than 20 % of the intended reactor temperature because it can have effects on the quality of the char. One of the primary functions is to ensure a low oxygen supply at < 2 %. (Schmidt et al., 2012)

If the fuel has low , there is a risk of the material being combusted instead of pyrolyzed. Pyreg, which is one of the two suppliers of pyrolysis plants studied in this report, has solved this by running the material faster through the plant. This reduces the retention time in the reactor and thus the risk of the material burning up instead of being charred. (Pyreg, 2013)

3.2.2.2 Construction

Depending on the chosen process requires focus on different parts and materials in the reactor. An important parameter is the selection of material in the reactor because very high temperatures are used. (Schmidt et al., 2012; Carbon Terra, 2013; Pyreg, 2013)

Since it is hard to maintain an even temperature in lager reactors the studied plants cannot easily be scaled up. The solution is to link more devices together so that the effect is increased. (Carbon Terra, 2013; Pyreg, 2013)

For slow pyrolysis processes generally horizontal reactors are used where the biomass is moved forward with controlled pace. A plant with horizontal reactor is described in chapter 4.2. Examples of different types of horizontal reactors are drum kiln, rotary kilns and screw pyrolyzers. (Brownsort, 2009) Development of vertical reactors with similar functions is on-going and described more in chapter 4.1.

For fast pyrolysis processes there are different types of reactors such as fluidized bed (Brownsort, 2009). In fluidized bed reactors more inert material (e.g. sand) is used as bed material and through pressuring liquid or gas through the bed it will start to move (Bioenergiportalen, 2013).

3.2.2.3 Chemical processes

The first reaction in the reactor is water evaporating from the biomass. Fibrous biomass contains mainly cellulose, hemicellulose and lignin (Lehmann & Joseph, 2009), but also a certain amount of extractives (Brownsort, 2009). Extractive substances are found particularly in cellulose pulp and consist of compounds which are soluble in petroleum ether, diethyl ether, dichloromethane, acetone, ethanol and water (Utbildningsstyrelsen,
Lipids, terpenoids, phenols, glycosides, small molecule carbon hydrates, pectin, starch and protein compounds belong to extractives (Utbildningsstyrelsen, 2013). The composition of cellulose, hemicellulose and lignin varies from different types of biomass but also the same type of biomass that have sprung up in different soil types in different climatic zones and harvested at different times of the year. Cellulose, hemicellulose and lignin behave in differently at different heating rates and temperatures. Hemicellulose will decompose first, which will occur between 220 and 315 °C. The cellulose begins its decomposition at 315 °C and continues until 400 °C. Lignin has a slow but stable decomposition process that occurs already at 160 °C and up to 900 °C. (Lehmann & Joseph, 2009) The minerals will generally stay in the char but is then called for ashes (Brownsort, 2009). The process is illustrated in Figure 3-3.

![Figure 3-3 Change in the biomass composition during pyrolysis (Inspired of Brownsort, 2009)](image)

In case of metals, the metals in the biomass will stay in the char but in higher concentration than in the original biomass. The metals will be bound in the char and thereby locking them in for a long period of time. (Schmidt et al., 2012) How long the heavy metals will be stored in the char is not yet known (Schmidt et al., 2012), but the estimated half-life of the char is about 6000 years (Lehman & Joseph, 2009).
3.3 Products

From a pyrolysis plant biomass is divided to two different products; pyrolysis gas and char. The carbon content of the biomass is generally distributed similar between the two products, that is, close to 50-50. (Brownsort, 2009)

3.3.1 Pyrolysis gas

The pyrolysis gas is a mixture of synthesis gas and biooil. Below these are described chemically, their properties and uses.

3.3.1.1 Chemical

Synthesis gas

The normal mixture of gases in the synthesis gas is:

- CO\textsubscript{2} (carbon dioxide) – 9 to 55 volume-%
- CO (carbon monoxide) – 16 to 51 volume-%
- H\textsubscript{2} (hydrogen gas) – 2 to 43 volume-%
- CH\textsubscript{4} (methane) – 4 to 11 volume-%
- Low amount of N\textsubscript{2} (Nitrous gas)
- Low amount of other hydrocarbons

(Brownsort, 2009)

CO\textsubscript{2} and N\textsubscript{2} have no heating value when combusted and therefore they affect the synthesis gas energy content negatively. (Brownsort, 2009)

Biooil

The liquid part in the pyrolysis gas is called biooil and consists of long hydrocarbon chains. Biooil contains between 45 % and 50 % oxygen which is primarily bound in water. In the biooil more than 300 different compounds has been identified that also varies depending on the type of biomass and process. (Ringer et al., 2006)

3.3.1.2 Properties

The pyrolysis gas is an energy carrier in high temperatures where the synthesis gas and biooil not has been separated. It is combustible and has a high energy value. Biooil is in gaseous form until the pyrolysis gas is cooled. (Bojler Görling, 2012)
**Synthesis gas**
The properties of the synthesis gas vary depending on which process is being used. They also depend on the distribution between the different gases. However, it can be mentioned that the gas is flammable and contains carbon monoxide, which is a health hazard. (Brownsort, 2009)

**Biooil**
The viscosity of the biooil increases with time and during storage it changes from liquid to solid in just a few weeks. However, various additives such as methanol can be mixed in to reduce the risk of the biooil solidifying. During storage, biooil can also stratify and give water phase, wax and tar. To avoid the problems of storage, recommends that the biooil is combusted directly together with the synthesis gas. (Ringer et al., 2006)

3.3.1.3 Area of use

Pyrolysis gas can be combusted and then produce heat. By using a turbine or Sterling engine electricity can also be produced. Although production of methane is possible from pyrolysis gas if first the long hydrocarbon chains are broken down into \( \text{CH}_4, \text{CO}_2, \text{CO} \) and \( \text{H}_2 \) (Bojler Görling, 2012). If the pyrolysis gas is divided into synthesis gas and biooil each product may be used as described below.

**Synthesis gas**
The synthesis gas can be combusted to produce electricity and heat. It is also possible to upgrade the synthesis gas to produce fuels such as biomethane, DME (dimethyl ether) or methanol. (Bojler Görling, 2012)

**Biooil**
Biooil has a high and can therefore be transported cost effectively. Biooil has similar properties to fossil oil but only half of the calorific value. Despite this, the industry sees it difficult to convert their applications to biooil. The main issues is that the biooil is inhomogeneous, aging rapidly and has high viscosity. The viscosity and aging can be handled by mixing it with methanol. According to this the industry is looking into upgrade the biooil to hydrogen which has a higher quality and higher . Even methanol, Fischer-Tropsch diesel and gasoline are products that biooil can be converted to. (Bojler Görling, 2012)
3.3.2 Char

The solid product, char, is described below chemically, its properties and uses.

3.3.2.1 Chemically

The solid product contains between 60 and 90 % carbon (Brownsort, 2009). Some carbon is fixed and some is volatile. The inorganic material in the char is called ash which consists of different mineral compounds (Lehmann, Joseph 2009). If the char is produced from wood material it contains approx. 6.8 g phosphorus per kg char (Lehmann & Joseph, 2009). Nutrients will bind to the char and only approx. 15 % of the phosphorus is soluble. Most of the nitrogen will end up in the pyrolysis gas in the process and only 1 % will be accessible in the char. For potassium the accessibility is about 50 %. (Schmidt et al., 2012) The level of carcinogenic chemical compounds, PAH, in char with sewage sludge as fuel is far below the threshold in biochar certification, 0.66 mg/kg compared to <12 mg/kg. (Pyreg, 2013)

3.3.2.2 Properties

The carbon atoms in the char are strongly bound to each other like graphite. Different types of biomass produce various strong bounds to each other. Scientists have shown that the half-life of biochar is about 6 000 years. The half-life depends on the choice of biomass, the soil quality, the temperature in the soil and the size of the biochar. The density of char is approx. 2 g/cm$^3$. (Lehmann & Joseph, 2009)

The char is full of microscopic holes; see Figure 3-4, that among other things absorb moisture and nutrients throughout their lifetime (Lehmann & Joseph, 2009). When adding the char to the soil the char has an adsorbing effect of nutrients, moisture which creates a favourable environment for microorganisms (Bruges 2009). Because of the cavities in the biochar and the increased amount of microorganisms, the presence of oxygen in the soil increases. In turn this decreases the formation of greenhouse gases such as methane and nitrous oxide. (Van Zwieten et al., 2008) Generally, one gram of char has an inner surface area of 500 m$^2$ (Bruges, 2009), and this can be affected by adjusting the operating parameter (Pyreg, 2013).
Ash

The amount of ash in the char depends on the ash content, the amount of minerals, in the pyrolyzed biomass. The minerals can plug the pores or fix to the surface of the char reducing the surface area slightly. (Lehmann & Joseph, 2009)

3.3.2.3 Areas of use

The char has many possible areas of use and below we discuss a few examples.

Soil conditioner

A statistical study on biochar as soil conditioner in farmland, with 16 different reports and 177 different experiments, has been carried out by Edinburgh University. The study shows that an increase in yield output is tangible and that the results depend on type of crop and type of soil. E.g. soils with low or neutral pH give a high percentage increase of the productivity. (Jeffery et al., 2012)

The Swedish University of Agricultural Science, SLU, has done two different projects on the effect of biochar on cereal production in Sweden. One project studied the production on a field where a kiln had produced charcoal between 1920 and 1945 and the second
project meant adding biochar to the soil at three sites in the region Småland in Sweden. (Kihlberg et al., 2013 A; Kihlberg et al., 2013 B)

Some of the parameters that affected the results in the first project at the old kiln were:

- The concentration of biochar was 1000 tons/hectare.
- The moisture content was 150 % higher than the surrounding land.
- The soil had 2-10 times higher levels of easily soluble nutrients such as, P, K, SO₄, B, Ca, Mg and Zn. The nutrients origin could not be proven with certainty, but what can be said are that the nutrients bound in the soil for a long period of time if it contains biochar.
- 32 % higher yield was documented in the cereal production in a year with low precipitation (insufficient rainfall) during the growing season. (Kihlberg et al., 2013 A)

The project with three sites in the Swedish region Småland, showed that with an addition of 10 tons/hectare of biochar the yield increased with 6 % the first year and no increase was detected year two. With 20 tons/hectare no significant increase of yield was detected the first year but the second year the yield increased with 12 %. (Kihlberg et al., 2013 B)

Trials were also made to allow the biochar to absorb the NPP (nitrogen, phosphorus and potassium) before adding it into the soil. The study was done with 10 tons/hectare, which gave an increase of the yield by16 % year one and 14 % year two. To apply biochar and NPP (Nitrogen, Phosphorus, Potassium) alone gave the first year, a 15 % increase in the second year no significant different was detected. (Kihlberg et al., 2013 B)

The main benefits of biochar as a soil conditioner are:

- The humus content increases. (Bates, 2010)
- The soil environment favours microorganisms such as mycorrhizae, bacteria, protozoa. (Bates, 2010) See Figure 3-5.
- The soil loosens up which increases the supply of oxygen further down in the soil. This benefits the microorganisms and plant roots to absorb nutrients. (Bates, 2010)
- Biochar is added in the soil a few times until desired amount is reached which saves the farmer a time consuming activity. (Lehmann & Joseph, 2009)
- The land drainage is improved. (Bruges, 2009)
• Nutrient leaching from agricultural land decreases because the biochar adsorbs and binds it into the soil. (Kihlberg et al., 2013 A)

• The emissions of methane decreases from the soil. Methane is 25 times worse greenhouse gas than carbon dioxide in a 100 year period of time but over the first 20 years methane is 72 times worse. However, methane has a shorter half-live in the atmosphere then carbon dioxide. (Bruges, 2009)

• pH in acidic soils can be increased because biochar is relatively basic. (Schmidt et al., 2012)

Figure 3-5 Mycorrhizae growing on biochar and into its holes (Cornell University, 2013).

It is important to mention that biochar breaks down slowly and therefore has a low fertilizing effect. Therefore it is important that biochar is mixed with nutrients, such as manure or compost before adding into the soil. Otherwise there is a risk that the biochar adsorbs existing nutrients in the soil. (Bruges, 2009)

One of today´s largest challenges for the agriculture is soil structure of the farmland. Mainly it is about how to increase the humus content, oxygen concentration in the soil, permeability of the soil, reduce soil compaction and reduce surface leakage of nutrients. Additionally, a method to solve these challenges must be easy to apply. (Sollenberg, 2013)

**Carbon storage**

The efforts to reduce the world´s carbon dioxide emissions and reduce the amount of carbon dioxide that already exists in the atmosphere are on-going (Zettersten, 2011). Sweden has so far focused on the controversial method of carbon capture and storage,
CCS, (Zettersten, 2011) which means that carbon dioxide is pumped down and trapped in rooms in the ground (Vattenfall, 2013).

Since between 60 % and 90 % of the carbon the plant has absorbed during its lifetime comes from atmospheric carbon dioxide (Brownsort, 2009) and the half-life for the biochar is estimated to approx. 6 000 years the biochar has great potential as carbon capture method (Lehmann & Joseph, 2009). Research on biochar as carbon storage method is on-going (Bates, 2010), but so far, the method is completely unknown to the responsible authorities in Sweden (Gunnarsson, 2013). 1 ton C = 3.7 ton CO₂ (Bruges, 2009)

**Increased biogas production**

When 5 weight-% char was added to the digester for biogas production with cow manure as substrate the methane production increased by 17 - 35 %. The reason is that the microorganisms in the digester have a larger surface to sit on and thereby the amount of bacteria increases. (Kumar et al., 1986)

**Feed supplements**

Carbon Terra, which is one of two visited suppliers of pyrolysis plants, is focusing on the market with biochar as a feed supplement. Research shows that adding 20 g/day of biochar to young livestock (80-100 kg) increased their growth during the study period of 21 days with 25 % and simultaneously reduced methane emissions from the animals by 22 % (Leng et al., not dated). Also, other studies demonstrate a reduced methane production by using biochar as feed supplement to ruminants by 10 % when adding 1 weight-% of biochar in the feed. (Inthapanya et al., 2012)

**Filter material**

Generally, one gram char has an area surface of 500 m² (Bruges, 2009) and can be used in the same manner as activated carbon. The surface area depends on the process and type of biomass. Carbon Terra’s biochar has a surface area of approx. 400 m²/gram biochar and Pyreg’s biochar has a surface area of 600 m²/gram. Activated carbon has a surface area between 800 m² and 1500 m² (Chemviron Carbon, 2013) and therefore one should probably use a greater amount of biochar to achieve the same effects (Carbon Terra, 2013). A study from SLU demonstrates that biochar is very good for greywater (water from bath, showers and washing) treatment in comparison with activated carbon (Berger, 2012). Activated carbon is charcoal or coal that has undergone an expansion process of
the pores to increase the absorbency. Activated carbon is used to purify water and air pollutions. (Chemviron Carbon, 2013)

**Energy carrier**
To use char as an energy carrier is still common around the world. The calorific value is approx. 35 MJ/kg which is equivalent to 9.7 kWh/kg. This means that the fuel has a high calorific value and can thus be transported longer distances than e.g. wood chips from an economic point of view. (Brownsort, 2009)

**Metal industry**
Metal and steel industry examines biochar as production materials to reduce their costs since the price of fossil carbon is increasing and the taxes on the emissions of fossil carbon increase. (Schulten et al., 2013)

### 3.4 Energy balance

The energy balance in a reactor depends on the demanded quality of the end products. The energy balance will differ depending on if focus is to produce char, synthetic gas or biooil.

![Figure 3-6 Schematic illustration of the visited pyrolysis plants energy balance (EcoTopic, 2013)](image)

In Figure 3-6 a schematic illustration of the energy balance of the visited biochar plants is shown. Input is 100 % of the potential energy. Starting the process requires an external energy source called start up energy. In a continuous process this energy is negligible. Generally it is stated that the input energy is distributed in the final products as follows: ⅓ pyrolysis gas and ⅓ char. The total efficiency is between 90 % and 95 % in the visited pyrolysis plants. Table 3-2 shows the energy balance specifically for the visited pyrolysis plants. These plants have different power capacities. (Carbon Terra, 2013; Pyreg, 2013)
Tab 3.2 Energy balance for biochar plants (Pyreg, 2013; Carbon Terra, 2013)

<table>
<thead>
<tr>
<th></th>
<th>Pyreg</th>
<th>Carbon Terra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass (kW)</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>External energy (kW)</td>
<td>~0</td>
<td>~0</td>
</tr>
<tr>
<td>Char (kW)</td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td>Pyrolysis gas (kW)</td>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>90-95</td>
<td>90-95</td>
</tr>
</tbody>
</table>

3.4.1 Comparison with conventional combustion technologies

Conventional combustion plants are more flexible concerning power input than the pyrolysis plants described in this report (Pyreg, 2013; Carbon Terra, 2013). In Pyreg’s and Carbon Terra’s plants the power input is fixed at 500 kW respectively 1000 kW (Pyreg, 2013; Carbon Terra, 2013), whereas a pellet plant and a wood chip combustion plant can be adjusted within a certain range (Lövgren, 2013).

The two most common combustion plants are designed for either wet unrefined fuels such as firewood or dried and in other ways pre-treated fuels such as pellets. One of the main strengths for the pyrolysis plant is the wide range of different fuels that can be used, which is positive from an environmental and economic point of view. (Pyreg, 2013; Carbon Terra, 2013)

Table 3-3 illustrates the energy balance for a pellet plant and wood chip plant. The efficiencies vary with input power. Lower input power results in lower efficiency.

Table 3-3 Energy balance for pellet plant and wood chip plant (Lövgren, 2013)

<table>
<thead>
<tr>
<th></th>
<th>Pellet</th>
<th>Wood chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass (kW)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Start up energy (kW)</td>
<td>~0</td>
<td>~0</td>
</tr>
<tr>
<td>Heat (kW)</td>
<td>458</td>
<td>425</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>91-92</td>
<td>82-88</td>
</tr>
</tbody>
</table>

From biomass combustion plants the ash can be seen as a resource since it thanks to its high mineral content can be recycled back to the forest. The ash is then seen as a revitalizing product, but before recycling the quality of the ash has to be controlled. If other fuels than woodchips or pellets are combusted the ashes are considered waste and a cost of disposal will be added. (Gulliksson et al., 2005)
4 Example plants

In this section the visited plants, Pyreg och Carbon Terra, are described.

4.1 Carbon Terra

Almost 10 years ago Dr. Berndt Schuttdorff started to develop the pyrolysis process illustrated in Figure 4-1. Carbon Terra focuses on large scale biochar production to give great effects. Today there is a plant with three reactors in Duttenstein in southern Germany, which mainly is used for process development. The plant was built in 2004 but has been upgraded a number of times throughout the years. Carbon Terra also has two plants in Romania where one plant has 36 reactors and the other has three reactors. Carbon Terra collaborates with a partner in Stuttgart who is manufacturing the plants. Unless otherwise indicated in the following chapter the source is (Carbon Terra, 2013).

Figure 4-1 Carbon Terra's pyrolysis process (Carbon Terra, 2013A)
The test facility in Duttenstein, Figure 4-2, uses mostly wood chips as fuel and produces biochar mainly to farmers who use it as feed supplement. The market as a soil conditioner for gardening is also growing strongly.

The reactors and possibly the storage for fuel take up most space. A plant with three reactors and a small fuel depot requires an area of about 200 m$^2$. The plant is shown in the picture below.

![Carbon Terra test plant in Duttenstein, Germany (EcoTopic, 2013)](image)

4.1.1 Pre-treatment

To use the biochar as a feed supplement it is required that the biomass is cleaned from impurities. Carbon Terra’s facility has an outlet for the biochar which is only about 50 mm in diameter, and therefore it is important to remove metals, stones and other large pollutants so that the holes will not clog. Metals can also form layers on the inside of the reactor.
Biomass with high moisture content should be dried or mixed with drier biomass before pyrolyzing. For the process to work optimally the moisture content should be maximum approx. 30 % but it is possible to use materials that have moisture content of up to 50 %.

Biomass with low calorific value should be mixed with biomass with high calorific value e.g. wood chips. One example is to mix ¼ horse manure with ¾ wood chips. Another way to handle biomass with low calorific value is to make pellets before adding it to the process. The same goes for the fine materials such as sawdust which can ”suffocate” the process because it prevents the pyrolysis gas from going up through the reactor. There is also a risk that the fine material will combust and turn into ashes. The optimum size of the biomass is 60 mm.

4.1.2 Process start

The process is started by lighting the biomass in the bottom of the reactor. Different techniques have been tested such as electricity rods and LPG torch.

4.1.3 Reactor

The capacity of the reactor is 1 MW input of biomass. The energy output for the products will be 300 kW pyrolysis gas and 600 kW biochar, which is equivalent to about 600 tons of char per year. The efficiency is between 90 and 95 %. The process operates under 800-900 °C. Today the pyrolysis gas is combusted in approx. 1200 °C. It is a continuous process and it has been tested to run around the clock for one year without complications. However, it is recommended to run the reactor for 3-6 month and after that go through the plant. The cooling of the plant takes approx. 2-3 days, maintenance approx. 2-3 days and 2-3 days to get an optimal process again with an even flow. In start-up phase, it is important that the biomass at the bottom of the reactor is dry. At the bottom of the reactor, in the char outlet, there is a filter with 50 mm large holes which the char passes through.

The char mass flow out from the reactor is constant. The char has to be cooled down and it is done by running it through a screw while sprinkling it with water. 20 weight-% water is used of which 10 % of the water will evaporate directly, 5 % is evaporated later and 5 % stays in the biochar. There is a risk that some chars keep glowing and hence, in worst case could ignite a char depot or turn the char around them to ashes. Therefore, the handling and control of the char is important. The heat in the biochar when it comes out
of the process is not worth taking care of because it only represents 1-2% of the total energy. The biochar will contain approx. 60% of the input power.

The produced pyrolysis gas will pass through the biomass to the top of the reactor and then out to a combustion chamber. The long carbon chains in the biooil are trapped in the biomass and will successively be broken down to shorter chains. When the carbon chains are small enough they travel in the pyrolysis gas up through the biomass and into the combustion chamber. The pyrolysis gas consists of 80% hydrogen and the rest is nitrogen, water, carbon dioxide, methane, carbon monoxide and hydrocarbons. When the gas is combusted the exhausted gas contains mainly carbon dioxide and water. (Carbon Terra, 2013)

4.2 Pyreg

In 2004 Helmut Gerber started the company Pyreg to find a solution to the problem of treating sewage sludge in an environmentally friendly manner. Specific requirements on sewage sludge are demanded if it should be used as biochar. He concluded that pyrolysis was a good solution and developed the current process. In 2008, a film about the process was made by BBC which took Pyreg from the academic world to the market. In Figure 4-3 is Pyreg’s process is illustrated. The pyrolysis gas is combusted directly and the exhausted gas heats up the process, continues into a heat exchanger and at last travels out through the chimney. Unless otherwise indicated in the following chapter the source is (Pyreg, 2013).

Figure 4-3 Pyreg’s pyrolysis process (Pyreg, 2013A)
The plant can use a variety of different types of biomass such as wood based fuels, straw, slaughter waste and of course sewage sludge. Today Pyreg has sold three plants to Lausanne and Zürich in Switzerland and Riedlingsdorf in Austria. The plant that they have in Dörth outside of Frankfurt in Germany is mainly used for research on the process and to test different types of fuels. The plant has focuses on biochar production but it also produces heat. All the plants are connected online so that they can service them from Germany. Pyreg is also doing research to, in a near future, produce electricity.

4.2.1 Pre-treatment

The size of the material can be maximum 30 mm because otherwise there is a risk that it will get stuck in the screw that takes the material through the reactor. With larger particles the charring process also takes longer time. Pyreg do not see any obstacles to using biomass with high quantities of plastics or chemicals. Because of the high temperatures in the reactor many of the large molecules will be broken down, making the chemicals to lose their original function. Stones in the material usually “float” on the other material and will therefore no be in contact with the machinery to damage it. However, it can tear on the screw, why it should be removed if possible. When Pyreg tested park waste as fuel metal parts from bicycles were accidentally added into the reactor which tore on the screw.

The calorific value of the biomass should at least be 10 MJ/kg but should at the same time not be too high because it will increase the temperature in the reactor. Too high temperature can affect the material of the reactor and cause the reactor to bend. One example of biomass with high calorific value is olive waste. Fuels of this type have to be mixed with fuels with lower calorific value.

The moisture content in the fuel should maximum be 50 % to get a well-functioning process. If the moisture content is too high too much energy is used for drying the material which affects the carbonization and can prevent it from being fully implemented. Sewage sludge and other wet materials should be dried before put into the reactor, alternatively mixed with dryer fuels to lower the moisture content.

4.2.2 Process start

To start the process approx. 30 kg of LPG is needed to heat up the reactor.
4.2.3 Reactor

In the reactor up to 1000 tons of dry substance can be feed into the plant annually. The amount is regulated depending on the calorific value in the fuel and through mass flow rate. The mass flow rate of biochar out of the plant is constant and the process is continuous.

The plant is constructed for a specific input energy of biomass equivalent to 500 kW and thus, the amount of input fuel has to be regulated to meet that energy level. The pyrolysis gas has a heating capacity of 150 kW and carbonization efficiency up to 60 %. The efficiency of the process is between 90 % and 95 %.

Temperatures in the reactor are between 400 and 850 °C depending on the fuel. Fuels with high calorific value give high temperatures. Normal reactor temperature is 800 °C. The pyrolysis gas is combusted in a FLOX-burner (FLOX, 2013) which has high efficiency and combust in high temperature, 1250 °C. The FLOX-burner is also designed to have low NOx emissions. The electricity consumption of the plant is 7.5 kW. When the char comes out from the plant it only has a temperature of 30 °C, which makes it possible to package it immediately.

Because of the reactor and the FLOX-burner high temperatures chlorides, biooil and corrosion are not a problem. The high temperatures will decompose the pollutants such as pesticides and medicine residues. Another rest product produced in the combustion chamber is similar to lava rock and varies on which type of fuel that has been used, see Figure 4-4. This rest product is easy to remove and samples have shown that it does not contain any hazardous substances. More studies on this material need to be done.

![Figure 4-4 The rest product, lava stone, from Pyreg’s pyrolysis plant (EcoTopic, 2013)](image-url)
Pyreg’s plant weighs 10 tons. The shape and size fits in a container and is 8m*2.5m*2.5m exclusive the chimney. Pyreg’s test plant in Dörth, Germany, is seen in Figure 4-5.

![Pyreg's test plant in Dörth, Germany](image)

**Figure 4-5 Pyreg’s test plant in Dörth, Germany (EcoTopic, 2013)**

Pyreg means that the plant could be in operation 24 hours per day in 12 days, then one day for cooling and one day for cleaning. Starting the process takes about 1h. The plant in Austria was operated 5000 h during 2012. Recurring daily maintenance is e.g. to clean the plant, and annually the chimney has to be replaced since the iron gets thinner because of the high temperatures.

(Pyreg, 2013)
5 Environment

Figure 5-1 below illustrates the impact of a pyrolysis plant and its products have locally and globally.

![Illustration of the pyrolysis environmental impact](EcoTopic, 2013)

5.1 Locally

In all new establishments it is important to consider the impact the new activity can have on people in the local area within 1 km. Most common complaints are about noise, odour, aesthetics and emissions.

5.1.1 Noise

The noise related to a pyrolysis plant comes primarily from transportation to and from the facility as well as handling the fuel when put into the reactor. This can be prevented by planning the logistics to and from the facility and inside the site. Noise from the pyrolysis plant is negligible because many of the suppliers today use container based plants. (Carbon Terra, 2013; Pyreg, 2013)

5.1.2 Odour

No odour will be emitted from the pyrolysis process and the final products char and pyrolysis gas are odourless. Depending on the fuel there can be some smell e.g. manure odour. This can be prevented by delivering the fuel in closed containers or mix it with char before pyrolyzing, which reduce the odour vigorously. (Carbon Terra, 2013; Pyreg, 2013)
5.1.3 Aesthetics

The reactor suppliers visited use container solutions which gives a compact plant. Moreover, if the fuel is delivered in containers a pyrolysis production site would look like a line-up of containers. If the opportunity is given, there is nothing preventing both the pyrolysis plant and the fuel from be put indoors. (Carbon Terra, 2013; Pyreg, 2013)

5.1.4 Leakage

The risk for gas emissions from the pyrolysis plant is small, especially if the pyrolysis gas is combusted for heat production immediately. The risk is of local emissions occur if the plant somehow is damaged allowing pyrolysis gas to leak or if the gas combustion is incomplete. In case of leakage it is mainly carbon monoxide which is a problem because it is toxic and can affect the cardiovascular system and the brain. (Naturvårdsverket, 2013 B)

5.1.5 Exhaust gas

During combustion NOx and SOx are formed which has an eutrophication respectively acidifying effect when the compounds reach the ground through e.g. acidic rain. Smog particles are also found in the exhaust gases from combustion, and they have both an adverse health effect and contribute to the global warming. Combusting a gas versus solid fuel reduces the amount of pollutants in the exhaust gases significantly, see Table 5-1. (Naturvårdsverket, 2005).

For small conventional combustion plants (500 kW – 3 MW) only smog particles are regulated. However, individual requirements are to be investigated for each plant for the other parameters. In this case, we used the maximum dust particles requirements approved in the city. (Gulliksson et al., 2005)

For larger (<10MW) conventional plants there are set requirement but they vary a lot. Therefore, also the requirements for natural gas combustion are shown in Table 5-1 below, since it is comparable to a pyrolysis plant. The emissions from combustion plants are compared with one of the pyrolysis plants studied in this thesis. (Naturvårdsverket, 2005)
Table 5.1 Emissions to air from different heat production plants

<table>
<thead>
<tr>
<th>Emission limits</th>
<th>CO (mg/m³)</th>
<th>NOx (mg/m³)</th>
<th>SOx (mg/m³)</th>
<th>Dust particles (mg/m³)</th>
<th>Dioxin (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional combustion in city 500 kW-3 MW²</td>
<td>700 (suggestion, no limit)</td>
<td>700 (suggestion, no limit)</td>
<td>No limit</td>
<td>100 (350 outside city)</td>
<td>No limit</td>
</tr>
<tr>
<td>Conventional combustion in city &lt;10 MW²</td>
<td>50-500</td>
<td>40-110</td>
<td>1-20</td>
<td>50-200</td>
<td>No limit</td>
</tr>
<tr>
<td>Requirements in combustion of natural gas²</td>
<td>&lt;100</td>
<td>30-70</td>
<td>~ 0</td>
<td>~ 0</td>
<td>No limit</td>
</tr>
<tr>
<td>Analysis of pyrolysis pyrolys³</td>
<td>20</td>
<td>141</td>
<td>Test value missing</td>
<td>3.8</td>
<td>0.013</td>
</tr>
</tbody>
</table>

1. (Gulliksson et al., 2005)
2. (Naturvårdsverket, 2005)
3. Analysis results for Pyreg with waste water sludge as fuel. (Pyreg, 2013)

5.2 Globally

The effect that the heat production has through combustion of the pyrolysis gas on our world globally depends largely on which alternative production method one chooses and what the char is used for.

If the heat production from pyrolysis gas replaces the combustion of fossil fuels it has a major effect globally since it replaces fossil carbon with renewable carbon in the atmosphere. This decreases the global warming. Same rules apply to dust particles which are much less when combusting a pyrolysis gas compared to solid or liquid fuels. Dust particles also contribute to the global warming. (Xiangpeng Gao & Hongwei Wu 2011).

Depending on what the solid product, char, is used for it has different, although always positive, impact on the global environment.

Char used as soil improver itself creates a carbon storage due to the half-life of about 6000 years (1 ton C = 3.7 tons CO₂) and thanks to the positive effect on the crop’s growth the absorption of carbon dioxide from the atmosphere increases even more. (Bruges, 2009)
When char is used as a **feed supplement** for animals it decreases the methane production in ruminant’s stomachs, which is one of the largest sources of greenhouse gas emissions. Moreover, increasing the animals’ resistance to disease reduces the use of drugs. (Inthapanya, et al., 2012)

If the biochar replaces some of the fossil coal used as **energy carriers** it reduces global warming by adding less fossil carbon dioxide in the atmosphere. To combust biochar instead of biomass has been found to produce less small particles in the exhaust gas, but may also give increased amount of large particles which are easier to filter. (Hiangpeng & Hongwei 2011)

**Metal industry** uses coal, usually fossil, in their process, and if this coal is replaced with char produced from biomass it will also reduce the global warming by less amount of fossil carbon dioxide in the atmosphere. (Schulten et al., 2013)
6 Permission and safety aspects

The developed pyrolysis technology where both the char and the pyrolysis gas are utilized is relatively new, which means that laws and regulations are not as extensive as for combustion. This leaves room for interpretation. The laws and regulations for combustion plants are often based on the concerned plant’s size and power interval.

Today it is difficult to determine a pyrolysis plant’s power size. This due to the fact that the energy pyrolyzed is not the same as the energy input since $\frac{1}{3}$ of the material’s energy ends up in the pyrolysis gas, normally combusted, and $\frac{2}{3}$ in the char. It is also unclear if the pyrolysis plant is a combustion plant or if it is a gas production plant. After discussing this with Environment Inspector Emelie Bretz (2013) at the Environmental Emergency Services at the municipality of Eskilstuna and Staffan Asplind (2013) officer at the Swedish EPA the pyrolysis plant should be classified as a combustion plant for the pyrolysis gas if the char is used for other purposes than energy carrier, but it is unclear what the law states.

Below the regulations (1998:889) (Rättsnätet, 2013) for combustion and gas production plants are studied.

6.1 Combustion

The plant’s power decides if it is licensable or not. The plants are divided into A, B and C plants where A and B are licensable and C only require notification.

- A – 40.40 installed input power more than 300 MW
- B – 40.50 installed input power more than 50 MW
- B – 40.51 installed input power more than 20 MW
- C - 40.60 installed input power more than 500 kW
- C* – 40.60 installed input power more than 10 MW, if no other fuel is used than heating oil or fuel gas

*Possibly the synthesis gas can go as fuel gas
The pyrolysis plant is thereby not licensable if installed input power is less than 500 kW or 10 MW if the pyrolysis gas can be seen as fuel gas. The regulations are changed if the material used is classified as waste. Pure wood waste, agricultural and forestry waste which are energy recovered are not classified as a waste fraction. (Rättsnätet, 2013)

6.2 **Gas production**

If the plant is seen as a gas producing unit the following rules apply:

- B - 40.10 Plant for production of more than 150 000 cubic meters of gaseous fuel per calendar year
- C – 40.20 Plant for production of gaseous fuel if the business is not licensable according to 40.10

(Rättsnätet, 2013)

If the pyrolysis gas is said to combust gas the Building and Planning department supply general advice for smaller newer heating plants fuelled with liquid or gaseous material (BFS 1997:58 EVP 1). These advices aim for more efficient energy use and a thoughtful use of natural resources. The Building and Planning department therefore also set technical requirements on the plant’s efficiency, corresponding to the EU regulations. (Lerman, 1997)

The regulations according to the Building and Planning department (BFS 1997:58 EVP 1) apply to plants with a maximum burner power of at least 4 kW and maximum 400kW. These plants should be CE classified according to the regulations of the Building and Planning department. The efficiency limits are ≥ 91 + 1 log Pn (maximum burner power) (Lerman, 1997). When buying a pyrolysis plant it is always recommended to contact with the municipality for consultation whether it is licensable or not (Asplind, 2013).

6.3 **Handling biochar**

In European Biochar Certificate the handling of biochar is regulated. Laws for fire and dust should be followed during production, transport and by the end user. During transport the char should be moist to reduce the risk of dust and dust explosions. The end user should get information of how to handle the biochar. During production proper
protection, like protective clothing and breathing apparatus, should be worn. (Schmidt et al., 2012)

Due to risks of fire it is recommended to do a small report on extinguishing water, in which the following aspects should be considered:

- What amounts extinguishing water are required to fight a fire in contact with the plant?
- What pollutions can come in contact with the extinguishing water?
- What are the consequences of extinguishing water coming to the waste water treatment plant and directly to recipients?
- What are the conditions for taking action so that the leakage of polluted extinguishing water is prevented?

(Alenius Bolin, et al., 2007)

Laws surrounding the spreading of biochar as a soil conditioner do not exist in Sweden today but there are regulations for spreading ashes. The spreading of ashes is done to return some of the nutrients that were taken from the forest during logging. It is crucial that the material is clean from heavy metals and other pollutants for it to be approved to be returned to agricultural land. Also the pH parameter is important to prevent the soil from being too basic. (Alenius Bolin, et al., 2007)
7 Economic analysis

In this chapter the economy for different pyrolysis plants are compared to the more conventional pellet and wood chip combustion plants of a similar size. The costs and potential revenues are divided. It is important to remember that the numbers are true for these specific plants and they should therefore be seen as indicators. The calculations below are based on 1 SEK = 0.116 euro.

7.1 Investment cost

The plants studied in this thesis are all constructed to operate optimally at a certain energy input. This means that the total investment costs can’t be compared since the plants aren’t of the same size. Therefore the key factor euros/kWh will be used.

The investment cost for Carbon Terra’s plant is 388 000 euros. This includes a reactor, a burner and a computer (Carbon Terra, 2013). For a full scale business 58 000 euros is added for a material feeder and wood chip storage (Lövgren, 2013). The smallest plant from Carbon Terra has a burner dimensioned for three reactors, which makes the key factor euros/kWh higher than for a plant with only one reactor. The computer can operate any number of reactors which decreases the investment cost per kWh the larger the plant is. (Carbon Terra, 2013)

The investment cost for the Pyreg plant is 300 000 euros. The Pyreg plant is a container solution where the reactor, the burner and the computer are integrated in each plant (Pyreg, 2013). The material feeder and wood chip storage have to be bought separately for 58 000 euros. (Lövgren, 2013)

The investment for a complete pellet plant with an input power of 500 kW is 267 000 euros. For a woodchip plant with an input power of 500 kW the investment cost is 372 000 euros including the woodchip storage and material feeder. (Lövgren, 2013)

7.2 Operating and maintenance costs

The operating cost is based on experiences from the visited pyrolysis plant suppliers and the plants they sold. The more plants in operation the better knowledge we will get about the operating costs. The companies have stated that the operating and maintenance costs are 5 % of the total investment, which would mean 17 000 – 20 000 euros/year. The
operating and maintenance costs also include insurance. (Carbon Terra, 2012; Pyreg, 2013)

Carbon Terra’s pyrolysis plant is operated 24 hours a day and is only shut down 2 – 4 times per year. Cooling down the reactor, carrying out the maintenance and restarting the process take 6 – 9 days per time. This means a total of 300-900 hours of non-production time per year. (Carbon Terra, 2013)

Pyreg’s pyrolysis plant is also operated 24 hours per day for 12 days in a row followed by one day cooling and one day cleaning. To restart the plant only takes one hour. This means a total of 1200 hours of non-production time per year. (Pyreg, 2013)

The operating and maintenance cost for a pellet plant is approx. 1 200 euros/year and it can be operated 8 695 hours per year. For a woodchip plant the operating and maintenance costs are 2 300 euros/year and the operating time is 8 630 hours. (Lövgren, 2013)

It is important to point out that the different suppliers include different costs within operating and maintenance costs. This means that the cost posts should be seen as indicators and more attention paid to the total cost.

### 7.3 Material cost

The price of wood chips and GROT are close to 0.025 euro/kWh and the price of pellets is 0.037 euro/kWh (Niva, 2013). The price of straw is 0.035 euro/kWh (Sollenberg, 2013). The value of manure depends on the nutrient content but in this thesis we put the price to 0 euro/kWh since we would only use types of manure seen as waste.

Concerning the cost for material the efficiency is a very important parameter. For the plants of Carbon Terra and Pyreg the efficiency is between 90 and 95 % depending on the quality of the material quality (Carbon Terra, 2013; Pyreg, 2013). In the calculations the mean value, 92.5 %, has been used. For pellet and woodchip plants the efficiency is 91-92 % and 82-88 % depending on how big the output power is. Smaller output power, worse efficiency. (Lövgren, 2013) In the calculations 91.5 % and 85 % are used for pellet and woodchip plants operated in full capacity.
7.4 Personnel cost

To compare the personnel costs it is important that the same activities are included. In this case the buying of material, the supervision, handling the heat distribution, selling the char or managing the ashes are included. The given costs of the different suppliers have varied as well as the included activities. Therefore this thesis has made decisions of what to include in the calculus after best ability. (Carbon Terra, 2013; Pyreg, 2013)

The personnel cost is somewhat different for the different plants but on average a halftime employment is needed, corresponding to 29 000 euros/year. Necessary hours to keep the plant running are seen as relatively few. Carbon Terra means that two hours per day, 700 hours per year is more than enough. The Pyreg plant in Austria is just visited from time to time, approximately 260 hours per year. (Carbon Terra, 2013; Pyreg, 2013)

A pellet combustion plant needs little monitoring and it has a very low personnel cost compared to the Pyreg plant and a woodchip combustion plant. The personnel costs are set to 20 000 euros/year for the pellet plant and for the woodchip plan, which needs some more attention, 29 000 euros/year. (Lövgren, 2013)

7.5 Comparison euros/kWh

To compare the costs for the different plants the key factor euros/kWh is used. The economic analysis below is simplified, not including the interest rate but this should not affect the comparison.

In Table 7-1 and Table 7-2 the largest cost posts for the two pyrolysis plants, a pellet combustion plant and a woodchip combustion plant are shown. In all the calculations below the material used is pellet in the pellet combustion plant and wood chips in the other three plants even if the pyrolysis plants can use several different types of materials. The most profitable business is made from using material that are cost free or even get paid to handle; horse manure, sewage water sludge and olive pits (Pyreg, 2013). It is important to point out that the pellet and woodchip combustion technology is well developed and an investment is often based on 15 years of depreciation. For a pyrolysis plant, which is a relatively new technology, the depreciation is shorter and in Table 7-1 and Table 7-2 set to 7 years for Pyreg and 10 years for Carbon Terra. Carbon Terra’s technology is very simple thus the longer depreciation time.
Table 7-1 Cost comparison between pyrolysis and combustion plants given in euros/kWh

<table>
<thead>
<tr>
<th>COSTS</th>
<th>Pyreg</th>
<th>Carbon Terra</th>
<th>Pellet combustor</th>
<th>Wood chip combustor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment (euros/kWh)</td>
<td>0.014</td>
<td>0.005</td>
<td>0.004</td>
<td>0.006</td>
</tr>
<tr>
<td>Maintenance (euros/kWh)</td>
<td>0.0047</td>
<td>0.0024</td>
<td>0.0003</td>
<td>0.0007</td>
</tr>
<tr>
<td>Fuel (euros/kWh)</td>
<td>0.027</td>
<td>0.027</td>
<td>0.040</td>
<td>0.030</td>
</tr>
<tr>
<td>Personal (euros/kWh)</td>
<td>0.008</td>
<td>0.004</td>
<td>0.005</td>
<td>0.007</td>
</tr>
<tr>
<td>SUM</td>
<td>0.053</td>
<td>0.038</td>
<td>0.049</td>
<td>0.043</td>
</tr>
</tbody>
</table>

Table 7-2 Cost comparison between pyrolysis and combustion plants given in euros/year

<table>
<thead>
<tr>
<th>COSTS</th>
<th>Pyreg</th>
<th>Carbon Terra</th>
<th>Pellet combustor</th>
<th>Wood chip combustor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment (fixed cost) (euros/year)</td>
<td>51 153</td>
<td>38 807</td>
<td>17 809</td>
<td>24 777</td>
</tr>
<tr>
<td>Variable cost (euros/year)</td>
<td>150 407</td>
<td>267 692</td>
<td>195 221</td>
<td>160 503</td>
</tr>
<tr>
<td>SUM</td>
<td>201 560</td>
<td>306 499</td>
<td>213 030</td>
<td>185 280</td>
</tr>
</tbody>
</table>

7.6 Revenues from pyrolysis gas

In this thesis we treat the pyrolysis gas as a fuel for heat production. As mentioned earlier in chapter 3.3.1.3 there are other alternatives for the pyrolysis gas, but these are not analysed in this comparison since it is not relevant when looking at the combustion plants. The price on heating in Sweden from a local heating plant is 0.1 euro/kWh (Niva, 2013).

7.7 Revenues from char

In Table 7-3 different alternatives for revenues from pyrolysis gas and the char are listed. Both have several areas of use as mentioned earlier. The price of biochar in Germany as soil conditioner and feed supplement is 350 euros/ton when buying quantities of at least one ton (Carbon Terra, 2013; Pyreg, 2013). When buying smaller quantities the price goes up. The most profit is made when selling the char as energy carrier or as filter material; charcoal 1 160 euros/ton (Zell, 2013), and active carbon 2 320 euros/ton (Wahlberg et al., 2009). The price for filter material in Table 7-3 is for active carbon. To
get the same effect from biochar as active carbon in filters you might need to increase the amounts of char.

In Sweden there is no established market for biochar why the price data is taken from the countries where there are pyrolysis plants operating.

Table 7-3 Revenues from pyrolysis gas and biochar

<table>
<thead>
<tr>
<th>REVENUES</th>
<th>Pyreg</th>
<th>Carbon Terra</th>
<th>Pellet combustor</th>
<th>Wood chip combustor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat production (GAS) (euros/year)</td>
<td>109 646</td>
<td>232 346</td>
<td>415 863</td>
<td>383 477</td>
</tr>
<tr>
<td>Soil conditioner (CHAR) (euros/year)</td>
<td>95 294</td>
<td>201 933</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Feed supplement (CHAR) (euros/year)</td>
<td>95 294</td>
<td>201 933</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Energy carrier (CHAR) (euros/year)</td>
<td>316 224</td>
<td>670 094</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Filter material (CHAR) (euros/year)</td>
<td>632 448</td>
<td>1 340 188</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The visited pyrolysis plants are dimensioned for different power input and output, described in Chapter 4. As mentioned earlier the costs are based on the pyrolysis plants using wood chips as material, even if other materials would give another result.

The char from the pyrolysis plants have a market value which varies very much depending on the area of use. To avoid promising too much, the revenues are based on the biochar being sold as soil conditioner and feed supplement. This means that if the char is sold for a higher price the result will change dramatically.

Table 7-4 show the results for the different plants where the new pyrolysis technology doesn’t show as good results as the traditional combustion technology. Though the pyrolysis plants have the possibility to be able to choose different materials, which is one of the largest costs. It is important to point out that the costs can be decreased if you can find a cheaper wood chip storage for Pyreg, Carbon Terra and the wood chip combustion plant and if you can sell the char for different purposes.
Table 7-4 Comparison of revenues and costs

<table>
<thead>
<tr>
<th>RESULT</th>
<th>Pyreg</th>
<th>Carbon Terra</th>
<th>Pellet combustor</th>
<th>Wood chip combustor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income GAS (euros/year)</td>
<td>109 646</td>
<td>232 346</td>
<td>415 863</td>
<td>383 477</td>
</tr>
<tr>
<td>Income CHAR (euros/year)</td>
<td>95 294</td>
<td>201 933</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cost (euros/year)</td>
<td>201 560</td>
<td>306 499</td>
<td>213 030</td>
<td>185 280</td>
</tr>
<tr>
<td>RESULT</td>
<td>3 380</td>
<td>127 780</td>
<td>202 833</td>
<td>198 197</td>
</tr>
</tbody>
</table>

The posts affecting the results mostly are the cost of material and the revenues for heating and char. The greatest advantage of the pyrolysis plants is the possibility to use different materials. Below we look at an alternative economic analysis where the pyrolysis plants are taking advantage of this. The cost of material for Pyreg and Carbon Terra is set to zero, which is a plausible situation if the material is considered as waste. Another post affecting the result is the revenue from the char. Though in the calculus below the price is still based on the price of soil conditioner or feed supplement to not risk giving a “joy calculus” since the market is undeveloped in Sweden.

Table 7-5 Comparison of revenues and costs when the cost for material to the pyrolysis plants is set to zero euros

<table>
<thead>
<tr>
<th>RESULT</th>
<th>Pyreg</th>
<th>Carbon Terra</th>
<th>Pellet combustor</th>
<th>Wood chip combustor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income GAS (euros/year)</td>
<td>109 646</td>
<td>232 346</td>
<td>415 863</td>
<td>383 477</td>
</tr>
<tr>
<td>Income CHAR (euros/year)</td>
<td>95 294</td>
<td>201 933</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cost (euros/year)</td>
<td>98 093</td>
<td>87 247</td>
<td>213 030</td>
<td>185 280</td>
</tr>
<tr>
<td>RESULT</td>
<td>106 848</td>
<td>347 032</td>
<td>202 833</td>
<td>198 197</td>
</tr>
</tbody>
</table>
In this chapter the strengths, weaknesses, possibilities and threats for the pyrolysis plants are analysed in a SWOT analysis, see Figure 8-1.

**8.1 Strengths**

The pyrolysis plant can handle material with lower quality than conventional combustion plants. The material can have lower calorific value, relatively high water level and be of all different types of origin only regulated by the biochar certificate. Specific types of biomass which otherwise is difficult to use as fuel, like for example horse manure and straw, can be used for pyrolysis.

To burn pyrolysis gas for heat production compared to conventional biomass combustion give less emissions of dust particles. A pyrolysis plant also has a higher efficiency.

The pyrolysis technology is simple and it has been practiced during a very long time, even if it has been replaced with other methods. Luckily the pyrolysis technology keeps getting developed.
The pyrolysis plants visited are working to develop their plants to fit in a container. This minimizes the esthetical disturbance. The plants are free from smell (depending on type of material) and the sound level is low.

From the pyrolysis process you get two main products which make the plant more resilient to price fluctuations on the market. The char has been used for agriculture for thousands of years both for soil improvement and feed supplement, but the last decades it has been replaced by products that we today start to realize have many negative effects. The char can be sold as a number of different products which increase the resilience of the plant.

The char can be used multiple times. An example is to first use it as feed supplement which decreases the methane production. The biochar in the manure decreases the stable smell and it increases the biogas production and in a final step the biochar works as soil conditioner when the sewage sludge from the biogas production is supplied to the farm land. Well applied to the soil the biochar helps to keep the nutrients and thanks to the slow degradation time it stays for a long time and keeps having positive effects on the production.

8.2 Weaknesses

Since the interest for pyrolysis is just recently awoken there are only a few different types of pyrolysis plants and just as few suppliers. This can make it difficult to find a plant that meets a customer’s specific needs.

The pyrolysis plants presented in this thesis do not have an effect output that can be regulated, meaning they have to operate on maximum effect complete the carbonization of the material. This fact decreases the potential market to only relatively large businesses with an even heat demand all year round. Though, by using water storage tanks this can be in some way regulated.

The knowledge and experience of biochar and its areas of use is poor in Sweden and even the earlier knowledge has in many cases disappeared. There is a need for marketing and education in how biochar can be used and replace other products. In Europe the biochar movement is growing and more and more conferences are taking place each year, which improves the outlook for the Swedish market.
The metal concentration in the material are concentrated in the char during the pyrolysis process. There is still a need to find out for how long these metals are bound to the char.

### 8.3 Opportunities

The market for pyrolysis plants is growing and right now the interest is focused on the biochar. Biochar can give increased production on farm land, decrease nutrient leakage and work as carbon storage. Biochar can be used as a feed supplement to decrease the risk of disease, increase growth and decrease the emission of methane from stock. This fits in well in the modern farmer’s environmental profile especially if they can use the heat from the pyrolysis plant.

To use biochar as soil conditioner and in that way store carbon is a much easier, environmentally and economically sustainable than the CCS method. An increase of plant growth binds more carbon from the air which also helps lower the carbon dioxide levels.

The possibilities of the pyrolysis technology are many; extracting the biooil and using it as energy carrier or vehicle fuel, turn the synthesis gas for different kinds of vehicle fuels and increasing biogas production by mixing in biochar in the digesters.

### 8.4 Threats

There is very little knowledge about pyrolysis plants within authorities and therefore laws and regulations are missing. The problems for the authorities are to determine whether the pyrolysis plant is a gas production plant, a gas combustion plant or both. Existing laws for combustion plants are often based on the plant’s effect, which in case of the pyrolysis plant can cause problems since only one third of the input material is combusted. The lack of regulations can cause extra administration when building the first pyrolysis plant.

The conventional combustion technology is well tested and established, which can make it difficult for the pyrolysis technology to compete on the market for heat production. The economic analysis of a pyrolysis plant is affected by the cost of material and the price of biochar. Since the market of biochar is underdeveloped in Sweden the uncertainty of the calculus increases.
9 Conclusion

In this chapter the questions in chapter 1.4 are answered.

- **What different types of materials can be used in a pyrolysis process?**
  All types of organic material can be pyrolyzed. This is one of the biggest strengths with pyrolysis compared to pellet and wood chip combustion since pyrolysis is not dependent on the prize of wood based material. Though to certify the char as biochar some requirements have to be met concerning origin and quality.

- **What alternative areas of use are available for the pyrolysis’ end products?**
  The pyrolysis gas may advantageously be combusted immediately after the pyrolysis process to produce heat. It is also possible to produce electricity by using a turbine. If the pyrolysis gas is not combusted you can extract the biooil and use it as energy carrier or upgrade it into vehicle fuel. The synthesis gas can also be turned into several kinds of vehicle fuel.

  The char can be used as soil improver, feed supplement, carbon capture, filter material, to increase biogas production in the digesters, energy carrier and ingredients in the metal industry. All areas of use mean environmental benefits, as well as economic benefits thanks to increased production and savings from substituting fossil char which is going up in price.

- **How does the pyrolysis technology measure up to the national emission requirements for local heating plants?**
  In a pyrolysis plant gas instead of solid fuel is combusted to produce heat and this ends up giving very low emissions of all types of environmentally hazardous chemicals. Existing emission requirements mostly concern bigger combustion plants. In spite of that the pyrolysis technology measures up very well against pellet and wood chip combustion plants.

- **Which regulations and demands exist on the pyrolysis plants today?**
  The pyrolysis technology is relatively new and this means that laws and regulations for this type of plants don’t exist in Sweden. They are under development in other countries like for example Germany. This means that supervisory authorities might initially be
unsure how to handle pyrolysis plants which might result in longer administrative processes.

- **What are the costs and incomes related to a pyrolysis plant?**

The large costs for a pyrolysis plant are the investment, operating and maintenance, personnel and material. Thanks to being able to choose different materials the pyrolysis technology the prize of material can vary from the price of wood chips to getting paid for taking care of the material which would otherwise be seen as waste. Income comes from heat production and from selling the char. The sales price for the char vary a lot depending on areas of use but the market is growing in other countries like Germany. The largest potential income comes from selling the char as filter material or energy carrier.

- **Which are the pyrolysis’ strengths and weaknesses compared to pellet and wood chip combustion?**

The strengths of the pyrolysis plant is the flexibility concerning materials, low emissions and increased resilience to price changes on the market thanks to two end products; pyrolysis gas and char. And the char has several areas of use which further increase the resilience. The weaknesses of the pyrolysis plant is that it always run on maximum effect which is less flexible than the pellet and wood chip combustions plants and it decreases the number of potential buyers. The market in Sweden is still underdeveloped and the knowledge about the possibilities of biochar is very little. There is a big need of marketing and education but if Sweden follows the development happening in Germany the future look promising.

Pyrolysis with its end products is an interesting technology both concerning environmental, technical and economic aspects. Strengths and possibilities win over the weaknesses of the technology and the threats. The conclusion of this thesis is that the pyrolysis technology is a good alternative to conventional pellet and wood chip combustion for activities where a static heat production doesn’t pose a problem. It is also important to realize the value of the char and contribute to increasing the Swedish market. If you succeed in finding a material free of charge and find a market for the biochar the economic analysis is very positive and the investment very resilient.
10 References

Written references


Bojler Görling, Martin (2012). *Energy system evaluation of thermo-chemical biofuel production*. Kungliga Tekniska Högskolan


Inthapanya, Sangkhom., Leng, R A., Preston T R., (2012). *Biochar lowers methane production from rumen fluid in vitro*. Faculty of Agriculture and Forest Resources, Souphanouvong University, Luang Prabang, Lao PDR.


Kumar, Sushil J., Jain, M. C., Chhonkar, P. K., (1986). A Note on Stimulation of Biogas Production from Cattle Dung by Addition of Charcoal. Division of Soil Science and Agricultural Chemistry, Indian Agricultural Research Institute, New Delhi--110012, India.


Leng, R A., Preston T R., Inthapanya, Sangkhom., (ej daterad). Souphanouvong University, Luang Prabang Province Biochar reduces enteric methane and improves growth and feed conversion in local “Yellow” cattle fed cassava root chips and fresh cassava foliage. Faculty of Agriculture and Forest Resources, Souphanouvong University, Luang Prabang, Lao PDR.


Strömberg, Birgitta (2005). *Bränslehandboken*. Värme forsk service AB

*Substrathandbok för biogasproduktion* (2009), Avfall Sverige utveckling.


Xiangpeng Gao och Hongwei Wu (2011). *Biochar as a Fuel: 4. Emission Behavior and Characteristics of PM1 and PM10 from the Combustion of Pulverized Biochar in a Drop-Tube Furnace*. Fuels and Energy Technology Institute, Department of Chemical Engineering, Curtin University of Technology

**Internet references**


**Personal communication**


Sollenberg, Olle (2013-06-19). ordförande Lantbrukarnas Riksförbund (LRF) i Eskilstuna Kommun

**Figure references**


EcoTopic AB (2013)


Guidelines

European Biochar Certificate

for biochar production

Version 4.2 of 13th June 2012
Impressum

These guidelines are effective as of 1 January 2012 and constitute the basis for biochar certification through the independent inspection agency q.inspecta.

Hans Peter Schmidt*, Delinat Institute
Samuel Abiven, University of Zurich
Claudia Kammann, University of Gießen
Bruno Glaser, University of Halle
Thomas Bucheli, ART Reckenholz
Jens Leifeld, ART Reckenholz

* corresponding author: schmidt@delinat-institut.org

All rights reserved.
No reproduction, whether in whole or in part, permitted without the written permission of the Delinat Institute.
Copyright: © 2012 Delinat Institute und Biochar Science Network
Table of contents

1. Objective of the biochar guidelines
2. Definition of biochar
3. Biomass feedstock
4. General requirements for keeping production records
5. Biochar properties
6. Pyrolysis
7. Sale and application of biochar
8. Quality assurance and certification
9. References

APPENDIX
10. Positive list of biomasses
11. Company declaration
12. Biochar production records
Guidelines on the production of biochar

Europäisches Pflanzenkohle Zertifikat / European Biochar Certificate

Publisher: Biochar Science Network

1. Objective of the guidelines and certification

For thousands of years, charcoal has been one of civilisation’s basic materials. By far the most common use of charcoal is for cooking, for heating and for smouldering when producing metal tools. However, for centuries charcoal and biochar have also been used for conditioning soils, or as litter (bedding) materials, as medicine and also as a feed additive. In the course of the last century most of this traditional knowledge has been lost and is only now being rediscovered.

Thanks to wide-ranging multidisciplinary research and field trials, the understanding of the biological and chemo-physical processes involved in the use of biochar has made great progress. Thus a major increase in the agricultural use of biochar is to be expected for the next years. Usage ranges from soil conditioning, compost additives and carrier for fertilizers, manure treatment and litter (bedding) materials to silage additives, feed-additives, medical applications and others.

Traditional kiln production of charcoal and biochar was unsatisfactory with regard to its carbon efficiency and especially its environmental footprint. Accordingly, it is unsuitable for producing larger biochar amounts to be used in future agriculture. Modern pyrolysis plants are now ready to produce biochar from a large variety of different feedstocks in energy efficient way and without harming the environment. As both, biochar properties and the environmental footprint of its production are very much dependent on the technical control of pyrolysis and the type of feedstocks, a secure control system for its production and analysis needs to be introduced.

The intention of the Biochar Science Network in issuing these guidelines on how to gain biochar certification is first to introduce a control mechanism based on the latest research and practices. Second, the biochar certificate aims to enable and guarantee sustainable biochar production. It is introduced to give customers a reliable quality basis, while (third) giving producers the opportunity of proving that their product meets well-defined quality standards. Fourth, it aims at providing a firm state-of-the-art knowledge transfer as a sound basis for future legislation. Finally, it is introduced to prevent and hinder misuse or dangers from the start, as long as no "special interests" are calling for exceptions (e.g. such as cutting down native forests to produce biochar).

Biochar production technology is currently developing very fast, with more than 500 research projects worldwide looking into biochar properties and interactions. Every
month new test results and numerous scientific studies appear on the subject. Every year sees new manufacturers of pyrolysis equipment entering the market and the areas in which biochar and biochar products are used are steadily and rapidly growing. This biochar certificate is closely linked to this research and technical momentum and will accordingly be revised annually to take into account the latest findings and developments. Thresholds and test methods will be adapted to reflect the latest findings and, if necessary, re-introduced.

The goal of the guidelines is to ensure control of biochar production and quality based on well-researched, legally backed-up, economically viable and practically applicable processes. Users of biochar and biochar-based products will benefit from a transparent and verifiable monitoring and quality assurance. It is our as well as every biochar user's duty to make sure that a good idea will not be carried into misuse. The certificate was designed to serve this goal.
2. Definition of biochar

Biochar is here defined as char produced by pyrolysis for use in agriculture (and other non-thermal applications) in an environmentally sustainable manner.

Biochar is produced by biomass pyrolysis, a process whereby organic substances are broken down at temperatures ranging from 350°C to 1000 °C in a low-oxygen (<2%) thermal process. Torrefaction, hydrothermal carbonisation and coke production are further carbonisation processes whose end products cannot however be called biochar under the above definition. Biochars are therefore specific pyrolysis chars characterised by their additional environmentally sustainable production, quality and usage features. For products produced using other carbonisation processes, specific certificates may be compiled once wider-ranging and better-secured knowledge is available on their quality and effects in soils and in other non-thermal applications.

In accordance with the certificate to which these guidelines apply, a differentiation is made between two different biochar grades, each with its own threshold values and ecological requirements: "basic" and "premium".

For gaining the European biochar certificate, the following criteria regarding the biomass feedstock, the production method, the properties of the biochar and the way it is applied have to be met.
3. Feedstock

3.1 Only organic wastes listed in the positive list (Appendix 1) may be used in the production of biochar.

3.2 It must be ensured that all non-organic waste such as plastic, rubber, electronic scrap has been removed.

3.3 Feedstocks must be free of paint, solvents and other non-organic contaminants.

3.4 When using primary agricultural products, it must be guaranteed that these were grown in a sustainable manner.

3.5 Biochar may only be produced from wood from forests or short rotation forestry plantations if their sustainable management, for example through appropriate PEFC or FSC certification, can be proven.

3.6 Feedstocks used for the production of biochar must not be transported over distances greater than 80 km. An exception is made for pyrolysis additives or special biomasses for use in production tests. [Since the current network of pyrolysis facilities is not yet extensive an exemption to this transport distance requirement can be granted as long as such exemption is only a temporary measure.]

3.7 Complete records of feedstocks must be kept.
4. General requirements for biochar production records

Each biochar batch must be clearly labelled and be given a unique identification number for reconstructing the circumstances of production and guaranteeing the quality of the biomasses used. For each biochar batch, separate production records are to be kept. Each batch must be tested to ensure compliance with the required threshold values.

A uniform biochar batch is deemed to exist when the following criteria are met:

1. The pyrolysis temperature in °C do not fluctuate more than 20%. Interruption of the production is allowed as far as the production parameters keep the same after the resumption of production.
2. The composition of the pyrolysed biomasses does not fluctuate more than 15%
3. The production period of the batch does not exceed 120 days of production within a maximum of 240 days.
4. Complete production records must be kept, providing detailed descriptions and dates of any production problems or halts.

Once any one of these four criteria is not met, the biochar subsequently produced belongs to a new batch for which new production records have to be kept.
5. Biochar properties

Current knowledge and the analytical methods are such that it is at present very difficult and expensive to attain a detailed physical-chemical characterisation of biochar. This means that no complete scientific characterisation of the certified biochar can be required. The focus is therefore on guaranteeing compliance with all environmental threshold values and declaring all product properties of relevance for the agricultural use of biochar.

5.1 The biochar’s carbon content must be higher than 50% of the dry mass (DM)

The organic carbon content of pyrolysed chars fluctuates between 10% and 95% of the dry mass, dependent on the feedstock and process temperature used. For instance the carbon content of pyrolysed poultry manure is around 25%, while that of beech wood is around 85%.

When using mineral-rich feedstocks such as sewage sludge or animal manure, the pyrolysed products tend to have a high ash content. Pyrolysed chars with carbon contents below 50% are therefore not classified as biochar but as “pyrolysis ash containing biochar”.

When pyrolysis ashes meet all other threshold criteria of this biochar certificate, they may be marketed as pyrolysis ash. Pyrolysis ashes have a high nutrient content, therefore representing a valuable fertiliser additive. This does however mean that they belong to a different product category.

In the sense of using resources as efficiently and sustainably as possible, it is preferable to compost or ferment mineral-rich biomasses, or for them to be concentrated into fertiliser. In doing so, the nutrients they contain can be recycled more efficiently than by pyrolysis.

The specification of carbon content is of particular relevance when working with CO₂ certificates

Permitted test methods: DIN 51732
(Specify for each batch)

5.2 The black-carbon content must represent 10 - 40% of overall carbon

Biochar carbon is made up of easily degradable organic carbon compounds and very stable, aromatic carbon structures (black carbon). Black carbon content is an important criterion for characterising biochar and also reflects the biochar’s stability in the soil. The latter aspect is of particular relevance with regard to carbon sequestration.

According to Schimmelpfennig und Glaser [2012], the black carbon content of biochars should represent 10 - 40% of the overall carbon. Chars where the black carbon content is under 10% of the overall carbon cannot be considered as biochar.

There is no standardised methodology yet available for analysing black carbon content. Consequently, no mandatory control of black carbon content as part of the certification process can yet be required. Nevertheless it is recommended to (optionally) include the value and details of the methodology used to determine the content in the production records.
5.3 The molar H/C ratio must be less than 0.6

The molar H/C ratio is an indicator of the degree of carbonisation and therefore of the biochar's stability. The ratio is one of the most important characterising features of biochar. Values fluctuate dependent on the biomass and process used. Values exceeding 0.6 are an indication of inferior chars and pyrolysis deficiencies (Schimmelpfennig & Glaser [2012]).

**Permitted test methods:** DIN 51732

(Specify for each batch)

5.4. The molar O/C ratio must be less than 0.4

In addition to the H/C ratio, the O/C ratio is also relevant for characterising biochar and differentiating it from other carbonisation products (Schimmelpfennig & Glaser [2012]). Compared to the H/C ratio, measuring the O/C ratio is relatively expensive. As the molar H/C ratio in association with the other data recorded in biochar certification permits the clear classification of the certified char as a pyrolytically produced biochar, mandatory control of the O/C ratio is not required. It is however recommended to (optionally) obtain this value for the production records.

5.5 The biochar nutrient contents with regard to nitrogen, phosphorus, potassium, magnesium and calcium must be available and listed on the delivery slip.

The nutrient contents of different biochars are subject to major fluctuations. For a carbon content exceeding 50%, they can range from 1% to 45%. Please note that, due to biochar's high adsorption capacity, these nutrients may only partly be available to plants. They may take decades to enter the biological life cycle. The nutrient availability of the phosphorus found in biochar is for instance only 15% in the first year, that of nitrogen a mere 1%, while that of potassium can reach 50%.

**Permitted test methods:** DIN EN ISO 17294 – 2 (E29)

(Specify for each batch)

5.6 The following thresholds for heavy metals must be kept

The following maximum values for heavy metals correspond - for the *basic* quality grade - to Germany’s Federal Soil Protection Act (*Bundes-Bodenschutzverordnung* or *BBodSchV*), and - for the *premium* quality grade - to Switzerland’s Chemical Risk Reduction Act (*Schweizerische Chemikalien-Risikoreduktions-Verordnung* or *ChemRRV*), Appendix 2.6 on recycling fertilisers. The respective thresholds refer to the biochar’s total dry mass (DM):

**basic:** Pb < 150 g/t DM; Cd < 1.5 g/t DM; Cu < 100 g/t DM; Ni < 50 g/t DM; Hg < 1 g/t DM; Zn < 400 g/t DM; Cr < 90 g/t DM

**premium:** Pb < 120 g/t DM; Cd < 1 g/t DM; Cu < 100 g/t DM; Ni < 30 g/t DM; Hg < 1 g/t DM; Zn < 400 g/t DM; Cr < 80 g/t DM

As in composting, practically the whole amount of heavy metals contained in the originally feedstock will remain in the final product. Here the heavy metals will naturally be more concentrated than in the starting material (educt). However biochar is able to very effectively bind a number of heavy metals, thereby immobilising them for a long period of time. How long has not however as yet been determined. As the amounts of...
biochar used in agriculture are relatively low compared to those of compost and manure, toxic accumulation of heavy metals can practically be ruled out, even when thresholds are higher. Nevertheless this is no reason to disregard the heavy metal thresholds stipulated in Germany’s Soil Protection Act or Switzerland’s Chemical Risk Reduction Act, or any other European legislation.

Abrasion in connection with the use of chromium-nickel steels in the construction of pyrolysis reactors may lead, especially in the first weeks of production, to an increased nickel contamination of biochar. An exemption can be granted for biochars with a nickel contamination below 100 g/t DM. Such biochars shall only to be used for composting purposes since the valid thresholds are complied with in the finished compost.

**Permitted test methods**

Heavy metals: DIN EN ISO17294-2 (E29)
Mercury: DIN EN1483 (E12)
(Specify for each batch)

5.7 The delivery slip must specify the biochar’s pH value, bulk density, water content and, for the premium quality level, its specific surface area and water holding capacity. The biochar’s pH value is an important criterion with regard to its specific use both in substrates and in binding nutrients in animal husbandry. When a biochar has a pH value exceeding 10, the delivery slip must feature appropriate handling information (regarding health and safety dangers). Please also note that only the application of larger amounts of biochar will lead to changes in a soil’s pH value. Details on bulk density and water content are necessary for the production of homogeneous substrate mixtures or filter ingredients requiring constant carbon contents. The specific surface area is a measure of a biochar’s quality and characteristics, and a control value for the pyrolysis method used. It should preferably be higher than 150 m²/g DM. The water holding capacity either pure or in mixture with a sandy soil is a valuable indication on the effectiveness of biochar in increasing a soil’s water holding capacity.

**Permitted test methods:**
PpH: analogous to DIN 10 390
Water content: DIN 51718; TGA 701 D4C
Specific surface area: BET measurement ISO 9277
(Specify for each batch)

5.8 The biochar’s PAH content (sum of the EPA’s 16 priority pollutants) must be under 12 mg/kg DM for basic grade and under 4 mg/kg DM for premium grade biochar. As in any combustion, pyrolysis also causes polycyclic aromatic hydrocarbons (PAHs) to be released. Their amount is dependent in particular on production conditions. Modern pyrolysis methods allow a significant reduction of the PAH pollution. High PAH levels are an indication of unsatisfactory or unsuitable production conditions. On the other hand, biochar is able to very effectively bind PAHs, with activated biochar being used as an air filter for removing PAHs from exhaust gases and for immobilising PAHs in contaminated soils. The risk of PAH contamination, when using biochar in agriculture, is hence considered to be low, even if higher thresholds would be taken into account.
Though some PAHs bound in biochar are available to plants, this takes place at an even lower level than with compost or manure due to biochars' adsorptive capacity. Moreover, whereas up to 40 tonnes of compost or manure may be applied per hectare over a 3-year period, current guidelines for biochar stipulate max. 40 tonnes over a 100-year period. Nevertheless current approval practice indicates that the PAH threshold defined in the Swiss Chemical Risk Reduction Act (ChemRRV) will also apply to biochar and that an exemption on the grounds of biochar's sorption properties is hardly feasible. Therefore, the threshold for premium grade biochar corresponds to the PAH threshold defined in the Swiss Chemical Risk Reduction Act (ChemRRV), also used as a guideline in the Compost Act (Kompostverordnung). No PAH thresholds are specified in the European soil protection regulations for soil conditioners and organic fertilisers. The threshold for basic grade biochar is therefore based on a value which, taking the latest research into account, only implies a minimum risk for soils and users.

Please note that, due to biochar’s high adsorption properties, most standard methods for testing PAHs are unsuitable for biochar. According to researches carried out by Agroscope ART (Hilber et al. [2012]), a longer-term Toluol extraction is needed before any suitably representative test value can be determined. However as this is not yet a standard method used in European test labs, the current standard test method (DIN EN 15527) remains in effect. The measured values should however be interpreted with caution. Additional tests using the method developed by Hilber et al. is therefore recommended.

The current standard method fulfils its purpose with regard to this certificate, since it is able to determine with sufficient exactitude higher PAH contamination levels deemed to be a problem (Schimmelpfennig & Glaser[2012]). As biochar PAH values are dependent on the pyrolysis method and seemingly less dependent on the feedstock used, an analysis once every six months is sufficient.

**Permitted test methods:** DIN EN 15527 (with caution); recommended: Hilber et al, 2012 Analysis once every 6 months

5.9 PCB content must be below 0.2 mg/kg DM; levels of dioxins and furans must be below 20 ng/kg (I-TEQ OMS).

Modern pyrolysis facilities produce only very low levels of PCB, dioxins and furans, meaning that annual control can be considered sufficient. Thresholds are based on the soil protection regulations applicable in Germany and Switzerland (BBodschV, VBo, ChemRRV).

**Permitted test methods:** AIR DF 100, HRMS
6. Pyrolysis

6.1 Biomass pyrolysis must take place in an energy-autonomous process.
The energy used for operating the reactor (electricity for power drive systems, ventilation and automatic control systems, fuel for preheating, etc.) must not exceed 8% (basic grade) or 4% (premium grade) of the calorific value of the biomass pyrolysed in the same period. With the exception of preheating, no fossil fuels are permitted for reactor heating. Industrial waste heat (e.g. from cement or biogas production) or renewable energy sources like solar heat may be used for reactor heating in order to use the syngases for energy production or for motor fuel.

6.2 The synthesis gases (syngases) produced during pyrolysis must be trapped. They are not allowed to escape into the atmosphere.

6.3 The heat produced by the reactor must be recycled.
Approximately one-third of the energy contained in the biomass feedstock can be found in the syngas at the end of pyrolysis. Its combustion can in turn be used for heating the biomass, whereby additional waste heat is produced. At least 70% of this must be used for drying biomass, for heating, for generating electricity or for similar sustainable purposes.
Syngas can also be stored and used later for subsequent energy purposes.

6.4 Syngas combustion must comply with national emission thresholds for such furnaces.
With emission thresholds and regulations differing from one European country to the next, any further definition of emission thresholds for pyrolysis facilities would exceed the purpose and proportionality of these guidelines. Therefore manufacturers must provide a guarantee that their facilities comply with national emission regulations.
7. Sale and application of biochar

7.1 Fire and dust protection regulations are to be complied with throughout the production, transport and end-user chain.

7.2 During transport and bulk transfers attention must be paid to the biochar being sufficiently moist to prevent dust generation or dust explosions. The moisture content of the delivered biochar has to be given to ensure that the customer knows how much dry biochar he/she obtained.

7.3 Production workers must be equipped with suitable protective clothing and breathing apparatus.

7.4 Delivery slips must contain well-visible usage instructions and health and safety warnings.

7.5 When applying biochar on fields or in animal stables and housings, biochar must be kept slightly moist to prevent dust formation. In this respect, producers must provide appropriate information on the delivery slip or on packaging.
8. Quality assurance and certification

Biochar producers’ compliance with European Biochar Certificate requirements is coordinated throughout Europe by the independent quality assurance agency q.inspecta, with inspections of production plants in individual countries carried out by independent national inspection agencies. Inspections take place once a year. Producers confirm that they will keep up-to-date production records.

Producers may submit applications to q.inspecta to take part in the certification programme once their production starts. They are recommended to contact q.inspecta beforehand, enabling them to integrate the necessary recording into their production process.

bio.inspecta AG
q.inspecta GmbH
Ackerstrasse
CH-5070 Frick
+41 (0) 62 865 63 00
+41 (0) 62 865 63 01
admin@bio-inspecta.ch
9. References


Schweizerische Verordnung über Belastungen des Bodens (VBo, SR 814.12), 1998

Schweizerische Chemikalien-Risikoreduktions-Verordnung (ChemRRV, SR 814.81), 2005

Vierte Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes (4.BlImSchV), 1997
### Biomasses

<table>
<thead>
<tr>
<th>Origin</th>
<th>Biomasse feedstock</th>
<th>Special requirements for basic grade biochar</th>
<th>Special requirements for premium grade biochar</th>
<th>Biomass for charcoal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local waste collection services with waste separation</td>
<td>Biodegradable waste</td>
<td>No street cleaning waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biodegradable waste with kitchen waste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biodegradable waste with kitchen waste and leftovers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garden waste</td>
<td>Leaves</td>
<td>No street cleaning waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flowers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vegetables</td>
<td>Only waste not / no longer usable as animal feed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roots</td>
<td>Attached soil is deemed an additive and must not account for more than 10% of DM</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prunings from trees, vines and bushes</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chippings from nature conservation measures</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hay, grass</td>
<td>Only waste not / no longer usable as animal feed</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Agriculture and forestry</td>
<td>Harvest leftovers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Straw, used straw, husks and grain dust</td>
<td>Attention: health &amp; safety precautions where dust is involved</td>
<td>Only waste not / no longer usable for human consumption or as animal feed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grain, feedstuffs, fruit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prunings from trees, vines and bushes</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seeds and plants</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bark</td>
<td>Only from untreated</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bark and chippings</td>
<td>Wood</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wood</td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sawdust, wood shavings, wood wool</td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Kitchens and canteens</td>
<td>Kitchen, canteen and restaurant leftovers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetable production</td>
<td>Material from washing, cleaning, peeling, centrifuging and separator processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulp, pips, peelings, shreds or pomace (e.g., from oil mills, spent grain)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waterway maintenance</td>
<td>Raked off material, flotsam, fishing residues</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(vegetable material)</td>
<td>harvested material, water plants</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Animal by-products</td>
<td>Hides and skins, bristles, feathers, hair Bones</td>
<td>Subject to national hygiene regulations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials from food and confectionary production</td>
<td>Expired food and confectionary</td>
<td>only vegetable Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leftovers from the production of canned food</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seasoning residues</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Residues from potato, corn or rice starch production</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Residues from dairy processing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fruit, grain and potato residues, alcohol distillery residues</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brewer's grain, gerns and dust from spent hops in beer production, lees and sludge from breweries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Marc, wine lees, sludge from the winemaking</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tobacco, tobacco dust, slacks, ribs, sludge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tea and coffee grounds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fruit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Treacle residues</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oilseed residues</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mushroom substrates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fish residues</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eggshells</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Textiles</td>
<td>Cellulose, cotton and vegetable fibres</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hemp, sisal and other fibres</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>wool leftovers and wool dust</td>
<td>only from untreated Textile fibres</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper production</td>
<td>Paper fibre sludge</td>
<td>only from wood fibres not treated chemically (a contamination analysis of the paper fibre sludge must be presented)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant-based packaging material</td>
<td>Cotton and wood fibres</td>
<td>not chemically modified of solely natural origin, untreated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Origin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biogas plants</td>
<td>Fermentation residues</td>
<td>biomass for biogas plants must be produced sustainably</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Additives**
Additives are used to improve pyrolysis conditions and biochar quality. They must not total more than 10% of the pyrolysed biomass (DM).

<table>
<thead>
<tr>
<th>Group</th>
<th>Initial materials</th>
<th>Special requirements for basic grade biochar</th>
<th>Special requirements for premium grade biochar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral-organic ingredients</td>
<td>Lime</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lignite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bentonite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rock flour</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clay</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loam</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Applications for the inclusion of other biomasses not listed in the positive list may be submitted to the Biochar Science Network (www.biochar-science.net)