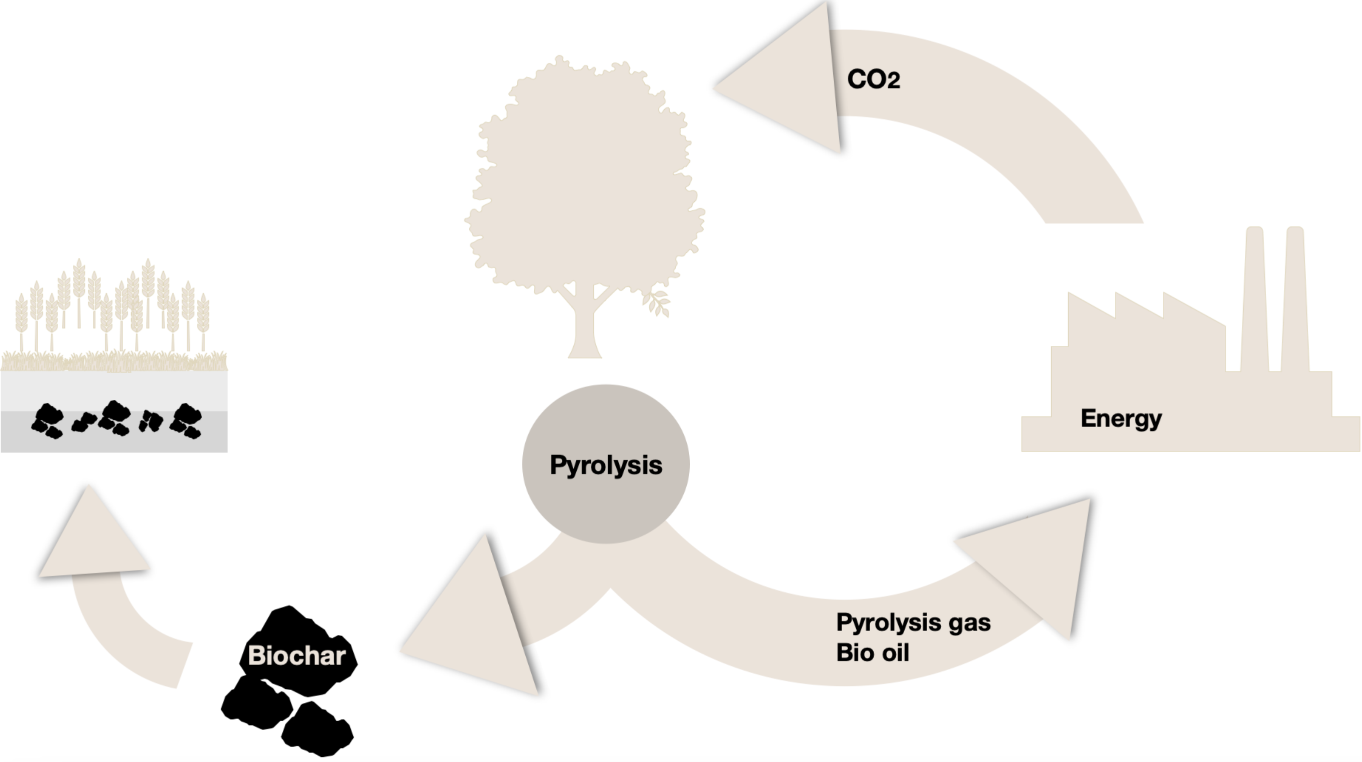

Biochar and the District Heating System

An investigation of how a district heating system may benefit from the implementation of a biochar production plant

Master’s thesis in Sustainable Energy Systems

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

Master's thesis 2021

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Typeset in LaTeX
Printed by TeknologTryck
Gothenburg, Sweden 2021

Abstract

In 2017, Sweden established a long-term climate goal of being CO_2-neutral by 2045 [1]. In order to reach this goal, 15% reduction of the CO_2 can be constituted of complementing measures, such as bioenergy carbon capture and storage (BECCS) and biochar. In line with the climate goal of Sweden, Göteborg Energi has set a goal of having a 100% renewable and recycled district heating system (DHS) by 2025. Biochar is one of the possible technologies that could contribute in reaching this goal.

The DHS in Gothenburg was modelled through a Linear Programming (LP) model in the software General Algebraic Modeling System (GAMS). A yearly biochar demand of 35,750 MWh, approximately 5500 tonne, was implemented. The model invested in the most suitable capacity for the biochar plant to fulfill the demand while keeping the yearly cost of the system as low as possible. Apart from producing biochar, the plant produce excess heat. In the model, the plant could choose to sacrifice biochar to only produce heat, providing some extra flexibility to the DHS. To investigate the robustness of the results the following parameters were evaluated in different scenarios: biochar demand, discount rate, variable cost, feedstock price, biochar price and reduction in investment cost.

The primary results showed no utilisation of flexibility and the capacity of the plant was instead decided by the biochar demand. The excess heat acted as a base load in the DHS during winter and the load of the plant was used to cover fluctuations in heat demand during summer. Flexibility was, however, initiated in four out of six scenarios. At low feedstock prices around 50-110 SEK/MWh, the production of extra heat amounted to approximately 9400 and 1000 MWh respectively. Further, a price of biochar have a significant impact on the investment of the biochar plant as increased prices shift the driving parameter from demand to generating an income to the DHS.

With suitable economic parameters, a biochar plant could offer both carbon negative DH as well as an energy buffer to the DHS. As flexibility is initiated between biochar and heat, the biochar plant becomes more of a intermediate load than a base load. There is still a scarcity in research regarding the technical possibilities of shifting from biochar to heat production, thus, more research is needed within this area.

Keywords: biochar, carbon sequestration, district heating, energy system modelling, linear programming, pyrolysis, biomass

Acknowledgement

We would like to thank each and everyone that has contributed to our thesis, either by sharing knowledge, helping us find the right person or contributing with uplifting words. Throughout our work we have been met with interest and collaboration from companies as well as municipalities for which we are grateful.

We would like to address a special gratitude to our supervisors at Göteborg Energi AB, Lennart Hjalmarsson, without whom, this project would never have happened, and Foluke Ishola for inspiring meetings and new perspectives.

Our warmest appreciation to our examiner Mikael Odenberger, who consistently broadens our horizons and helps us see challenges from a different point of view, and our supervisor Karl Vilén who can lift our spirits in every setback and keeps us on track.

At last, thanks to all of you who have made our days at the office a delight, you know who you are.

Sofia Rosén and Fanny Nilsson
Gothenburg, June 22, 2021

List of Abbreviations

Ag silver.
ASEK Analytical method of socio-economical calculations.

BECCS bioenergy carbon capture and storage.

CCS carbon capture and storage.
Cd cadmium.
CHP combined heat and power plant.
Cr chromium.
Cu copper.

DH district heating.
DHS district heating system.

EBC European Biochar Certificate.
EBF European Biochar Foundation.

GAMS General Algebraic Modeling System.
GHG greenhouse gas.
grot tree tops and branches.

Hg mercury.
HHV higher heating value.
HOB heat only boilers.
HP heat pump.
HTC hydrothermal carbonisation.

LP Linear Programming.

Ni nickel.
NPV Net Present Value.

PAC powdered activated carbon.
PAH Polycyclic Aromatic Hydrocarbons.
Pb lead.
PC pulverised coal.
PCB-7 Polychlorinated biphenyls No 7.
PFC Perflourinated compound.

SLU Sveriges lantbruksuniversitet.
SOU Statens Offentliga Utredningar.

Zn zinc.

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1 Introduction

Since pre-industrial times, the atmospheric carbon dioxide CO_2 concentration has continuously increased from 280 ppm [2], reaching 415 ppm in November 2020 [3]. The rising concentration of CO_2 traps heat and leads to global warming and other interrelated climatic changes. The main reason for the increasing CO_2 levels are fossil fuels burnt for energy [4]. To combat climate change, renewable energy sources such as wind, solar, hydro power and biomass are integrated [5]. Biomass was the first source of energy in human history, and remained the largest until the 20th century when fossil fuels took over [5]. Today, biomass is used as a source of fossil fuel-free electricity and district heating (DH) among other areas of applications.

All major cities and towns as well as several villages in Sweden have a district heating system (DHS) [6]. Common ways to supply heat to the DHS are through combined heat and power plants (CHP), heat only boilers (HOB), heat pumps (HP) and waste heat from industries. The fossil CO_2 emissions from DH has reduced significantly since the 1980's. The decrease in emissions is due to more bio-fuels as well as taking care of waste heat instead of using fuel oil and natural gas, but there are still measures that need to be done to improve it further [6]. In 2017, Sweden adopted a climate policy framework where the long-term goal is for Sweden to have zero net emissions by 2045 [1]. After zero net emissions have been accomplished, the next step is to produce negative emissions. For this goal to be achieved, several initiatives have been taken on national, regional and local levels [1].

In 2020, Statens Offentliga Utredningar (SOU) presented bio-CCS and biochar as technologies that can contribute in reaching the climate goals [7]. Bio-CCS is, however, still an expensive technology that suits better for large scale facilities due to scalable profits. Biochar production, on the other hand, can lower the net anthropogenic greenhouse gas (GHG) emissions and mitigate climate change while being a cheaper alternative to CCS. These technologies are seen as complementary measures in the climate goal and can be used to achieve up to 15% in lowering the net GHG-emission [1].

Apart from offering CO_2 capture, biochar offers several benefits to soils such as improving soil fertility and retaining water [8]. Using biomass from organic waste also gives the opportunity for organic waste to become a feedstock in producing biochar, moving the resources from energy recovery to material recovery in the waste hierarchy [7]. Also, the process of producing biochar results in excess heat that can be utilised in the DHS.

Small scale production and use of biochar is already available in Sweden [7]. Projects span from Helsingborg [9] and Österlen [10] in the south of Sweden to Stockholm [11] in the middle and Skellefteå [12] up north. The feedstock used is currently garden waste or agricultural residues from within the cities or the nearby region, or residues from the construction sector. The produced biochar is used as soil amendment in parks and tree-plantations or soil conditioner primarily. The capacity of the plants varies between 0.4-1.5 MW. In general, the biochar plants are connected to the local DHS, contributing with a steady amount of excess heat [9][13]. As more technologies need to be replaced in DHS to meet Sweden's climate goal, biochar plants could play an important role in contributing with carbon negative DH. Furthermore, by adjusting the ratio between the products biochar and heat, onwards referred to as flexibility, a biochar plant could contribute with other services to the DHS.

1.1 Aim and research questions

The aim of this project is to investigate if and when it is viable to shift from biochar production to producing heat to the DHS. The following questions will serve as a basis for the research:

- How do biochar plants work today and how can they contribute with flexibility to the DHS?
- Under what conditions is it beneficial to integrate biochar production in DHSs to gain flexibility from the plant?
    - What size benefits the DHS the most?
    - What influence does the market of biochar have on the flexibility and size?
    - When is it most beneficial to produce heat versus biochar over the year?
- What other benefits (aside from carbon separation) could a biochar plant supply to the DHS?

2 Literature study

To understand what parameters are important for biochar production, a literature study was performed. The study began with an overview of the element cycles of carbon, nitrogen and phosphorous in section 2.1 to continue with a more thorough description of biochar and the different aspects of biochar production in section 2.2.

2.1 Element cycles

Element cycling is the transport and transformation of chemicals within and among ecosystems and link the living and nonliving parts of ecosystems [14]. Biomass growth relies, foremost, on carbon (C), nitrogen (N) and phosphor (P) cycles.

The element cycling of C is usually divided into the slow and fast C cycles. In the slow C cycle, C moves between rocks, soil, ocean and atmosphere through a time period of 100-200 million years [15]. Through volcanic eruption, chemical weathering, erosion and sediment formation on the sea floor, the slow cycle exchanges C with the fast cycle [16]. The fast C cycle consist of C in the atmosphere, the ocean, and vegetation, soils and freshwater on land and could be measured in a lifespan since it is highly related to the life forms on Earth [17]. Through human manipulation, C from the slow cycle enters the fast cycle faster than it is returned to the slow cycle [16]. The increasing atmospheric CO_2 is caused by anthropogenic emissions primarily due to combustion of fossil fuels, converting forests into cleared land and making cement from carbonate rocks [18]. A way to avoid the combustion of fossil fuels is to use biomass-derived matter.

The use of biomass-derived matter can be considered to be part of a balanced cycle. Biomass grows and absorbs CO_2 from the atmosphere through photosynthesis and store C as organic compounds to later be harvested and utilised through e.g decay, combustion or animal respiration, emitting CO_2 back to the atmosphere [19]. For the cycle to close, the provided biomass should be grown sustainable, for example, in managed plantation forests. With sustainably grown biomass, the production and utilisation of products are near CO_2 neutral and offers the possibility to be CO_2 negative. As more C is restored to the ground than let out to the atmosphere, the net emissions can become negative. In addition, putting C in soil provides several services. Soil C boost the ability to retain water which in turn improve crop yield during droughts, decrease soil erosion and increase biodiversity [20]. Further, C in soil helps the retention of N and it promotes fungi that assist in plant uptake of N.

The availability of N is limiting the growth of biomass, especially in temperate forest and saltwater ecosystems. To increase crop production, humans manipulation on the natural N cycle is intense. The reactive N needed to increase yields is produced as a by-product from fossil fuel combustion [21]. The release of N manipulated by humans causes an excess of N that endangers the quality of air and water as well as the integrity of ecosystems. Fertilisers also add excess N intended to promote the crop production, but as leaching occurs, N is transported through streams to lakes and oceans, causing eutrophication.

Another limiting element for growth of any organism is P which is a key component in DNA, RNA, ATP and the formation of cell membranes [22]. The global phosphorus cycle is one of Earth's slowest, approximately 500 million years. Humans accelerate the P cycle through rock mining and distribution around the world as fertilisers, animal feeds and detergents. Of all phosphorus produced for food production, only one fifth is consumed by humans globally [22]. Phosphorous is primarily lost through erosion in agricultural lands, runoff manure and crop losses. The human alteration of the P cycle creates a closing problem as P moves faster towards the streams, lakes and the ocean than back to the bedrock. As P accumulates eutrophication, it threatens the aquatic ecosystems where it leads to overproduction of algae and consequently algae blooms. Furthermore, increased soil erosion, due to land use change, together with release of sewage sludge and leakages in septic tank leaks, leads to increased movement of P from terrestrial to aquatic ecosystems. Consequently, in order to prevent scarcity of P, its recovery from manure and sewage sludge is essential [22]. Biochar could play an important part in recycling of N and P while offering a potential C sink to combat climate change.

2.2 Biochar

Humans have been using carbonisation to produce charcoal from biomass for centuries [23]. Charcoal has been used for several applications such as heating, production of gunpowder and metal extraction. Figure 2.1 shows a simplified cycle of biochar. The following chapter aims to describe the importance of a well-grounded decision when choosing feedstock (2.2.2), pyrolysis process (2.2.3), biochar technology (2.2.4) and what use and markets that can be expected for the products (2.2.5). But first, an introduction to the definition of biochar and what policies to address is made in chapter 2.2.1.

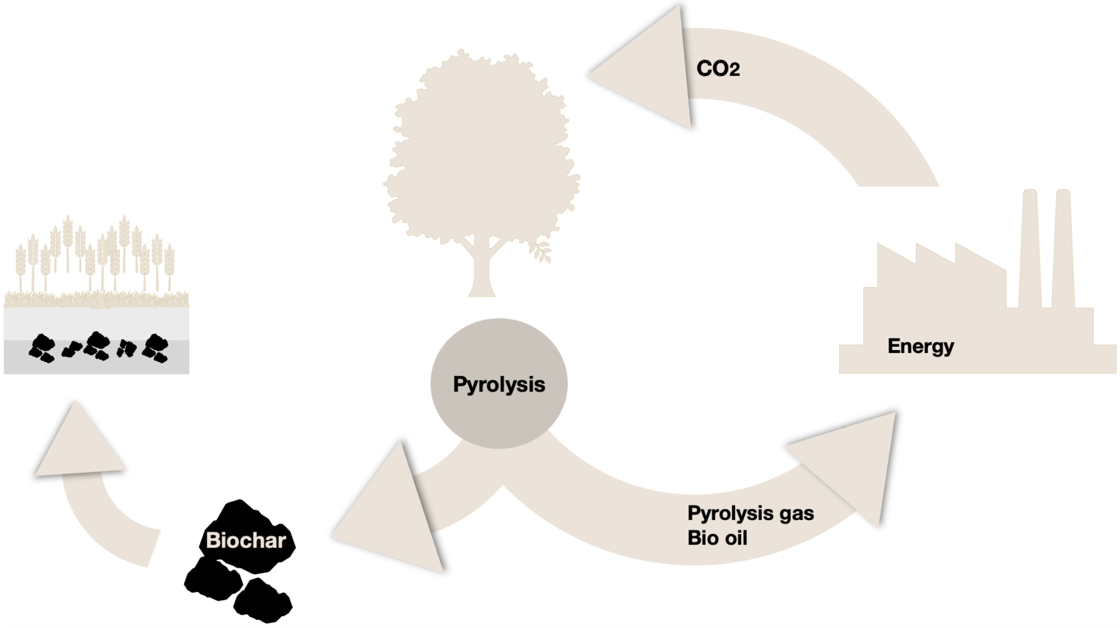

Figure 2.1: Simplified schematic of biochar production.

2.2.1 Definitions & policies

In the European Union, biochar was considered a waste until December 2019, and therefore regulated by the European Directive on Waste (2008/98/EC) [24][25]. As the majority of char was regarded as a by-product from bio-energy production it had to comply with waste protocols that blocked its agronomic utilisation. In 2019, it was decided that from the beginning of 2020, the use of biochar in organic farming as a fertiliser and soil conditioner within the European Union should be allowed. The new regulation defines biochar as a *"pyrolysis product made from a wide variety of organic materials of plant origin"* [25]. In line with EU's change toward acceptance of biochar, KRAV approved biochar in ecological farming in the end of 2019 [26]. KRAV is an economical association that strives for the progress of ecological and sustainable food production. The utilisation of biochar as a soil amendment for ecological products must comply with the restriction of heavy metals added to the soil [27]. The restricted heavy metals are lead (Pb), cadmium (Cd), copper (Cu), chromium (Cr), mercury (Hg), nickel (Ni), zinc (Zn) and silver (Ag) and are listed in table 2.1.

Table 2.1: KRAV's limitations of soil amendment for ecological farming [27]

Metal	**Pb**	**Cd**	**Cu**	**Cr**	**Hg**	**Ni**	**Zn**	**Ag**
g/ha_{year}	25	0.45	300	20	0.8	25	600	3

European Biochar Foundation (EBF) has introduced a voluntary certificate for biochar to secure sustainable production and utilisation of biochar. Consequently, a quality standard of biochar was put in place [28]. The definition of biochar according to the EBF is *"[...] a porous, carbonaceous material that is produced by pyrolysis of plant biomasses and is applied in such a way that the contained carbon remains stored as a long-term C sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation."*. The EBC specifies different qualifications for different areas of application such as animal fodder, industrial material, agricultural and organic agricultural usage. The biochar used in fodder has the toughest requirements followed by organic agricultural usage, agricultural usage and lastly industrial material. The EBC has a goal of being continuously updated to remain in the front edge with respect to environmental and technical development, but also to be in line with regulations in different countries.

The following requirements need to be fulfilled in order to produce EBC certified biochar [29]:

- All inorganic materials need to be removed.
- The feedstock must not contain colours, solvents or inorganic pollution.
- When agricultural products are used they must have been cultivated in a sustainable way.
- Forest residues must only be used when sustainable forest management can be ensured.
- The feedstock must not be transported further than 80 km to reach the plant.

2.2.2 Feedstock

In order to produce biochar, biomass is used as feedstock. Biomass generally contains large amounts of complex organic compounds, moisture and a small number of inorganic impurities [30]. The four most common elements in the organic compounds are carbon (C), hydrogen (H), oxygen (O) and nitrogen (N). Almost any biomass can be used to produce biochar but the produced biochar offers different properties depending on feedstock and pyrolysis process [7]. For instance, the fixed C content and nutrients contained in the biochar have a strong correlation to the feedstock used. The more homogenous feedstock, the easier it is to predict what characteristics the biochar will have. In the following section, manure, lignocellulosic waste and sewage sludge will be discussed further as these materials have been previously investigated and have been reported as potential substrates [29][31][32].

Manure

Untreated manure can lead to several environmental problems including N and P pollution of water, methane emissions and odour pollution [33]. Manure wastes are nutrient-rich and could offer benefits to soils as fertiliser apart from being a soil conditioner as biochar. Manure pyrolysis could reduce the problems with nitrogen leaching from soils compared to when manure is put directly in the soil as fertiliser. Furthermore, phosphorus and potassium could be almost completely recovered in the biochar. A competitive use of manure is biogas production. Through digestion of manure and food waste, biogas is formed together with a nutrient rich slurry that can be used as fertiliser [34].

A study made by Cely, P. *et. al.* [33] showed that the thermostability index increased with pyrolysis temperature for the analysed manures from pigs, chickens and cattle. A high thermostability index indicates the presence of stable C and biochar as a soil amendment could therefore be a way to enhance C storage in soils. Furthermore, the study presented a decrease in mobile forms of Zn and Cu after the pyrolysis process, reducing the risk of groundwater contamination in comparison to the direct application of raw materials.

Lignocellulosic waste

Lignocellulosic waste originate from woody plants and is primarily composed by cellulose, hemicellulose and lignin with low to moderate levels of inorganic components [35]. The pyrolysis of lignocellulosic feedstocks to biochar can reduce waste volume while avoiding gases such as CO_2, methane and nitrous oxide that are released when the waste is incinerated or decomposed through aerobic or anaerobic microbial metabolism. In a study made by Mitchell *et. al.* lignocellulosic municipal waste from three sectors were compared: institutional waste, demolition waste and garden waste [35]. In the study, biochars produced from construction wood were found to have similar properties to unprocessed wood biochar regarding low ash and volatile matter content as well as high fixed C content. Biochar from leaves and grass had higher ash content and lower amounts of fixed C. Biochar with a high amount of fixed C is typically preferable to provide a long term reservoir of C sequestration or to amend soils with low organic C content. In comparison, biochar with little fixed C and high ash yield can be useful to amend soils that require an enrichment of inorganic minerals.

Most of the current projects in Sweden, have chosen different kind of lignocellulosic waste as feedstock [9]-[12]. In Helsingborg and Stockholm, garden waste and waste from the city parks are the primary feedstock to which the biochar is later returned. Other companies, like Skånefrö, produce biochar from the residues from seed cleansing while Skanska plan to use conctruction residues. Grot, a Swedish acronym for branches and tree tops, is another example of lignocellulosic waste that could be used as feedstock and is currently used in CHPs to generate renewable electricity and heat. Grot generally comes from tree felling and industries where the tree trunk is of interest [36]. The price of grot is currently between 180 and 217 SEK/MWh_{fuel} [37][38]. When grot is retrieved from forests it is important to do it responsibly with regard to the local ecosystem [36]. Therefore, at least one fifth of the available grot must be left in the forest. The synthesis report by

Enegimyndigheten concludes that the harvest of grot can increase from today's 14 TWh to 24 TWh in a sustainable way [39].

Even though lignocellulosic waste is presented as one category of feedstock in this report, it is important to emphasise that even within this group, the characteristics of the biochar is highly influenced by the type of lignocellulosic waste that is used.

Sewage sludge

Production of biochar from sewage sludge have the potential of shifting sludge from an end-of-line product to a recyclable product. Sewage sludge contains high levels of humus and the nutrients phosphor and nitrogen [40]. Recycling of these materials would be beneficial for biomass growth as substitute to conventional fertilisers and mitigate depletion of the mineral cycles [22]. However, the toxicity of the sludge is limiting the spread of sludge on arable land [40][41][42] and, thus, the spread of biochar made from sewage sludge. In table 2.2, the limiting concentrations of lead (Pb), cadmium (Cd), copper (Cu), chromium (Cr), mercury (Hg), nickel (Ni), zinc (Zn), silver (Ag) and Polychlorinated biphenyls No 7 (PCB-7) are listed with regard to the Swedish law, voluntary EBC certificate and recommendations from the Swedish Environmental Protection Agency for year 2023 and 2030. As a reference, the mean concentrations of these substances from sludge leaving Ryaverket in 2012 are included. Ryaverket is a sewage treatment plant in Gothenburg. Applying these limitations on biochar for sequestration purposes creates challenges in the production stage due to intensification of different toxins [31]. Cd have a boiling point of 765°C and pyrolysis above the boiling point will cause the Cd to gasify and lower the concentration in the biochar. Aside from Hg, with a boiling point of 357 °C, the remaining metals in table 2.2 concentrate in the biochar [31].

Table 2.2: Concentration limit in mg/kg dry matter of different metals in sewage sludge based on law [43], EBC [28], Naturvårdsverket [40] and mean values from Ryaverket 2012 [44]

Element	**Law [43]**	**EBC [28]**	**2023 [40]**	**2030 [40]**	**Ryaverket 2012 [44]**
Pb	100	45	30	25	31.8
Cd	2	0.7	0.9	0.8	0.95
Cu	600	70	550	475	486
Cr	100	70	45	35	26.7
Hg	2.5	0.4	0.8	0.6	0.5
Ni	50	25	35	30	19
Zn	800	200	750	700	770
Ag	-	-	4	3	2.3
PCB-7	-	-	0.05	0.04	0.034

In the *Rest till bäst* project, pyrolysis of sewage sludge produced biochar with concentrations of copper, nickel, lead and zinc above the limitations for EBC organic agricultural usage at a pyrolysis temperature of 800 °C [31]. These elements have a boiling point above 800 °C, hence, an intensification can be expected.

2.2.3 Processes

The primary processes used to produce biochar are torrefaction, fast pyrolysis, slow pyrolysis, gasification and hydrothermal carbonization [45]. In figure 2.2 a simplified process schematic of the first four technologies is illustated. In the following chapter, these processes are described in order to give an understanding on how the different processes affect the heat production as well as the biochar characteristics.

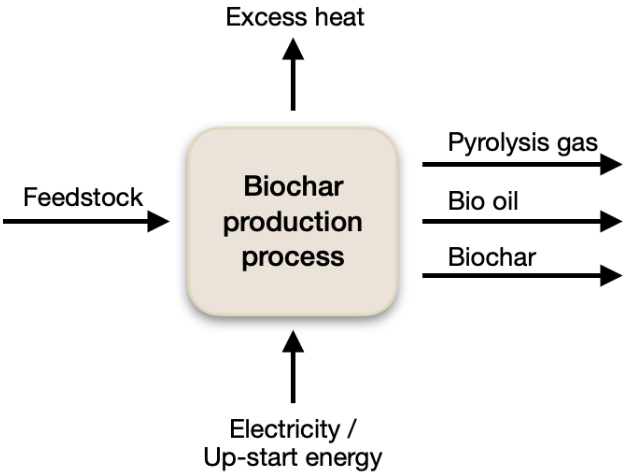

Figure 2.2: Simplified schematic of a standard biochar production process.

Torrefaction

Torrefaction and pyrolysis are thermal decomposition processes in inert or limited oxygen environments. In torrefaction processes, biomass is slowly heated at a maximum rate of 50 °C/min to a temperature of 200-300 °C [23]. The biomass is retained in the temperature range until it is near complete degradation of its hemicellulose content while the mass and energy yield is maximised on the solid product. The aim is to increase the energy density of the biomass by increasing its C content while decreasing its oxygen and hydrogen content. The heating value of biomass is rather low compared to most fossil fuels, especially on a volume basis [30]. In order to maximise the solid yield of the process, it is important to have a slow heating rate. With a higher heating rate, the liquid yield could increase at the expense of solid products, such is the case for pyrolysis.

Pyrolysis

Pyrolysis of biomass is generally performed in a temperature range of 300 - 650 °C [23] and is divided into fast and slow pyrolysis depending on temperature and residence time fast. During fast pyrolysis, the feedstock is heated to around 500 °C in approximately 1 second [29]. Fast pyrolysis is the only of the introduced processes that directly delivers a high yield of liquids of approximately 75%, while less gas (13%) and char (12%) is produced [46]. The purpose is generally to maximise production of liquids for upgrading to transport fuels [47]. Biochar from fast pyrolysis is typically very fine and difficult to handle and may be contaminated with the sand material used as fluidising medium. Furthermore, there are limited data on the characteristics of the biochar produced from fast pyrolysis [47].

In slow pyrolysis processes, biomass is heated to lower temperatures, about 400 °C, through a longer time of minutes to days. The process leads to a maximised biochar yield of 35 % [29] but results in equal yields of gas (35%) [48]. The remaining 30% of products are liquid. The exact ratios vary in literature. Pyrolysis is a necessary pre-step in gasification.

Gasification

Through gasification, carbonaceous solids, liquids and gaseous fuels are converted into desired gaseous products with a usable heating value [23]. The gaseous product can be used as fuel to produce heat or for production of chemicals. In gasification processes, the H:C ratio is generally increased while combustion oxidises the C and H into water and CO_2. A gasification process typically involves several steps, such as: drying, thermal decomposition or pyrolysis, partial combustion of some gases, vapours and char and gasification of decomposed products. During gasification, biomass is partially oxidised at temperatures of approximately 800 °C for 10-20 seconds [49]. The pressure in the process can be either atmospheric or elevated. Unlike torrefaction and pyrolysis, gasification requires a gasifying medium such as steam, air or oxygen. The main product from the process is gas [49] of about 85% [48]. Small amounts of char (10%) and liquids (5%) are formed. Biochar produced from gasifiers undergoes higher temperatures and an oxidative environment and is therefore partially combusted [47]. The properties of the char depends on the technology used to gasify the biomass.

Hydrothermal carbonisation

While torrefaction, pyrolysis and gasification are effective for dry biomass, they become inefficient for biomass with high moisture content [23]. For biomass with high moisture content, the moisture would first have to be driven away. A technology that uses the high moisture content as a benefit is hydrothermal carbonisation (HTC). In HTC, biomass undergoes elevated temperatures of 180-220 °C in a suspension with water under elevated pressure for several hours [49]. Since the moisture in the biomass is used in the process, energy that would otherwise be needed to dry the feedstock can be saved. No oxygen is supplied to the reactor with biomass-water suspension, making it a pyrolysis process. From the HTC process, gas, aqueous chemicals and solid products, here called hydrochar, are produced [23]. In figure 2.3, a simplified schematic of the HTC process is presented.

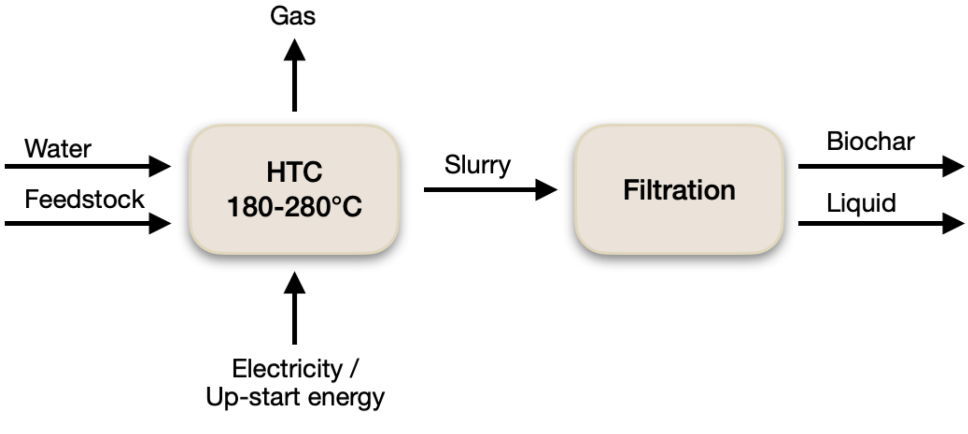

Figure 2.3: Simplified schematic of a hydrothermal carbonisation process.

Summary

From the processes discussed above, it can be summarised as lower process temperatures and longer vapour residence times favour the production of biochar. High temperatures and longer residence times increase biomass conversion to gas, and moderate temperatures and short vapour residence times are optimal for producing liquids [48]. The different processes are summarised in table 2.3.

Table 2.3: Temperatures, residence times and typical product yields from biochar production of wood for different processes [23][47][48][50]

Process	**Temperature (°C)**	**Residence time**	**Liquid (%)**	**Char (%)**	**Gas (%)**	**C content of solid product (mass%)**
Torrefaction	200-300	10-60 min	-	52-89	-	51-55
Slow pyrolysis	300-650	min to days	0-15	20-50	40-75	95
Fast pyrolysis	400-600	~1 s	40-70	10-25	20-40	74
Gasification	500-1,500	~10 to 20 s	0-5	5-15	85-95	-
Hydrothermal carbonisation	180-220	1-12 h	0-80	0-60	0-90	<70

2.2.4 Technologies

In 2018, a study made by Pamoja Cleantech AB compared four different biochar production technologies through a SWOT analysis[51]. The technologies were chosen from two criteria:

1. Scale of System: Possibility to turn 10.000 tons of biomass per year into biochar with one or several units
2. Reference of installed systems: The manufacturer would need to have a minimum of five references in the field of pyrolysis. No manufacturers in pilot or demonstration stages were considered.

This comparison resulted in the following technologies: batch kiln reactor, reactor with internal auger, rotary kiln reactor and reactor with internally heated spiral or auger. Since the two criteria benefits this study as well, the four technologies will be described further in the following section. In addition, suggested technologies to produce biochar through fast pyrolysis and gasification are introduced.

Batch kiln reactor

In the batch kiln reactor, different kind of biomass is heated with hot pyrolysis gas within the reactor kiln at temperatures of 400-700 °C [51]. Before the biochar is packaged, it is slowly cooled down in the kiln. From this processes close to 50% of a plant's C content can be transferred into an inactive C pool where it stays as stable C. Through the process, both heat and electricity can be generated [52]. The advantages of the technology include its relatively high temperature control, efficient heating process and simple and robust system. The disadvantages are the long cooling periods of a few days that require large area and that full automation might not be available, among others [51].

Screw reactor

Screw, or auger, reactors were first applied in 1969 for biomass pyrolysis and could be used for both fast and slow pyrolysis processes [53]. An auger reactor is generally composed by a tubular externally heated wall with an auger within the reactor that transport and stirs the feedstock to improve the heat transfer between the feedstock and the heated wall. Using a motorised auger prevents the feedstock from coagulating and makes it possible to regulate the residence time of the feedstock in the reactor.The exhaust gas, of approximately 1,400 °C, of the chamber is recirculated through the outer chamber of a double-walled reactor. The exhaust gas does not have any direct contact with the feedstock within the reactor. Screw reactors can be built in modular layout and configured as pre-installed of-the-shelf units. The benefits of a reactor with internal auger are among others the compact and modular design, a low energy requirement and the fully automated and remotely controlled system. The disadvantages of the technology include that the moving parts in a hot environment causes wear, tear and fatigue of steel, clinkers, the difficulties in temperature control and the relatively high investment cost.

Rotary kiln reactor

In a rotary kiln reactor, the kiln is heated inside the combustion chamber and is rotated outside of the chamber and is a typical example of a slow pyrolyser [47][51]. Biomass is continuously fed to the top chamber of the rotary hearth where it is rapidly heated, dried and pyrolysed [54]. Inside the hot environment, the feedstock is moved with internal fins and gravity providing a higher flexibility in terms of feedstock particle size compared to the screw reactor [51]. The system can also be scaled easier [54]. Studies show that the ratio between condensable and non-condesable vapours can be regulated through biomass feed rate and operating temperatures while the biochar ratio is rather constant in the range of 20-24% [47]. Through partial combustion of volatile gases, the process becomes autothermal [54].

Inside the hearth, the temperature and oxygen profiles are regulated to achieve the desired char yield and quality but can also affect the heat yield. Temperatures may vary between 450 and 700 °C inside the hearth. The system also offers a rapid start-up time, from cold to full throughput in 60-90 minutes. Largest available plant produce 4.4 MW heat and requires diesel for light-up. The benefits of the technology are among others the compact and modular design, a 2-stage principle that allows high control of biochar process and quality, that no drying is required, a fully automated and remotely controlled process and the relatively low investment cost [51]. The drawbacks are among others that clinkers may form and that the exhaust gases from the reactor potentially could affect the biochar quality.

Internally heated auger reactor

A reactor with an internally heated auger, or spiral, differs from the previous screw technologies in that the auger in itself is electrically heated [51]. Using a spiral (an auger without the shaft) with properties like a spring, it avoids shear forces, avoiding fatigue in the material. The spiral is also in direct contact with the biomass which makes it easier to adjust the temperature in the process and thereby predict the quality of the biochar.

The temperature can be set in a wide temperature range up to 800 °C. Thereby, making it possible to use the technology for torrefaction, pyrolysis and gasification processes based on the desired products [55]. Furthermore, the speed of the spiral makes it possible to regulate the residence time. To gain heat from the pyrolysis process, heat exchangers and further conversion of the pyrolysis gas are needed. The strengths of the internally heated spiral are among others the robust and reliable principle, high control of temperature, compact and modular design and fully automated and remotely controlled [51]. The disadvantages are that the feedstock needs drying and the high power demand that makes it dependent on the electricity price. To solve the high power demand, utilisation of the process heat for electricity can be an alternative, at the expense of decreasing the output heat to the DHS.

Gasifiers

So far, the technologies presented has mainly focused on slow pyrolysis, to continue, technologies suitable for fast pyrolysis and gasification will be described. For fast pyrolysis, the high heat and mass transfer rates obtained in fluidised bed reactors, make them ideal [47]. When biochar is produced as a co-product during gasification of biomass, different gasifiers designs greatly influence the biochar yield, type and quality [47]. The gasifiers most suitable for co-production of producer gas and biochar are updraft, downdraft and fluidised bed. Downdraft gasifiers are typically used for capacities between 10 kW and 1 MW while updraft gasifiers are used for larger capacities between 1 MW and 10 MW. Fluidised bed gasifiers are typically built for capacities between 1MW and 100MW.

Updraft gasifiers show several similarities with charcoal kilns apart from the availability of oxygen in the gasifier [47]. A drawback is the large quantities of tar in the produced gas while an advantage is the relatively low investment cost of the plant. Downdraft gasifiers force the tarry vapours through a zone of hot charcoal were they decompose resulting in a producer gas that is relatively free of tar. The disadvantages are the need for tightly controlled fuel properties and a tendency for sintering of ash.

In a fluidised bed gasifier, biomass is injected into the bed where it is rapidly heated and pyrolysed. Advantages of fluidised beds are the possibility to scale them into large sizes and that they can process a wide variety of fuels [47]. The drawbacks include relatively high power for gas blowers and high particulate loadings in the gas leaving the fluidised bed. Even though there are several possibilities for producing biochar through gasification, there is a scarcity of reported data that investigate the relationship between processing conditions and properties of the biochar for agronomic and environmental management. In the literature regarding gasifiers, a focus on gas production is dominant.

2.2.5 Products and their markets

Products from the pyrolysis process are bio oil, pyrolysis gas, biochar and heat that can be used in district heating systems [7]. Bio oil can be used to replace fossil oil or diesel in applications like boilers, furnaces, engines and turbines for electricity production [48]. Bio-oil has a heating value of approximately half of conventional fuel oil. Furthermore, different chemicals such as food flavourings, fertilisers and emission control agents can be extracted or derived from the oil.

Pyrolysis gas is a combination of carbon monoxide, hydrogen, carbon dioxide, methane, ethane, propane and nitrogen [48]. The gas can either be combusted for heat and electric-

Table 2.4: Biomass throughput, biochar output, heat or pyrolysis gas, pyro oil and CAPEX for different technologies [51].

Technology	Biomass throughput (t/h)	Biochar output (w %)	Heat or Pyrolysis gas (kW)	Pyro Oil	Indicative CAPEX (euro)
Batch kiln reactor	0.5	40	700	Yes	600,000
Screw reactor	0.56	25	900	No	1,000,000
Rotary kiln reactor	1.3	25	4,330	No	1,800,000
Internally heated auger	0.7	30	1,200	Yes	1,300,000

ity, used in the chemical industries, by being converted into methanol or hydrogen, or be refined to become fuel replacing fossil oil and diesel.

Biochar consists of elements such as carbon, oxygen, hydrogen, sulphur and nitrogen as well as minerals [56]. What applications biochar is suited for are highly dependent on feedstock and pyrolysis process and biochar can therefore be considered a heterogeneous product [29]. The specific area of biochar varies from 100 m^2/g to 1,400 m^2/g and the density span from 190 kg/m^3, produced from pine, to 270 kg/m^3, produced from salix [29]. Further, in a study made by M. Mierzwa-Hersztek [57] the higher heating value of biochar made from sawdust was estimated to 23.4 MJ/kg, but spanned from 16 MJ/kg from poultry litter to 26 MJ/kg from miscanthus straw.

Soil amendment

The porous structure and large surface area make it easier for biochar to adsorb nutrients, fluids and pollution [7]. Biochar used as soil amendment also offers a C sink, making it beneficial from two perspectives [29]. With more C in the ground, the vegetation increases and coal is bound to the growing plants. As plants grow on the ground, the soil becomes more fertile. For soils with poor nutrients, biochar can make it possible to replant forests and cultivate the soil. The soil amendment qualities are foremost obtained when biochar is used in combination with nitrogen as nutrient. When vegetation is increased through biochar and nitrogen use, the use of synthetic fertilisers can be reduced at the same time as the water retaining capability in muddy soils is improved. The water retaining qualities help to keep the nutrients from being leached out.

Since the production of fertilisers is an energy intense process, energy can be saved by the utilisation of biochar [29]. For urban soils contaminated with Polycyclic Aromatic

Hydrocarbons (PAH), a group of chemicals that occur in coal, crude oil and gasoline, activated biochar has showed absorbing properties [58]. Today, Sweden import biochar, mainly from Germany, the Baltic states and Finland to fulfill the need for biochar in soil amendment, indicating that there is a market for locally produced biochar [32]. The price for the imported biochar is varying between 3,800 - 15,000 SEK/tonne [32] while the Statens Offentliga Utredningar (SOU) provides an average market price of 4,500 - 6,000 SEK/tonne [7]. In a report from Anderson et al. [29] the price was estimated to 2,600 - 3,000 SEK/m3 for biochar as soil amendment in Sweden.

In 2020, the interest for biochar in the surrounding municipalities to Gothenburg was investigated [59]. Out of the ten municipalities asked, nine expressed an interest in producing biochar as a way to handle waste and six an interest in biochar as a product [59]. The volumes of biochar were however rather small and the largest demand came from the Gothenburg region with 670 tonnes per year. The company Renova in Gothenburg, together with the municipality, is currently looking into the different prerequisities needed for a biochar plant [60].

Agricultural profitability

Biochar implemented in agricultural soils have the possibility to reduce soil acidity, improve soil cation exchange capacity, pH, water-holding capacity and improve the habitat for soil microbes [61]. The char is not in itself a fertiliser but functions as a catalyst in soil where it sustains water and nutrients [29]. In liquid manure and deep litter beddings, ammonia can be bound to biochar. As biochar retains nutrients, the leakage of these substances can be reduced in the agricultural sector. The ability for biochar to retain nutrients depends on feedstock, pyrolysis technicalities, soil and nutrients. The reduction has been measured to span between 5-94% [29]. The reduction of leaking nutrients do not only benefit the farm, but also the surrounding areas. Fertilisers that reach lakes and oceans, lead to eutrophication that contribute to poisonous algal blooms and dead seabeds in Östersjön. The leakage of nutrients to Östersjön is a prioritised problem that put value on biochar, both as a measure and economically.

The increase in pH in the soil leads to a reduced need for structural liming [29]. Further, the soil quality and soil ecosystems are improved as the amount of organic material is increased. With biochar contributing to soil amendment, increased yields may be obtained. The effect becomes more significant for poor soils. Increased soil qualities open up for reforestation, which contributes to reduced soil erosion and CO_2 in the atmosphere. In Sweden, 2.65% of agricultural soils are estimated to be depleted [29].

The market for biochar in the agricultural sector is seen as one of the most promising [32]. Even though there is currently limited research regarding the profitability in crops yield of using biochar, the potential as a carbon sink is considered to be large. The price of biochar with qualities suited for agriculture is estimated to be 10,000 - 12,000 SEK/tonne [32]. A price of 10,000 - 12,000 SEK/tonne is generally seen as too high in relation to the potential increase in crops yield whereby subsidies most likely are needed to make it profitable for farmers. Currently, public opinions differ regarding using biomass for biochar as a C sink versus other uses of biomass. However, soil C have a saturation point and thus more benefits will be gained from sequestration of C in soils further from saturation [62].

Sequestration of C from the atmosphere

For biochar to become a stable C sink, the temperatures during production must be above 450 °C [7]. This is because biochar produced at high temperatures result in low levels of hydrogen and oxygen and have a porous structure with large surface area. With an O:C ratio below 0.2, biochar has a half-life between 100 to 1,000 years [31]. The lifetime in the soil is determined by the C binding abilities of the char. Further, the low amount of hydrogen and oxygen gives biochar a higher stability compared to other biomass and is therefore considered resistant to degradation [7]. For best outcome as a C sink, it is therefore preferable with slow pyrolysis at high temperatures (>450 °C)[7]. In table 2.5, the quality for biochar from different feedstock is compiled with regard to its C sequestering abilities.

Statens Offentliga Utredningar (SOU) suggests a subsidy of 900-2800 SEK/tCO_2 for CO_2 emissions that are avoided [7]. Subsidies for a C sink can be compared to the implemented C tax of 950 SEK/tCO_2 [38]. Further, Trafikverket have in the report Analytical method of socio-economical calculations (ASEK) assessed the socio-economical cost for CO_2 eq [63]. The 6th edition recommend an ASEK vaule of 1.3 SEK/kgCO_2 for 2021 but increased significantly in the 7th edition to 7 SEK/kgCO_2. The ASEK value is highly dependant on political means and to be able to reach the current environmental goals a value of 13-17 SEK/kgCO_2 is needed. However, in order to prevent a sudden increase in demand of bio-fuels a maximum value of 7 SEK/kgCO_2 is legislated for the transport sector and lay the ground for the recommended ASEK value [63]. The CO_2 sequestration potential can be calculated from equation (3.2).

$$CO_2\ seq = \frac{44}{12} \cdot \frac{ASEK \cdot ratio_C \cdot B_y}{HHV} \tag{2.1}$$

Where the fraction 44/12 represents the conversion from C to CO_2. The $ratio_C$ is the ratio of carbon in the biochar. B_y is the amount of biochar and the higher heating value (HHV) is used for conversion from MJ/$\text{kg}_{\text{biochar}}$ to SEK/$\text{MWh}_{biochar}$. With a carbon content of 95% (see table 2.3), and a mass conversion of 44/12, one kg of biochar would represent approximately 3.5 kgCO_2.

Animal feed

Charcoal has historically been used to reduce indigestion for both animals and humans [29]. In Switzerland, Austria and Germany, 90% of biochar produced is used in animal feed [7]. The biochar mixed in fodder requires the highest quality in order to get an EBC certificate [28]. Biochar counteracts diarrhoea and adsorb E-coli and salmonella which reduce the risk for the bacteria to spread through the manure [29]. Several studies indicate that the use of antibiotics have been reduced through the use of biochar. This has partly to do with the fact that the hygiene in stables increases. The general health and vitality has increased when biochar is added to the animal feed together with reduced odour from the manure [29]. Furthermore, studies show that methane from ruminants can be reduced with 12.5-20% if 0.5-0.6% of the feed is biochar. However, the results vary and some studies show no affect from introducing biochar in the feed.

If manure from animals, with feed containing biochar, is spread on soil, it reduces the need for nitrogen fertiliser and sequest the C in the soil [29]. Kamman *et al.* [64] estimate a reduction of 1.2% of global emissions if 1% biochar is put in feed for all cattle. A market

Table 2.5: Characteristics of biochar produced from bioagro-pellets from sludge, park and garden waste and sewage sludge [31]

	Bioagro-pellets	**Park & garden waste**	**Sewage sludge**
Biochar per pre-treated feedstock (%)	33	34	50
Moisture content (%)	25	25	33
C content, dry (%)	70	65.5	33
O:C	0.054	0.053	0.089
H:Corg	0.38	0.23	0.54
Stability (%)	95	95	95
Correction factor (%)	95	95	95
CO_2 sequestration (kg)	2.31	2.16	1.09

for biochar as an animal feed does not exist in Sweden today, primarily due to the lack of research within the subject. As research is limited, few farmers are willing to take the risk that is associated with the production and wealth of the animals since it could affect their profits. In a study made by Anderson *et al.* [29], the interest from farmers to use biochar as animal feed is however large and a theoretical calculation suggest an annual need for 150 000 tonnes of biochar with a turnover of 1 780 MSEK if biochar is added to all production animal feed.

Steel industry

Until now, the applications and markets presented have been limited to biochar as a product. In the following applications, biochar offers a replacement of fossil coal. As replacement of fossil coal, one of the principles of biochar is violated, since the C is released back into the atmosphere. Charcoal is used as an alternative term as the C is released into the atmosphere. Replacing fossil coal could reduce the net emissions from coal extraction and processes as a whole.

In Sweden, the industry sector accounts for approximately 32% of the total national greenhouse gas (GHG) emissions in 2019 [65]. Within the industry sector, the iron and steel industry produced 38% of the GHG emissions where the most contributing processes are the combustion of industrial residual gases from coking plants and iron and steel processes and the use of coke as reducing agent in furnaces. New processes focus on substituting CO with H_2 as reductant, to produce H_2O rather than CO_2, or using CCS. However, as steel needs between 0.3-3% C there will still be a need for C in the steel production. As an alternative, biomass-derived renewable fuels are investigated to substitute non-renewable fuels such as coal, fossil stone coal or coke, natural gas and oil [19].

Most research regarding biomass derived fuels in steel production has focused on charcoal injection to blast furnaces [66]. Injection of charcoal instead of coal to blast furnaces leads to lower plant site, process and life cycle CO_2 emissions. For injected reducing agents ignition, reactivity, chemical composition and physical properties are important [66].

The difference in chemical and physical composition between fossil coal and coke, and solid biomass derived alternatives provides both opportunities and barriers. For example, the high reactivity of biomass benefits injection in blast furnaces but too high reactivity may decrease the iron ore sintering efficiency. Furthermore, charcoal with a high C ratio, compared to coal, can exhibit advantages such as higher calorific value, higher fixed carbon content, lower contents of impurities, larger porosity and higher surface area [45], especially if it is based on wood. Compared to fossil stone coal, biochar in form of charcoal shows lower fixed carbon content and calorific value but contains less impurities, such as sulphur, and ash.

Modelling studies made in Bio4Metals [67] show that the fossil emissions can be reduced up to 34% as the injected fossil pulverised coal (PC) is replaced with charcoal with high C ratio. The amount of CO_2 emissions that can be reduced depend on the characteristics of the biochar. Charcoal with a low O:C ratio and low amount of volatile matter gives a higher replacement ratio and can replace PC with 100%. In order for charcoal to reach the carbon content and heating value of coal and coke, a pyrolysis temperature above 500 °C should be used [68].

The largest threat to using biomass derived reducing agents in iron and steel making is the high price compared to fossil alternatives together with the limited research [66]. There is a need for production platforms that could increase the competitiveness of biomass derived reducing agents. Another way to shift the steel industry towards more biomass derived substances is increased carbon tax. Gaseous and liquid biomass derived fuels, such as biogas and bio oil, could also contribute in lowering the CO_2 emissions from steel production.

Filling material in asphalt and concrete

In 2019, the mineral industry accounted for 18% of GHG emissions within the industry sector in Sweden. The process producing most GHG emissions is the calcination of limestone and dolomite in cement production [65]. The benefit of using biochar as a filling material is foremost the stable C sink and the possibility to reduce emissions from cement production [29]. Biochar used in concrete and asphalt is not only beneficial as a C sink during the user phase but continues in large extent after demolition. For every cubic meter of concrete produced, approximately 200 kg of CO_2 is produced depending on additives and class [29]. With 25% of the filling material replaced with biochar, the CO_2 produced becomes approximately 46 kg, resulting in a reduction of 77% compared to conventional materials. In order to make concrete C neutral, one third of filling materials must be replaced with biochar. With 50% of filling materials being replaced with biochar, the concrete becomes a C sink of 110 $kgCO_2/m^3$concrete. For concrete to be a sustainable way of storing C, it is important to maintain the properties of the concrete with an increased share of biochar as well as it being economically competitive. The effects of using biochar as filling material in concrete needs to be studied further. As the knowledge is currently limited, a market for biochar within the concrete sector does currently not exist.

According to Anderson *et al* [29], the price of filling material is currently 100 - 150 SEK/-tonne. The relatively low price of the filling material makes it difficult for biochar to be competitive. Therefore other benefits are crucial for biochar to outcompete other materials, such as providing environmental profits to the industry. Furthermore, biochar is more likely to substitute plastics and leca as it has the potential of making cement lighter. The price for plastics and leca is somewhat higher than the price for filling material [29].

Filtration

Some wastewater treatment facilities use powdered activated carbon (PAC) to adsorb organic micro-pollutants that have negative impact on aquatic life and downstream drinking water quality [69]. The C used to produce PAC is usually generated from nonrenewable coal and requires energy-intensive thermal activation to develop adsorption properties. Biochar from wood offers adsorbent properties with improved environmental performance compared to PAC primarily due to C sequestration and energy production during pyrolysis. Furthermore, the low weight of biochar (190-270 kg/m^3) [29] compared to sand (1,700 kg/m^3) and activated C (560 kg/m^3) makes it easier and cheaper to transport [29].

Studies at Sveriges lantbruksuniversitet (SLU) conclude that biochar filters have a high cleaning capacity for pure organically degradable materials during different hydraulic loading rates and grain size [29]. The adsorption of ammonia varies between 90-99% and the total amount of nitrogen decreased between 62-88%. The reduction of phosphorous was also noted as significantly better with an activated biochar filter rather than a sand filter or unactivated biochar that showed similar results as sand. In studies, a 95-99% reduction of medicine residues was observed as well as 89-99% reduction of Perflourinated compound (PFC) [29]. In Helsinki, Finland, biochar has been used in a filtration system placed in a stream where storm water from an industry area was discharged [70]. Apart from reducing the amount of oil, nutrients and heavy metals, the concentration of cadmium, cobalt, chromium, nickel, copper and oil were reduced.

Industrial utilisation of biochar as a filter material is currently not in use in Sweden although there is some knowledge about it [29]. Instead, activated C is used in the municipal water distribution system and sewage treatment. The price on activated C is 10,000 - 30,000 SEK/tonne in applications where biochar could replace it with a potential yearly demand of approximately 4,000 tonne [32]. Even though there is limited knowledge of biochar as a filter, the interest from the actors seem to be high [29].

Energy

At last, regardless of feedstock and process, biochar can be used as a fuel to produce heat and electricity. However, biochar where the C is released back into the atmosphere and environment can not be considered a C sink and is therefore labelled biocoal. To produce biocoal, torrefaction is commonly used. If biocoal is used for energy, the income is related to the other fuels in the system, according to the merit order.

3 Method

As the different aspects affecting biochar production were understood, the study focused on investigating how a biochar plant could interact with the DHS. To represent the DHS, a linear programming model approach was chosen. Using a model to represent the DHS offers several benefits. For instance, it can act as a tool to make a complex reality into a simpler form making it easier to comprehend and analyse [71]. An established model also makes it easier to evaluate several scenarios to broaden the results. As a better understanding of the system is achieved, well-founded decisions can be made. There are several different energy system model approaches, and for this project a linear optimisation model was chosen. A linear optimisation model consists of parameters, variables and sets that are related through linear constraints and are adjusted to minimise or maximise a linear objective function [72]. The optimised result is found within a feasibility region, a region were all points comply with all constraints. To model the DHS, the software General Algebraic Modeling System (GAMS) was used.

The data used in the model is introduced in section 3.1 and 3.2 for the reference DHS and biochar plant respectively. The method continues with a description of the objective function and constraints in section 3.3 and the scenarios evaluated in chapter 3.4.

3.1 District heating system parameters

The parameters for the DHS used in the model was based on the DHS in Gothenburg that is owned by Göteborg Energi AB. Göteborg Energi AB is an energy company that provides the city of Gothenburg with electricity, heating, cooling and fiber. In line with the climate goals for Sweden, Göteborg Energi AB is working for a sustainable city and to reduce their impact on the environment [73]. The DH piping network is close to 123 km long and Göteborg Energi AB has decided for the system to only use renewable energy or recycled waste heat from 2025 [74]. Today, a large part of the heat in the system comes from industrial waste heat [75]. When temperatures get lower, bio- and gas-fuelled CHPs are used. In order to meet the peak demand, pellets-, gas- and oil-fuelled plants as HPs and HOBs are started. The power-to-heat ratio of the CHPs was assumed constant in the model. The different facilities within the DHS as well as the available fuels were implemented as sets to the model and are compiled in appendix A.

The linear programming model was based on the DHS of Gothenburg, as it can be seen as a representative DHSs due to its technologies [76]. In this thesis, it was assumed that the existing plants remained in the system and that a biochar plant complemented it. The heating demand used in the model was based on the demand in Gothenburg during 2012 and had an hourly time resolution [76]. The variable electricity price used to balance the production cost of the CHP and HP units was from 2012 with an hourly time resolution as well [76].

A merit order of the different technologies in the system is presented in figure 3.1. The merit order was used to understand during which conditions the system chose to produce heat instead of biochar. Fuel costs and O&M costs as well as CO_2-taxes and energy taxes were taken into consideration when constructing the merit order. To simplify the figure, a constant mean value of electricity was chosen which have a flattening impact on the technologies that produce or use electricity, in this caseCHPs and HPs. Since the electricity price has an hourly time resolution, the placement of these technologies in the merit order will change over time. Based on the technology that was on the margin at the observed time in relation to the biochar production, patterns could be found and analysed.

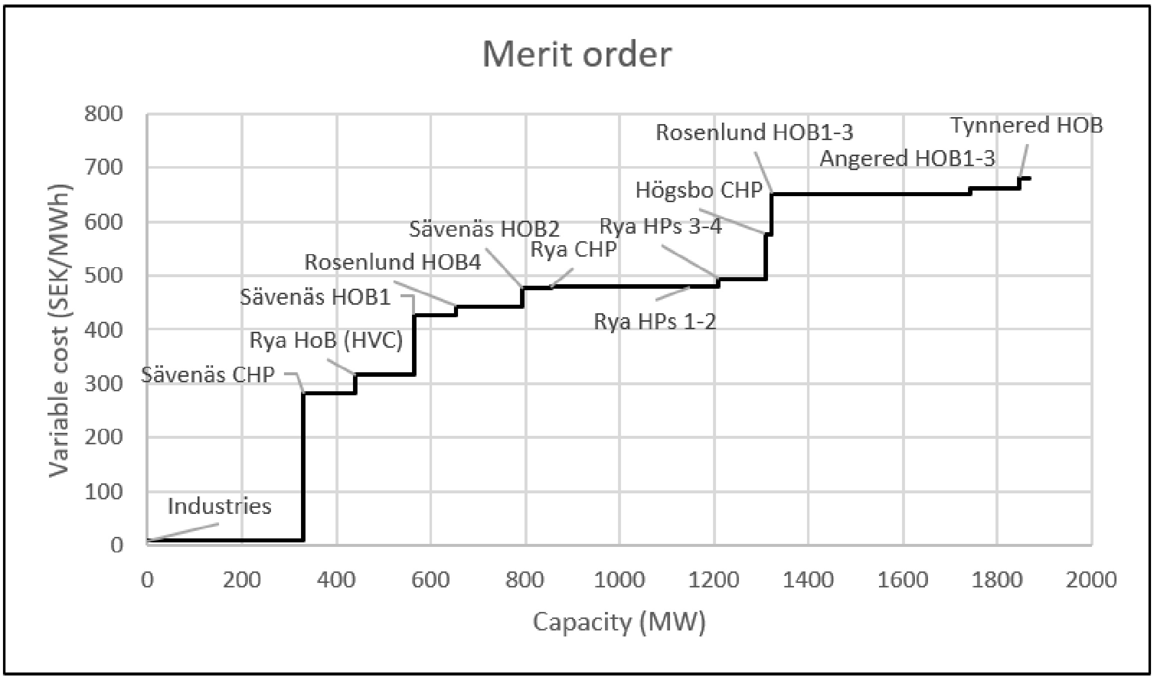

Figure 3.1: The merit order based on the variable costs and capacities of the existing technologies in Gothenburg's DHS

3.2 Biochar plant parameters

To be able to model the implementation of a biochar plant, several parameters needed to be found. These were the feedstock, O&M cost, investment cost, life time, discount rate, biochar demand, efficiency, start up and ramp up times. In the model, the feedstock for the biochar plant was set as grot due to its accessibility in the Gothenburg region [38]. Apart from availability, using grot provides a relatively homogeneous feedstock which makes it easier to predict the qualities of the biochar and thus, what markets can be expected. The price for the biochar feedstock was therefore set as the price for grot, 217 SEK/MWh$_{fuel}$ [38]. The availability of grot was assumed to be constant over the year.

The investment cost was based on the mean indicative CAPEX from the technical review by Pamoja Cleantech AB [51] and with a SEK to EURO conversion of 10.3 SEK/EURO. The companies do not offer the flexibility service between heat and biochar production as assumed in the model. Instead, the indicative CAPEX is mainly used to get an indication on the costs and properties of a biochar plant. Thus, the investment cost was set to 12 MSEK/MW and the full load hours to 7500h. In the model, the investment cost is assumed to be proportional to the size in order to make it possible for it to invest in larger capacities. Through communication with Göteborg Energi AB, it was understood that for the biochar plant to have an impact on the DHS, a capacity of at least 10 MW would be needed [38]. To calculate the annual cost for the investment ($C_{p,inv}$), the Net Present Value (NPV) was calculated accordingly:

$$C_{p,inv} = I_p \cdot \frac{r}{1-(1+r)^{-t}} \tag{3.1}$$

where I_p represents the investment cost per MW, r the discount rate of 7% [77] and t the expected lifetime, 20 years, for the plant. The discount rate is set slightly above the recommendations from other sources [78][79] in order to account for insecurities.

Different approximations of the O&M cost was found in literature and through communication with companies. In general the annual costs, excluding the investment cost, was higher than for the other technologies in the DHS. Since there were uncertainties in what parameters were included in the data provided from Göteborg Energi AB, it was decided for the biochar plant to have the same O&M cost as the facility with the largest O&M cost in the system, 87 SEK/MWh$_{heat}$. Due to the difficulties in finding a representative value for the O&M cost for the biochar plant, a scenario evaluated how different O&M costs influenced the DHS.

The total efficiency of the plant was estimated to 90%, based on the biochar plant in Stockholm [80]. Out of the 90%, at most 45% of the energy can end up in biochar and at least 45% become other products or heat. In the model, it was assumed that all products could be burned to produce even more heat, as well as that the biochar in itself can be combusted if it becomes profitable.

The ramp up time for the plant was set to six hours [80] and the ramp up capacity was based on the maximum capacity divided by six hours. This value was continuously updated as the installed capacity was maintained from the model. The time to change temperature, was updated in a similar way but was assumed to be two hours. Once again, lack of data led to an assumption regarding the time to change temperature within the plant. The two hour shifting time to change from biochar production to only producing heat was implemented as a precaution to avoid making the system overly efficient and since it was declared through interviews that changing the settings of the plant was difficult.

In the model, all variable costs were in the unit of SEK/MWh$_{heat}$. In order to represent the marginal price on biochar in terms that reflect the biochar market, the unit was transposed to SEK/t$_{\text{biochar}}$. The higher heating value (HHV) used was 23.42 MJ/kg$_{\text{biochar}}$ and is based on biochar from sawdust [57]. It should be clarified that the heating value differs depending on feedstock and process and could thus affect the conversion from SEK/MWh$_{biochar}$ to MJ/kg$_{\text{biochar}}$. In equation (3.2), the conversion equation is presented.

$$\text{Biochar}[SEK/t_{biochar}] = \frac{HHV[MJ/kg]}{3600[s/h]} \cdot \text{Biochar}[SEK/MWh_{biochar}] \cdot 1000[kg/t] \quad (3.2)$$

The demand for biochar was based on the existing biochar plants in Sweden, and that a larger facility of 9 MW is planned for in Stockholm [80]. Since most projects in Sweden plan to use their biochar locally, it was assumed that the same was valid for Gothenburg. The demand was therefore set to 35,750 MWh$_{biochar}$/year, or 5500 tonne using equation (3.2). Assuming a global market could open up for a larger demand. Unlike the hourly resolution of the heat demand, the demand for biochar was set as an annual demand, giving the model the flexibility of choosing when it would suit the system best for the plant to produce biochar and when to only produce heat. The data for the biochar plant is summarised in table 3.1.

Table 3.1: Data for a biochar plant.

Parameter	**Value**
Fuel cost (SEK/MWh$_{fuel}$)	217
O&M (SEK/MWh$_{fuel}$)	87
Investment cost (MSEK/MW)	12
Efficiency (%)	90
Start up time (h)	6
Shift parameter (MWh/h)	2.4
Ramp parameter (MWh/h)	1.6
Lifetime (years)	20
Discount rate (%)	7
Full-load hours (h)	7,500
Annual biochar demand (MWh$_{biochar}$)	35,750

3.3 The linear programming model

As mentioned earlier, the linear programming model includes parameters, sets and variables as well as constraints and an objective function. With the different parameters and sets introduced in section 3.1 and 3.2, this section aims to describe the objective function in section 3.3.1 and the constraints in section 3.3.2. In section 3.3.3, the approach to analysing the results is described.

3.3.1 Objective function

The objective function of the model is to minimise the yearly cost of the DHS while meeting the demand for heat and biochar. The total yearly cost of the system is calculated as the sum of the system cost for each hour together with the investment cost of the biochar plant where the latter depends on how much capacity is invested in. Equation (3.3) displays the objective function where C$_{tot}$ is the yearly cost of the DHS, $g_{p,t}$ is the generation of each plant in each hour, $C^{run}_{p,t}$ is the running cost for each plant in each hour, $cc_{p,t}$ the cycling cost for each unit, $G_{biochar}$ the installed capacity of the biochar plant and $C^{inv}_{biochar}$ the annualised investment cost per MW for the biochar plant.

$$Min\ C_{tot} = \sum_{p,t}(g_{p,t} \cdot C^{run}_{p,t} + cc_{p,t}) + G_{biochar} \cdot C^{inv}_{biochar} \tag{3.3}$$

3.3.2 Constraints

Constraints are implemented to represent the DHS in a realistic way. The constraints can be divided into explicit and implicit constraints. Explicit constraints are related to the specific system studied while implicit constraints describes the phenomenon in general. This section will begin with describing the explicit constraints to end with a definition on the implicit constraints.

The load-balance constraint (3.4) make sure that the demand is met for each hour by stating that the total production of heat from all plants for each hour is larger or equal to the demand, D_t. The term $extra_t$ refers to the extra heat coming from the biochar plant and is described further down.

$$\sum_p (g_{p,t}) + extra_t \geq D_t \tag{3.4}$$

To account for the ramp up and down time of each plant, the generation at a given time, t, is restricted to the generation in the previous hour, t-1, adding or subtracting $ramp_p$, as can be seen in equation (3.5) and (3.6).

$$g_{p,t} \leq g_{p,t-1} + ramp_p \tag{3.5}$$

$$g_{p,t} \geq g_{p,t-1} - ramp_p \tag{3.6}$$

Equation (3.7) states that the generation for each plant in each hour must never exceed the installed capacity of the plant, G_p.

$$g_{p,t} \leq G_p \tag{3.7}$$

The two-variable approach

In order to model the minimum load level for the different plants while still using a linear programming model, the *two-variable approach* was used. The minimum load level was considered important since some of the technologies in the DHS have start up costs, and several of the biochar plants studied need diesel during start up and should be avoided. The two-variable approach was first introduced by C. Weber [81] and aggregates thermal units instead of using binary values to indicate each plant being on and off, reducing the calculation time. The following section was highly influenced by the work of L. Göransson [82] who uses the two-variable approach to model electricity systems. The approach implements a variable for the "hot capacity", $gs_{p,t}$, apart from the variable generation, $g_{p,t}$. The gs variable gives time-dependent upper and lower, together with r_p, limits for the heat generation for each aggregate in each hour and was modelled accordingly:

$$g_{p,t} \leq gs_{p,t} \tag{3.8}$$

$$r_p \cdot gs_{p,t} \leq g_{p,t} \tag{3.9}$$

where r_p is the minimum-load level of the aggregate p divided by the maximum capacity. As introduced in the objective function, a cycling cost for the different aggregates is needed as a measure to avoid binary values. The cycling cost produce a cost as the aggregate moves below its minimum capacity. To calculate the cycling cost for each aggregate in each hour, $cc_{p,t}$, the increase in hot capacity was needed and was introduced as $gon_{p,t}$. Further, the difference between the actual generation and the hot capacity was needed. In equation (3.10), the cycling cost is defined.

$$cc_{p,t} \geq gon_{p,t} \cdot Con_p + (gs_{p,t} - g_{p,t}) \cdot Cpl_p \tag{3.10}$$

where Con_p is the start up cost for the aggregate and represents the cost to run technology p at minimum-load level through the start-up time, k. Cpl_p is defined as the part load cost for a plant and is calculated as:

$$Cpl_p = \left(\frac{1}{G_p - G_p \cdot r_p}\right)\left(\frac{C^{run}_{p,t}}{\mu_{min,p}} - \frac{C^{run}_{p,t}}{\mu_{max,p}}\right) \tag{3.11}$$

where μ is the maximum and minimum efficiency at minimum-load level and at rated power, respectively. The cycling cost is thereafter integrated in the objective function (3.3).

The increase in hot capacity, $gon_{p,t}$, is declared accordingly:

$$gon_{p,t} \geq gs_{p,t} - gs_{p,t-1} \tag{3.12}$$

Further, $gon_{p,t}$, is limited by relating the maximum start-up capacity to the spin k_p hours backwards in time:

$$gon_{p,t} \leq P_p - gs_{p,t-k_p} \tag{3.13}$$

Biochar production constraints

To model the introduction of a biochar plant, a yearly demand for biochar was set. The yearly demand for biochar was based on how much biochar could be used by actors in the nearby region and therefore have a value in its own. The demand-constraint is presented in (3.14), where B_y represents the yearly demand and b_t is the biochar produced in each hour, summarised to represent the whole year.

$$B_y \leq \sum_t b_t \tag{3.14}$$

When modelling how much of the input energy that remained in the biochar, some assumptions were made. Assuming a 10% energy loss, at most 45% of the energy can end up as biochar leading to a ratio of 1:1 between biochar and heat. This indicates that at least 45% of the energy that enters, ends up as heat, represented by $g_{biochar,t}$. If more heat is generated, less biochar is produced. The biochar generation can therefore be equal to $g_{biochar,t}$ at most or become lower. To model this relation, the extra heat-concept was introduced. $extra_t$ represents the biochar that is sacrificed to generate more heat, instead of ending up as a solid product. In equation (3.15), the biochar produced in each hour is presented.

$$b_t = g_{biochar,t} - extra_t \tag{3.15}$$

The total amount of heat for each hour was calculated as presented in equation (3.16). The heat is a sum of the extra heat produced instead of producing char, and the generation of heat from the biochar plant $g_{biochar,t}$. The extra heat is accounted for in the load-balance constraint to give a correct representation of the system.

$$heat^{tot}_{biochar,t} = extra_t + g_{biochar,t} \tag{3.16}$$

As for the case with the ramp up times for the other technologies in the system, constraints were implemented that regulated the shift from biochar to heat production accordingly:

$$b_t \leq b_{t-1} + shift \tag{3.17}$$

$$b_t \geq b_{t-1} - shift \tag{3.18}$$

The $shift$ parameter to go from producing biochar to producing extra heat was assumed to be two hours and was continuously updated, based on the installed capacity. This indicates that the biochar production, equal to $g_{biochar,t}$, could go from full load to zero in two hours and vice versa.

At last, the capacity, $G_{biochar}$ of the biochar plant was calculated. $G_{biochar}$ capacity had to be larger than the combined heat and biochar production in every hour. Since the model is a simplification of reality, it can invest linearly in capacity unlike reality where the capacity is predetermined. From the capacity the investment cost for the biochar plant could be calculated.

$$G_{biochar} \geq g_{biochar,t} + char_t + b_t \tag{3.19}$$

Implicit constraints The implicit constraints are related to the generation of heat and biochar and the capacity of the biochar plant. Non of these variables can go below zero, if the system should replicate reality.

$$g_{t,p}, gs_{t,p}, gon_{t,p}, b_t, B_y, extra_t, G_{biochar}, char_t, heat^{tot}_{biochar,t} \geq 0 \tag{3.20}$$

3.3.3 Analysing the results

To compare different scenarios and how the different parameters affect the result, five indicators were chosen. These were the number of hours when extra heat was used (h), how much heat was generated over the year (MWh_{heat}), the marginal cost of biochar ($\mathrm{SEK/t_{biochar}}$), the system cost (SEK) and the capacity of the plant (MW). The number of hours when extra heat was used was chosen as an indicator of how often the flexibility of the plant was used. To fully understand when and during what conditions the flexibility was adapted, the hours when extra heat was used over the year were analysed as well as which other technologies the biochar plant competed with. The extra heat generated indicated in what way the extra heat was used, if it was full capacity or just regulating smaller fluctuations. The marginal cost of biochar played an important role in understanding when it was profitable to either invest in larger capacities or use extra heat, and connects biochar production to heat generation. The system cost might not be completely representative of the real DHS, but was merely analysed to compare how different measures affected it. The capacity of the plant indicated if the system chose to invest in the minimum needed production or if it would be beneficial to invest in a larger facility to replace alternative heat generation.

3.4 Scenarios

As an initial result was achieved, several scenarios were evaluated in order to understand which parameters affect the result the most and in what way. The parameters investigated were the biochar demand, discount rate, variable cost, reduction in investment cost, availability of grot, price of biochar and how a future electricity price profile scenario might affect the dynamics of the DHS.

The demand for biochar was analysed since it is an uncertain biochar market and depends on whether it is a local or global perspective, as well as how the different markets evolve. To investigate how the biochar demand affect the system and flexibility of the biochar plant, both higher and lower demands were evaluated. How the biochar demand would affect the flexibility was analysed to understand how a varying market might affect the capacity of the plant needed and how it would further affect the flexibility. The demands evaluated varied from 8,937.5 to 286,000 $\mathrm{MWh}_{biochar}$.

The discount rate was analysed as part of understanding in what way and extent the different economic parameters affect the system dynamics and flexibility of the plant.

Since different values of the discount rate was found in literature both higher and lower values were evaluated between 3-11%. The variable cost includes fuel and O&M costs for the biochar plant and results in a total cost of 570 SEK/MWh$_{heat}$, with an efficiency of 45% for heat, in the original investment model. The reductions to the original cost varied from 14.5 to 170 SEK/MWh$_{heat}$.

As a last economic analysis, a reduction in investment cost was analysed. Investing in a biochar plant could replace other technologies that would otherwise be invested in to maintain the needed capacity of the system. In addition, the Swedish government provides subsidies for technologies that has the potential of producing a carbon sink and the plant could replace other technologies that would otherwise be needed. Also, the investment cost is based on a mean value from different technologies and could therefore be expected to vary. The implemented investment cost does not take scalability into consideration, a simplification of reality. Thus, the investment cost is one of the most uncertain parameters and was seen as an important parameter to evaluate. The reductions in investment costs analysed were in the span of 2.5 - 12 MSEK/MW. The last case of 12 MSEK/MW, eliminated the whole investment cost to see what the optimal capacity would be if the investment cost could be considered a sunk cost. In this scenario, it was assumed that a biochar plant was already integrated in the DHS and could be used for heat when suitable.

In previous runs, there had been taken no consideration to the price of the biochar. Instead, a demand needed to be fulfilled. Therefore, a scenario investigating how a price for biochar affect the system and flexibility of the plant was included. At this point, several prices for biochar was modelled to see if there was any breaking points and at approximately what price these occurred. The values evaluated were in the span of 0-5720 SEK/t$_{\text{biochar}}$. Implementing a price of biochar was modelled both with and without a biochar demand to see if there was any differences between the two.

Since the electricity system is expected to change dynamics through the integration of more renewable energy sources as solar PV and wind, an estimated electricity price profile from 2050 was investigated [83]. The price profile primarily affects the dynamics of the HPs and CHPs and could thus have an influence on how and when the biochar plant is used. The electricity profile includes the whole of Europe but was performed with southern Sweden as main region. The largest difference is that price fluctuations occur throughout the year, and not follow a seasonal patter, as is the case for the original electricity price profile. The mean price of electricity is higher in 2050 but the peak price is lower than in the original case and prices also reach lower values in 2050 than in the original case. The price profile includes the heating sector as well as some production of hydrogen. The net emissions need to be zero but fossil fuels are allowed as long as they are compensated for with bio energy carbon capture and storage.

Similarly as the electricity price profile might change in the future, the availability and price of grot could change. As biomass becomes more and more attractive to replace fossil substances in society, the price can be expected to vary. To see how robust the investment model is to the fuel price, prices for grot between 50 and 300 SEK/MWh$_{fuel}$ were run. The difference between this scenario and the one performed on the variable cost is that the price of grot also affect CHP, Sävenäs, that run on the same fuel. Additionally the fuel efficiency creates an amplifying relation in the reduction of variable cost.

In appendix B, the input data for the scenarios is summarised.

4 Result

In this chapter the modelling results are presented. The results are divided into the base case in section 4.1, primary results from dimensioning the biochar plant in section 4.2 and lastly the different scenarios in section 4.3.

4.1 Base case

The base case shows how the DHS behaves without the biochar plant. The base case scenario is used as a reference to determine what technologies the biochar plant competes with and is visualised in figure 4.1. In figure 4.1 it can be seen that the industry waste heat is the primary base load due to a take-or-pay contract and its relative cheapness. As more heat is needed, the CHPs are started and remain on through the colder months. Since rya_chp (light blue) have a start up cost, rya_hvc (dark grey) is used to complement the production when capacity is needed and rya_chp is off. When the heating demand increases further, HOBs are started. The order in which the technologies are used, complies well with the merit order presented in figure 3.1 although rya_chp is an outlier. This depends on the variable electricity price that is not taken into consideration in the merit order, but is based on a mean value. In Appendix C, the annual heat generation for each technology is listed. In the base case, the system cost was approximately 392 MSEK.

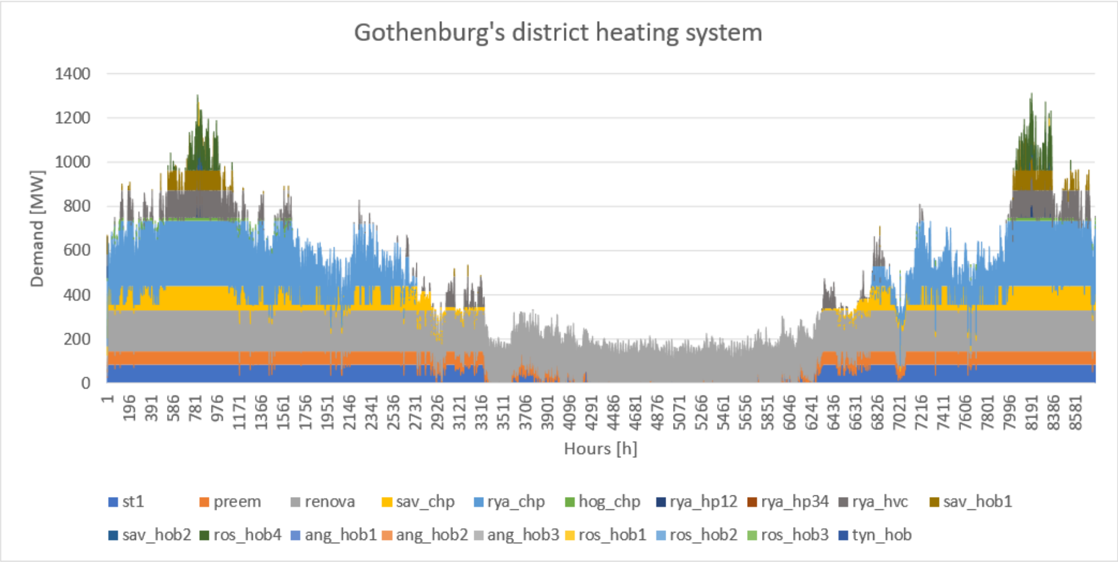

Figure 4.1: The technologies used to fulfill the heating demand in Gothenburg's DHS .

4.2 Dimensioning the biochar plant

As the model was allowed to invest in a biochar plant to fulfill the annual biochar demand of 35,750 $\text{MWh}_{biochar}$, the capacity of the plant became 9.53 MW which represents the minimum capacity needed to meet the demand. This indicates that in the initial model run it is not profitable to change from biochar production to producing any extra heat during any hours. The marginal cost of biochar amounted to approximately 670 SEK/$\text{MWh}_{biochar}$ (4,400 SEK/$\text{t}_{\text{biochar}}$). For the biochar plant to start using the flexibility, the variable cost for the other plants in the system would need to be higher than the marginal cost of the biochar plant since it is the difference that makes the profit. Furthermore, the heat must be worth more than 670 SEK/MWh_{heat} to make it viable for the biochar plant to shift from producing biochar to producing extra heat. From the merit order in figure 3.1, the most expensive technologies are in the range between 600-700 SEK/MWh$_{heat}$, and since several of these are not used by the model, such as Tynnered HOB and Angered HOB1-3, it could explain the lack of flexibility from the biochar plant. The total heat from the biochar plant is 35,750 MWh$_{heat}$ and the indicators are summarised in table 4.1. The system cost increased to 416 MSEK, compared to 392 MSEK in the base case. An increase in the system cost suggest a non-profitable investment. That is, the biochar produced from the biochar plant is at this point too expensive to be used for heat, providing flexibility.

Table 4.1: Summary of indicative values from the initial model run.

Indicative values	**Value**
Capacity (MW)	9.53
Total heat (MWh$_{heat}$)	35,750
Extra heat hours (h)	0
Extra heat (MWh$_{heat}$)	0
Marginal cost (SEK/MWh$_{biochar}$)	672
System cost (MSEK)	416

In the DHS, the biochar plant acts as a base-load during winter months and regulates fluctuations during summer, as can be seen in figure 4.2. While it serve to regulate smaller fluctuations in heating demand during winter months, it can be seen that it runs on full capacity when the heating demand is at its highest through comparison with figure 4.1. From figure 4.2, it is implied that to follow the constraint on full load hours, the biochar plant rather run on part-load than being shut down. During summer, the biochar plant replaces waste heat from the industries. Since the heat from the industries still need to be cooled away, the heat generated has no use. Since no extra heat is generated, the ratio between heat and biochar is 1:1 and thus the biochar production follows the same pattern as the orange line visualising the heat in figure 4.2. The blue line represents the total capacity and includes both biochar production and heat generation.

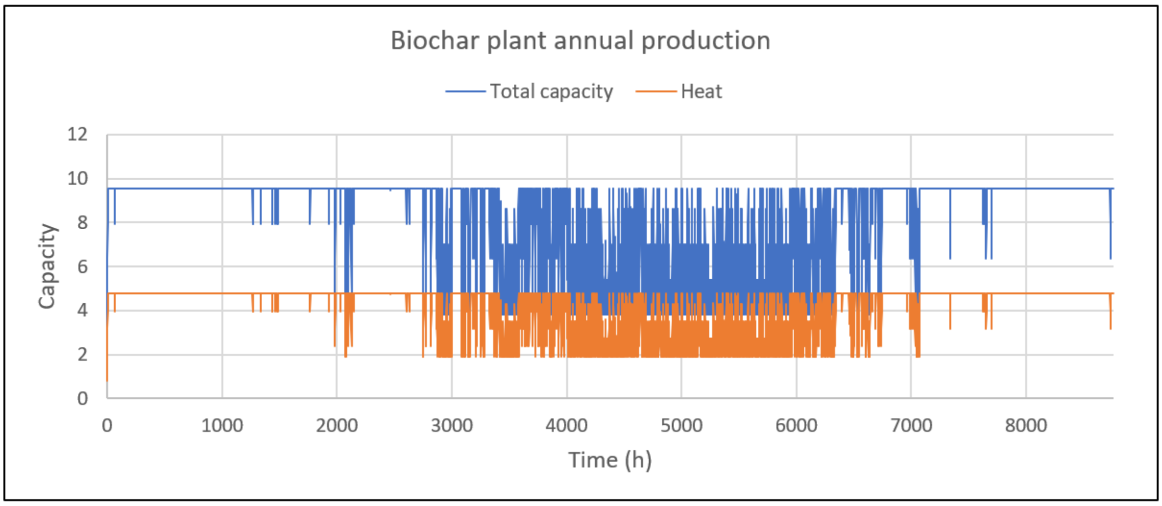

Figure 4.2: Annual production of biochar and heat from the biochar plant.

4.3 Scenarios

To gain understanding in how robust the results from the initial model run were, different scenarios were modelled. Out of the six scenarios evaluated, flexibility was initiated in four of them. The change in electricity price profile showed negligible impact on the DHS. Following cases and parameters had notable impact.

The demand for biochar was analysed between 8,938 and 286,000 MWh$_{biochar}$ and did not have an influence on the flexibility since the extra heat stayed at zero production. As no extra heat was produced, the increased biochar demand provides heat to the DHS no matter the variable cost. The marginal cost of biochar only increased with 2.5% within the range, which is negligible. The installed capacity on the other hand, increased linearly with 32 times the start value. The total heat follows the production of biochar. As the capacity of the biochar plant increases, all other heat generating plants have an overall decrease, whereas, st1, Renova, sav_chp, rya_chp, rya_hvc, sav_hob1 and sav_hob2 stands for 87% of the increase at the highest biochar demand. Figure 4.3 shows the change in heat generation from the different plants in the DHS as the biochar demand is changed.

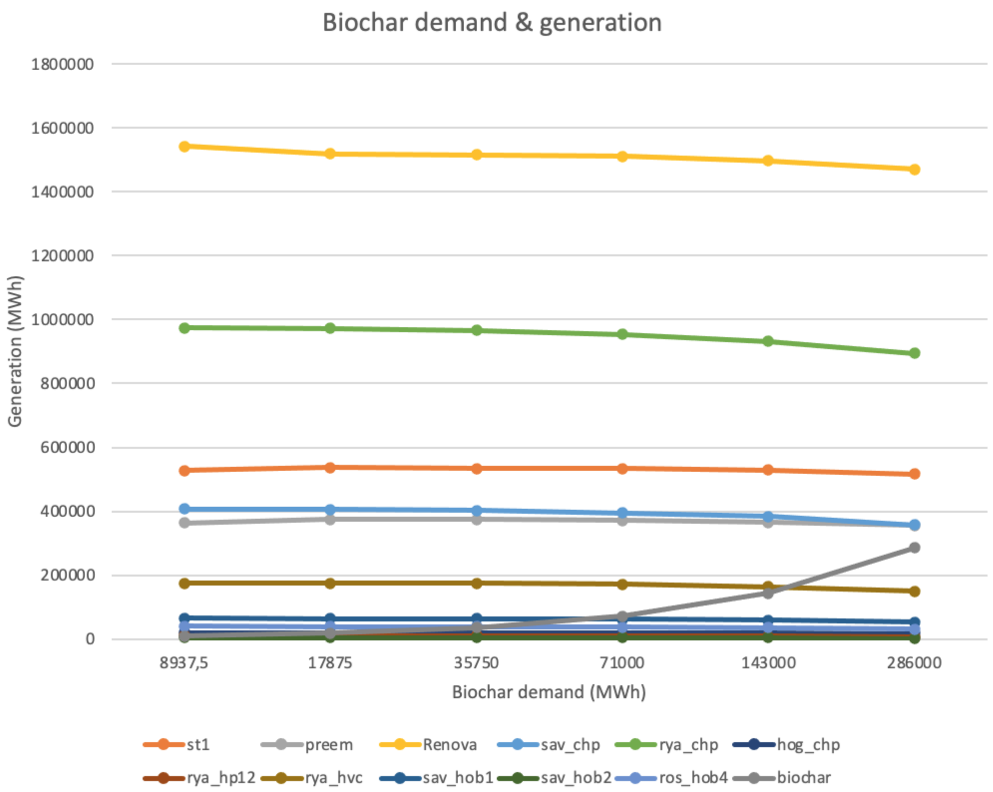

Figure 4.3: Change in heat generation from the different plants with increasing biochar demand.

The decrease in discount rate opens up for utilisation of extra heat in low levels and extra heat increases exponentially as the discount rate is lower than 7%. A discount rate of 1 and 3% result in 34.7 and 14.4 MWh$_{heat}$ during 10 and 6 h respectively. The total heat from biochar are approximately equal to the biochar production of 35,750 MWh$_{biochar}$. With an increase in discount rate the marginal cost of biochar increases with approximately 23 SEK/MWh$_{biochar}$ starting from 543 SEK/MWh$_{biochar}$ (3530 SEK/t$_{\text{biochar}}$) at 1%. The increase in capacity form 7 to 3% is negligible, however, going down to 1% the increase becomes 36%. The change in discount rate did not have any affect on the dynamics of the DHS.

A reduction of investment cost showed a step-wise increase in capacity with a slow increase between 0-2.5 MSEK and 5-7.5 MSEK reduction, as can be seen to the right in figure 4.4. To the left in figure 4.4, the produced extra heat shows a steeper increase for every step. Hence, a relative low increase in capacity (44%) resulted in a noticeable increase in extra heat, 1,057 MWh$_{heat}$ during 183 h when the reduced investment cost was 7.5 MSEK/MW. The total heat increases with 3% in this scenario. Looking at an investment reduction of 10 MSEK/MW the total heat production from biochar increases with 26% with extra heat of 9,235 MWh$_{heat}$ during 1,029 h. As the investment cost is reduced, the biochar plant takes on a role as an intermediate load, as can be seen in figure E.3 in appendix E.

Not until the investment cost is zero (reduction of 12 SEK/MW) a significant decrease in production from several plants was noted. In this scenario, the reduction in rya_chp, rya_hvc, sav_hob1, ros_hob4 corresponds to 86% of the increase in biochar generation. As the investment cost was neglected, the model chose to invest in a biochar plant of approximately 460 MW. In this scenario, the role of the biochar plant changed. Instead of serving as a base load with some fluctuation regulation, the biochar plant served as an intermediate load, as can be seen in appendix E. Considering the demand remaining the same, it could be fulfilled during these few hours instead of through a lower capacity and several more hours. Regardless of the increase in capacity, the biochar demand was met but not exceeded. Since no price for biochar was included in this scenario, it is viable that the heating peak demand was of more interest. While the contribution of waste heat and CHPs remained approximately the same in this scenario, the heat generation from the remaining technologies were generally reduced to close to zero.

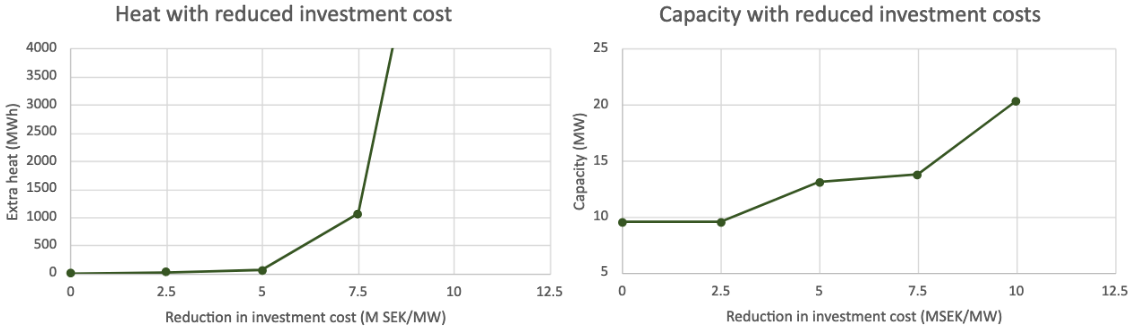

Figure 4.4: Reduction in investment cost regarding capacity and production of extra heat.

Reducing the variable cost resulted in a small increase in extra heat and capacity. A plateau occurs where the production of extra heat stays at 6 MWh$_{heat}$ with a decreasing variable cost of 29 SEK/MWh$_{heat}$ to 72.5 SEK/MWh$_{heat}$. Overall the variable cost showed to be a robust parameter and only reached approximately 90 MWh$_{heat}$ of extra heat during 36 h at a reduction of 170 SEK/MWh$_{heat}$. The reduction in marginal price of biochar in this scenario was however 25%. In figure 4.6 the extra heat is plotted relative to the reduction in variable cost. Even though some extra heat is generated, it does not affect the dynamics of the other plants in the system with the tested values.

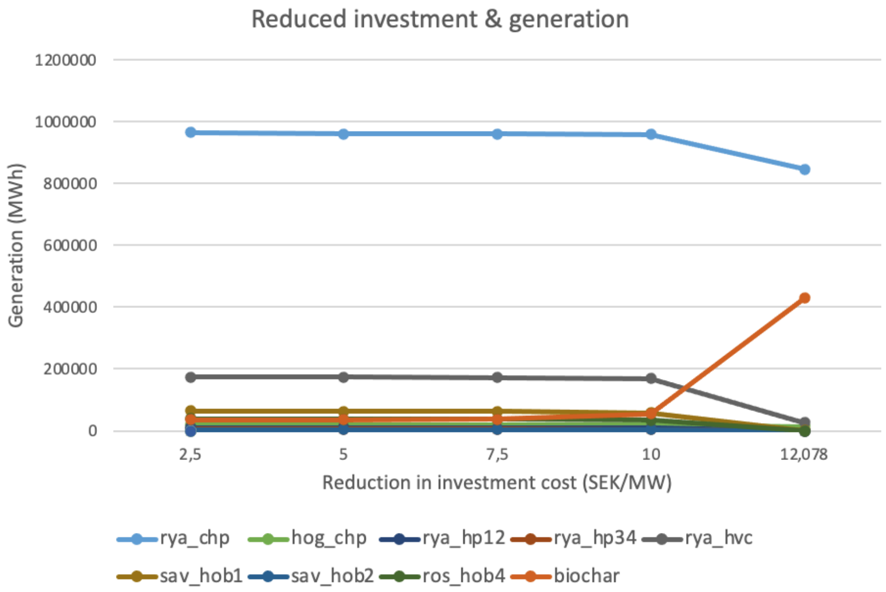

Figure 4.5: The change of heat generation from the different plants due to reduction in investment cost for the biochar plant.

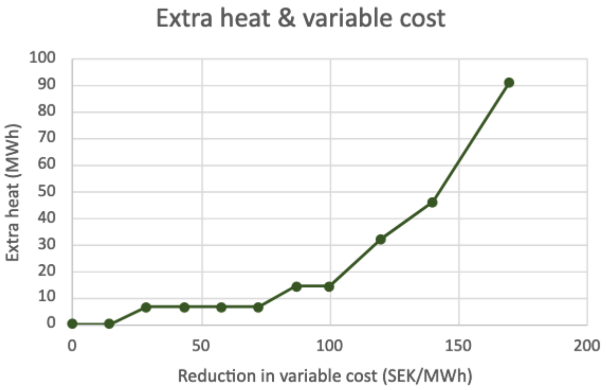

Figure 4.6: Extra heat with decreasing variable cost

The different scenarios regarding price of grot seemed robust until 125 SEK/MWh$_{fuel}$ where the model starts to significantly increase the production of extra heat. Between 110 and down to 90 SEK/MWh$_{fuel}$ the extra heat increases form 957 to 4,099 MWh$_{heat}$ during 292 and 942 h respectively. During the highest peaks of the demand the biochar plant only produces heat. At thous hours all the costs of the biochar plant can be allocated to heat generation. Decreasing from 53 to 50 SEK/MWh$_{fuel}$, the extra heat shoots up from 5,944 to 9,422 MWh$_{heat}$. Here, the total heat has increased with 26% whereas the increase amounted to 11% at a price of 90 SEK/MWh$_{fuel}$. As seen in figure 4.7 the capacity follows the same pattern as the extra heat, but with a low magnitude from 9.53 to 12 MW. The changes in generation of different technologies is illustrated in appendix E.1 and is mainly from 100 SEK/MWh$_{fuel}$ and up.

By allowing the model to sell biochar the limiting factor of biochar production shifts from meeting the demand to getting income from selling the biochar. The shift occurs at a biochar price of 4,360 SEK/t$_{\text{biochar}}$. Once the biochar price is the dominant parameter the

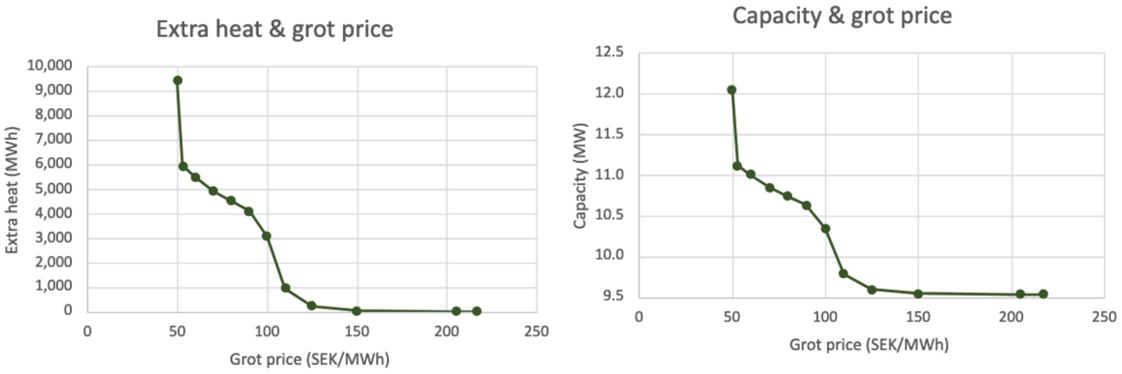

Figure 4.7: Sensitivity of grot prices regarding capacity and production of extra heat.

capacity and produced biochar increases significantly with small changes of the price. At 4,554 SEK/t_{biochar} the capacity becomes 123.3 MW. Evaluated values can be seen in table 4.2. At a price just above 5,660 SEK/t_{biochar} the system cost becomes zero. However, the market needs to handle approximately 910,000 tonne biochar in this scenario. In appendix E.2, the change in generation of different technologies is visualised and show a fast decrease in the CHPs form 4,360-4,550 SEK/$t_{biochar}$. From a price of 4,800 SEK/$t_{biochar}$ and on, the biochar plant is the technology with highest generation in the DHS. In appendix E, the DHS is visualised with a price of 5500 SEK/tonne in figure E.4. Figure E.4 shows a scenario where the biochar plant outcompetes most of the other heat generating technologies.

In appendix D, the indicators are summarised for each scenario.

Table 4.2: Sensitivity of biochar price relative to capacity, system cost and produced biochar.

Biochar price (SEK/t_{biochar})	Capacity (MW)	System cost (MSEK)	Biochar prod. (MWh$_{biochar}$)
0	9.5	416	35,750
4,164	9.5	393	35,750
4,359	9.5	392	35,750
4,554	123	385	462,208
4,749	268	361	1,004,928
4,944	425	322	1,596,306
5,139	558	267	2,095,520
5,335	712	196	2,672,324
5,530	1,072	99	4,019,471
5,660	1,571	5	5,893,295
5,725	4,668	-131.3	17,505,720

5 Discussion

This study investigated how a biochar plant could contribute with flexibility regarding heat to the DHS and the produces biochar. A literature study was made to understand what aspects affect the biochar production and a linear programming model was constructed to model the DHS and how a biochar plant affects it.

5.1 Literature study

A range of different feedstocks are feasible in the production of biochar. Due to variety in material characteristics, different feedstocks contribute with different services. While sewage sludge contains toxic substances to a larger extent, it could be a way of recycling phosphorous. Manure contains a lot of nitrogen that can be stored in the biochar, closing the nitrogen cycle. Grot offers a way of slowing down the fast carbon cycle while achieving a relatively homogenous biochar with few impurities. The choice of feedstock to be used depends on availability and this affects the characteristics of the produced biochar. Due to the variety in characteristics on the biochar it is beneficial to make an informed decision of feedstock to know what market and price of the biochar that can be expected. Previous studies emphasise the importance of using a feedstock that does not have other purposes but would otherwise be treated as waste. The concept of using biomass as feedstock is in itself an interesting subject since biomass in larger extent is used to replace fossil materials. However, the discussion of how biomass in general should best be utilised, is left for another study to conclude.

Another parameter that affects the characteristics of the biochar is the production process. The available technologies that focus on biochar are relatively small, 0.5-4.4 MW, in relation to the heat demand in the DHS, 200-1400 MW. In general, modular and decentralised solutions are used and the primary aim seemed to be to produce biochar with heat as a potentially valuable by-product. To increase the capacity, more modules are needed, rather than scaling up the technology. Several smaller facilities could be used to maintain the required heat capacity outside of the main region, Gothenburg, but would likely require more logistics. In a DHS the size of Gothenburg's, several smaller facilities to achieve a larger total capacity could mean that more effort is put in to the technology than the benefits obtained from it. At the same time, biochar is an area on the rise and new technologies and research are evolving, something to pay attention to for future decision making.

Most biochar distributors encourages the excess heat to be used to heat nearby facilities or DHS, where it acts like a base load and shows similarities with industrial waste heat. Even though the excess heat was often mentioned as a positive attribute, few technologies and studies were found were the flexibility between biochar and heat production was possible. Some companies, indicated that their technology could be made to favour heat or biochar, which is something that is interesting to look into further [54].

Technologies that can potentially be large enough to influence the DHS are updraft and fluidised bed gasifiers. Since gasifiers mainly produce gas that can be burnt they have the possibility to significantly contribute to the DHS. However, less biochar is produced and there is a scarcity of data regarding how the gasifing process affects the biochar characteristics. Uncertain biochar characteristics could make it harder to sell. For the biochar plant to become an attractive addition to the DHS, rather than a way to handle waste heat, more research and development is needed in this area.

As for the product biochar, many applications were found that made use of different characteristics of the biochar. For agriculture, soil amendment and animal feed, biochar is already in use. Having a certificate such as the EBC could have an impact on the agricultural and animal feed markets, since it is a quality-guarantee of the product. For industries like water filtration, steel production and concrete production, biochar integration is currently on pilot stages to replace fossil materials. Even though the market can currently be considered immature, new applications are continuously researched. In addition, reports suggest that the market is expanding [29][32]. As biochar is currently being imported to Sweden, there seems to be a demand that is currently not fulfilled.

For several of the discussed applications, two main problems have been noted. The first being the relatively high cost compared to alternative substances. The second being the inconclusive research regarding the effects of using biochar, for instance in agriculture. Since the price is currently high, actors might not be prepared to invest in something that might not increase their profits. Subsidies for the carbon sink could change the economic parameters and make biochar an attractive substitute.

With an expanding market, it is important to take other parallel projects into consideration. There are currently several projects were biochar plants are being built. As more actors become interested, the market might change in the future. It is hard to predict how the future will unfold, with regard to markets as well as policy measures to reach the climate goals. Therefore, it is strongly suggested to stay updated with coming development and research.

5.2 Modelling results

With the initial parameters that was used in the model, a biochar plant of 9.53 MW was invested in to meet a biochar demand of 35,750 $\mathrm{MWh}_{biochar}$. The lack of flexibility was a result of the comparatively high running costs of the biochar plant in relation to other available technologies. A capacity of 9.53 MW also suggests that the investment cost was too high for it to become beneficial to invest in a larger biochar plant in order to replace other heat generating technologies.

Since several of the parameters were based on assumptions, they were changed in different scenarios to understand how they influence the system. Although the initial scenario showed no use of the flexibility, flexibility could be initiated in four out of six scenarios. In general, the utilisation of the flexibility correlated to the increase in heat demand during winter months. During summer, the biochar plant produced the highest ratio of biochar to heat or was shut down. Over the year, the biochar plant reduced the heat generation from all other technologies. During peaks, the biochar plant mostly influenced the use of HPs and HOBs. In this thesis it was assumed that all products apart from biochar could be used for heat. In reality, both bio-oil and pyrolysis-gas could have other applications, making the system even more dynamic. These products were, however, not part of the scope of this study, but could be looked into in future research.

For the variable cost of the biochar plant, O&M and fuel costs were included. As the variable cost was reduced with at least 29 $\mathrm{SEK/MWh}_{heat}$, the model started to use the possible flexibility during the coldest winter days. A decrease in variable cost can, for instance, be reached if the biochar plant is controlled in the same control room as for another technology, instead of having an operator of its own. On the other hand, the O&M cost in reality might be higher than what was implemented in the model. A higher O&M cost could make it less beneficial for the system to use flexibility. The availability of grot had a larger influence on the flexibility than decreasing the variable cost. This can depend on the efficiency of the plant in the model. Overall, they influenced the system in the same way. Choosing a cheap feedstock could influence the use of flexibility provided by the plant. Sewage sludge is probably the cheapest feedstock alternative. Currently there are a lot of regulations regarding sludge, regulations that might change in the future as more elemental cycles need to be closed.

As the investment cost was reduced, the model invested in larger capacities and used the flexibility to cover the heat demand during winter months. With a larger reduction in investment cost, the biochar plant was shut down during summer, making it more of an intermediate load. Since there was insecurities regarding investment cost, the analysis of this parameter is significant. For example, a larger plant would likely not have such a high investment cost per MW. In addition, the Swedish government gives financial support to projects that could generate negative emissions. A biochar plant could also replace other technologies that would otherwise be needed to invest in, in the DHS. A similar pattern as with the investment cost could be seen when the discount rate was reduced. Since the discount rate is related to the investment cost, it is not surprising that the two parameters have the same effect on the system. The discount rate chosen in the initial case, 7%, was rather high compared to other studies. Flexibility was used by the system when the discount rate was lower than 7%, indicating that use of flexibility in the system is within reach.

Before discussing the results from the scenario with a price on biochar, it should be clarified that the price in this case is the price that is returned to the system. In addition to this price, costs for transportation and similar expenditures would need to be made. As the price for biochar became larger than 4550 SEK/tonne, the model started to invest in a larger plant. As more biochar is generated, more excess heat reach the DHS and other technologies are outcompeted. Therefore, it might affect the DHS even if it is not through the flexibility, as was first thought. These results must however be looked at with a critical eye since there is a small gap between when the model starts to invest in a larger biochar plant and when it invests in such a large plant so that the whole DHS generates an income. A technology that could provide such a large biochar plant, >1000 MW, is not available and would require comprehensive logistics. Results like these are typical for optimising models. When the objective function is to minimise a cost and an income on biochar can be made, the potential income becomes a mean to optimise the system. Nevertheless, the thresholds provide some valuable information since they show what value on biochar that initiate a profit to the system.

As mentioned previously, the price on biochar is an important factor to understand what markets can be expected. Compared to imported biochar that has a value of 3,800 - 15,000 SEK/tonne, the prices implemented in the model is within the same range. Even though some additions would need to be added to the prices evaluated in the model. As soil amendment, the average market price is between 4,500 and 6,000 SEK/tonne. In agriculture, the qualitative biochar used is generally too expensive and have a cost between 10,000 and 12,000 SEK/tonne. To make the biochar more competitive on the different markets, a subsidy for the carbon sink could be beneficial. A subsidy of 0.9 - 2.8 SEK/kgCO_2 has been suggested, this would indicate a subsidy of approximately 3,000

- 10,000 SEK/tonne$_{\text{biochar}}$. With a subsidy in this range, the possible markets could be influenced significantly. The potential subsidy can be compared to the carbon tax used in the model, 950 SEK/tCO_2. Biochar could avoid costs of CO_2 with approximately 3000 SEK/t$_{\text{biochar}}$.

In the scenario where the biochar demand was changed, no flexibility was used. Since no economic parameters were changed, the biochar plant had the same role in the system even though the size increased. However, as the capacity of the biochar plant became larger, more base load heat was generated, similarly as putting a price on biochar. During winter months, the increase in base load heat replaces heat from other technologies. During summer, the heat has no value which could be problematic. Over the year, biochar is produced in equal amounts as heat.

Since both biochar and heat can generate income, the costs become crucial for the dynamics within the plant. The fact that the flexibility could be initiated by changing the economical input parameters, suggest that the results are highly dependent on what system the biochar plant is integrated into as well as the parameters related to the plant. The size of the DHS, the technologies in it and the fuels used, are all parameters that affect the dynamics within the system. An increase in variable cost for other technologies could benefit the flexibility of the biochar plant just as well as lowering the costs for the biochar plant.

In conclusion, from the model it became clear that flexibility could be initiated by either lowering the running costs or the investment cost of the plant. Flexibility between biochar and heat could offer a new type of technology in the DHS were both products are of interest. The production of biochar generates carbon negative base load DH, while the flexibility between biochar and heat can be used to cover intermediate peaks. By using the biochar plant to cover intermediate peaks, other technologies can be outcompeted. In both cases, the DHS benefits from having a biochar plant.

5.3 Future research

In the literature study, several studies were found regarding what feedstock to use for biochar production and what characteristics that can be expected based on process temperature. The results were, however, divergent leading to difficulties in finding consistency in what characteristics that can be expected of the biochar. The lack of consistency makes it hard to predict a market and for actors that are interested, the results become unreliable. The applications of biochar have been researched, even though it seems as more applications are still being found. In a majority of the reports found, focus is put on biochar as main product and there were few studies found regarding how a biochar plant could fulfill more needs than producing biochar, for instance flexibility in heat production. The following recommendations are therefore made for future research:

- Studies that investigate the possibility for a biochar plant to shift from biochar production to heat production and what aspects are crucial for such a plant.
- Studies that investigate what the outcome is if combining the scenarios performed in this thesis.
- Studies that investigate how other feedstocks, such as manure and sludge, could be used in order to recycle nutrients.
- Studies that look into how grot should be best utilised in the Nordic countries.
- Studies that investigate further in what sectors biochar could replace fossil coal and what volumes can be expected.
- Studies that continue research in how different production processes, such as gasifiers, affect the characteristics of the biochar.
- Studies that investigate where a biochar plant should be located with respect to capacity need and operation costs.

6 Conclusion

In order to reach the Swedish climate goals in 2045, processes with negative emissions are expected to be in place. Through biochar production, carbon can be returned to soils, creating a carbon sink, while the excess heat from the process can be utilised in DHSs. This thesis has investigated how the integration of a biochar plant into a DHS may affect the district heating and if it could contribute with other benefits than a carbon sink.

Several biochar initiatives were found in Sweden during the literature study. For most of them, the biochar plant has been integrated to the local DHS contributing with excess heat from the pyrolysis process. A scarcity in research was found regarding how the heat from the biochar plant could be utilised and if it could contribute with other benefits than being a base load. Likewise, little information was found regarding the possibility to change process technicalities within a biochar plant to change the ratio of the products. The thesis focused on understanding what benefits a more flexible relation between the products biochar and heat could provide to a DHS.

The initial results indicated that the initial biochar parameters made the plant too expensive to provide flexibility. The capacity invested in was the minimum capacity, 9.53 MW, needed to fulfill the demand and the biochar plant primarily contributed as a base load to the DHS due to the excess heat from the pyrolysis process. Two of the parameters that had the greatest influence on the biochar plant was the price on biochar and the feedstock price. As the price was larger than 4360 SEK/t_{biokol}, it became profitable for the model to invest in a larger plant than the minimum capacity needed to fulfill the demand. However, no biochar was sacrificed to produce extra heat. Instead, biochar became the primary product and influenced the DHS mostly as a larger base load. Another parameter that influenced the biochar plant was the price of the feedstock. As the price became lower than 125 SEK/MWh, the model started to invest in larger capacities to produce extra heat to the system. With a feedstock price of 50 SEK/MWh, the generated extra heat was approximately 9400 MWh and a capacity of approximately 12 MW.

From the study it can be concluded that the economic parameters have a significant impact on what role the biochar plant has in the DHS. With lowered costs, a biochar plant could offer both carbon negative energy as well as flexibility to the DHS. Furthermore, with the variety in feedstock and applications of biochar found during the literature study, there seems to be several benefits locally and on national level with biochar production and a need for biochar as a product in Sweden. The largest threat to biochar as a product is the general lack of conclusive research leading to an insecure market. As for decision making for investors, it is important to keep an eye on regulations and markets as these are still being updated and are evolving.

6.1 Recommendations

The following recommendations to Göteborg Energi AB conclude this thesis:

- Investigate the technicalities within the available biochar technologies to understand how flexibility between biochar and heat can be possible.
- Follow the development of biochar technologies and influence the direction of development by expressing an interest in technologies that can contribute with several purposes to the DHS.
- Stay updated with the different markets of biochar. New applications are continuously being researched and could play an important part in the dynamics within the system.
- Evaluate what feedstock that would, in the long run, benefit the region the most and how grot should best be utilised.

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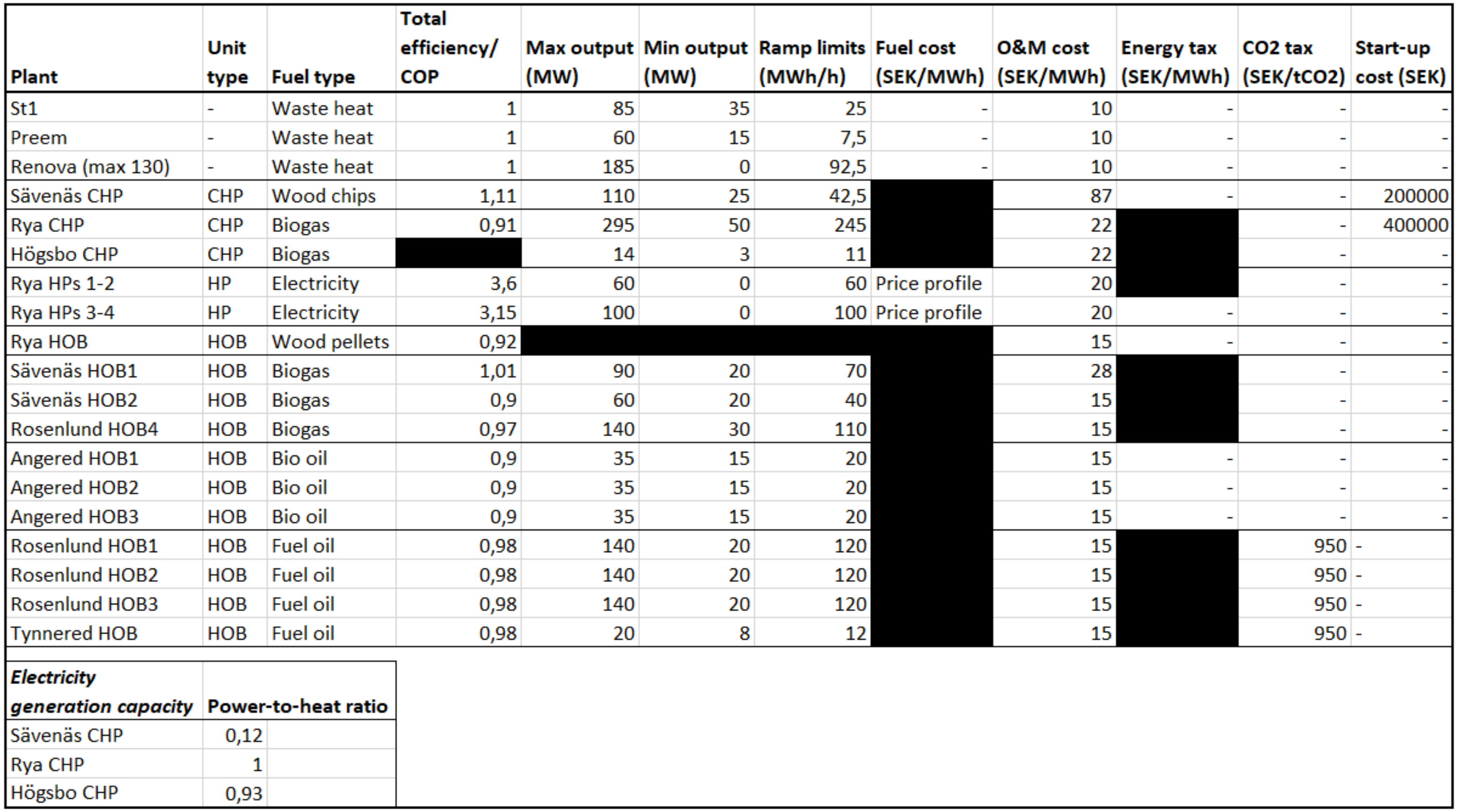
A Data for Gothenburg's DHS



Plant	Unit type	Fuel type	Total efficiency/ COP	Max output (MW)	Min output (MW)	Ramp limits (MWh/h)	Fuel cost (SEK/MWh)	O&M cost (SEK/MWh)	Energy tax (SEK/MWh)	CO2 tax (SEK/tCO2)	Start-up cost (SEK)
St1	-	Waste heat	1	85	35	25	-	10	-	-	-
Preem	-	Waste heat	1	60	15	7,5	-	10	-	-	-
Renova (max 130)	-	Waste heat	1	185	0	92,5	-	10	-	-	-
Sävenäs CHP	CHP	Wood chips	1,11	110	25	42,5	[redacted]	87	-	-	200000
Rya CHP	CHP	Biogas	0,91	295	50	245	[redacted]	22	[redacted]	-	400000
Högsbo CHP	CHP	Biogas	[redacted]	14	3	11	[redacted]	22	[redacted]	-	-
Rya HPs 1-2	HP	Electricity	3,6	60	0	60	Price profile	20	[redacted]	-	-
Rya HPs 3-4	HP	Electricity	3,15	100	0	100	Price profile	20	-	-	-
Rya HOB	HOB	Wood pellets	0,92	[redacted]	[redacted]	[redacted]	[redacted]	15	-	-	-
Sävenäs HOB1	HOB	Biogas	1,01	90	20	70	[redacted]	28	[redacted]	-	-
Sävenäs HOB2	HOB	Biogas	0,9	60	20	40	[redacted]	15	[redacted]	-	-
Rosenlund HOB4	HOB	Biogas	0,97	140	30	110	[redacted]	15	[redacted]	-	-
Angered HOB1	HOB	Bio oil	0,9	35	15	20	[redacted]	15	-	-	-
Angered HOB2	HOB	Bio oil	0,9	35	15	20	[redacted]	15	-	-	-
Angered HOB3	HOB	Bio oil	0,9	35	15	20	[redacted]	15	-	-	-
Rosenlund HOB1	HOB	Fuel oil	0,98	140	20	120	[redacted]	15	[redacted]	950	-
Rosenlund HOB2	HOB	Fuel oil	0,98	140	20	120	[redacted]	15	[redacted]	950	-
Rosenlund HOB3	HOB	Fuel oil	0,98	140	20	120	[redacted]	15	[redacted]	950	-
Tynnered HOB	HOB	Fuel oil	0,98	20	8	12	[redacted]	15	[redacted]	950	-

Electricity generation capacity	**Power-to-heat ratio**
Sävenäs CHP	0,12
Rya CHP	1
Högsbo CHP	0,93

Figure A.1: Data for the different technologies in Gotheburg's DHS [76]. For further insight in the numbers, please contact the authors.

B Input data to the different scenarios

Table B.1: Input data to the scenarios changing six different parameters

Biochar demand (MWh)	**Discount rate (%)**	**Variable cost (SEK/MWh)**	**Biochar price (SEK/kg)**	**Reduced investment cost (MSEK)**	**GROT availability (MWh)**
8937.5	1%	-14.5	4.16	-2.5	50
17875	3%	-29	4.36	-5	100
35750	5%	-43.5	4.55	-7.5	150
71500	7%	-58	4.75	-10	205
143000	9%	-72.5	4.94	-12.078	217
286000	11%	-87	5.14		250
		-100	5.33		300
		-120	5.53		
		-140	5.66		
		-170	5.72		

C Heat generation during base case

Table C.1: Annual heat generation from the different technologies in the DH system for the base case of 2012.

Technology	**Heat generation [MWh]**
st1	517 398
preem	369 830
renova	1 547 842
sav_chp	409 575
rya_chp	977 713
hog_chp	19 839
rya_hp12	10 852
rya_hp34	5 953
rya_hvc	175 400
sav_hob1	65 177
sav_hob2	4 963
ros_hob4	39 961
ang_hob1	0
ang_hob2	0
ang_hob3	0
ros_hob1	281
ros_hob2	0
ros_hob3	0
tyn_hob	0

D Data from scenarios

Table D.1: Compiled data from sensitivity analyses.

Scenario with varying biochar demand

Biochar demand (MWh)	Capacity (MW)	Extra heat hours (h)	Extra heat (MWh)	System cost (M SEK)	Marginal price. (SEK/MWh)
8,938	2	0	0	398	670
17,875	5	0	0	404	671
35,750	9.53	0	0	416	672
71,500	19.1	0	0	440	674
143,000	38.1	0	0	489	679
286,000	76.3	0	0	586	687

Scenario with varying biochar price

Biochar price (SEK/kg)	Capacity (MW)	Extra heat hours (h)	Extra heat (MWh)	System cost (M SEK)	Biochar prod. (MWh)
0	9.53	0	0	416	35,750
4.164	9.53	0	0	393	35,750
4.359	9.53	0	0	392	35,750
4.554	123	0	0	385	462,208
4.749	268	0	0	362	1,004,928
4.944	426	0	0	323	1,596,306
5.139	559	0	0	267	2,095,520
5.335	713	0	0	196	2,672,324
5.530	1072	0	0	99	4,019,471
5.660	1572	0	0	48	5,893,295
5.725	4668	0	0	-131	17,505,720

Scenario with reduced investment cost

Reduction in investment cost (SEK/MW)	Capacity (MW)	Extra heat hours (h)	Extra heat (MWh)	System cost (M SEK)	Marginal price (SEK/MWh)
0	9.53	0	0	416	672
2.5	9.54	6	19	414	609
5	13.09	10	52	411	543
7.5	13.77	183	1057	408	456
10	20.35	1029	9235	404	345
12	463.5	3193	629704	378	285

Scenario with reduced variable cost

Variable cost (SEK/MWh)	Capacity (MW)	Extra heat hours (h)	Extra heat (MWh)	System cost (M SEK)	Marginal cost (SEK/MWh)
0	9.53	0	0	416	672
14.5	9.53	0	0	416	657
29	9.54	6	6.4	415	643
43.5	9.54	6	6.4	415	628
58	9.54	6	6.4	414	614
72.5	9.54	6	6.4	414	599
87	9.54	10	14.3	413	584
100	9.54	10	14.3	413	572
120	9.54	14	32	412	552
140	9.55	20	46	411	532
170	9.56	36	91	410	502

Scenario with varying discount rate

Discount rate (%)	Capacity (MW)	Extra heat hours (h)	Extra heat (MWh)	System cost (M SEK)	Marginal price (SEK/MWh)
3	9.539	10	21	413	584
5	9.536	6	9	415	626
7	9.533	0	0	416	672
9	9.533	0	0	418	721
11	9.533	0	0	420	772

Scenario with varying grot price

Grot price (SEK/kg)	Capacity (MW)	Extra heat hours (h)	Extra heat (MWh)	System cost (M SEK)	Marginal cost (SEK/MWh)
50	11.8	2009	8652	332	310
100	10.3	722	3059	360	429
150	9.5	21	33	385	534
205	9.54	6	4	411	648
217	9.53	0	0	416	672
250	9.53	0	0	429	738
300	9.53	0	0	442	845

E Figures from scenarios

Figure E.1: Change in generation with increasing grot price.

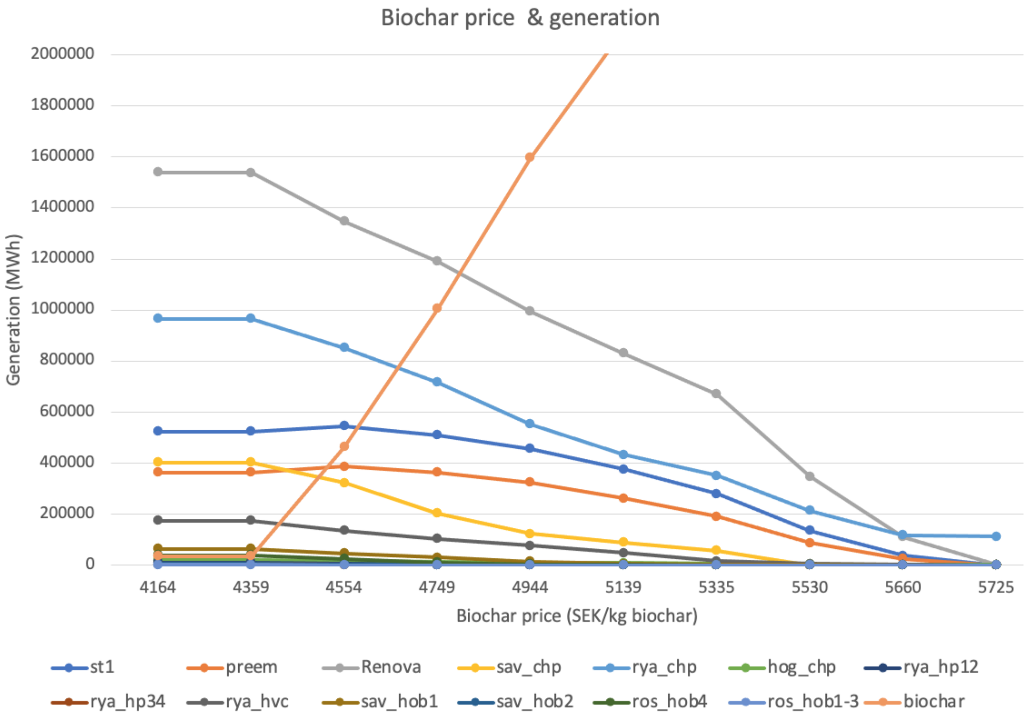


Figure E.2: Change in generation with increasing biochar price.

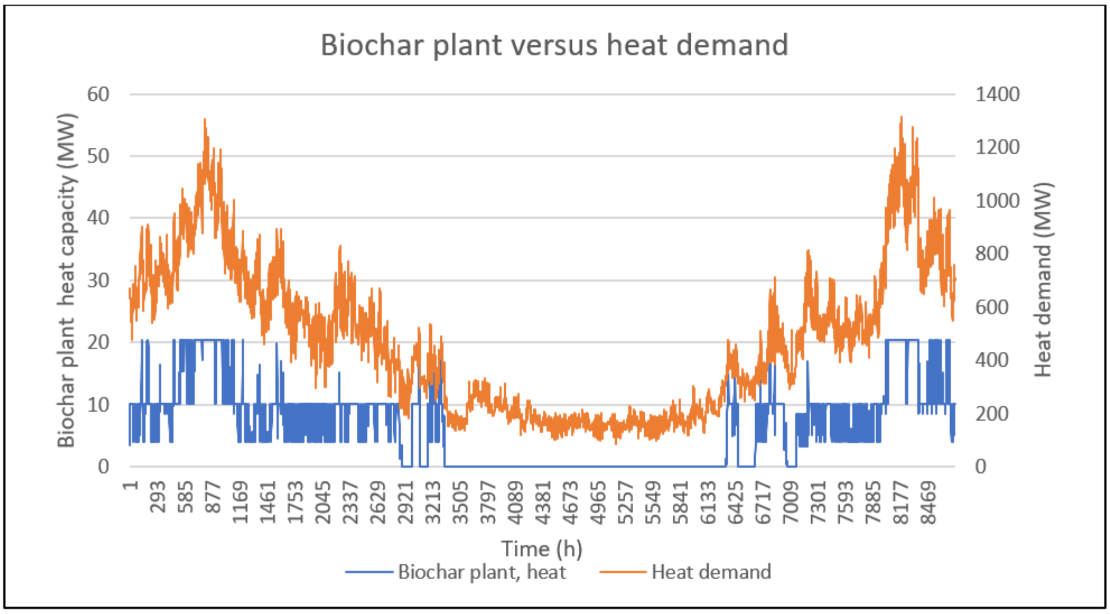


Figure E.3: The biochar plant's heat generation in relation to the heat demand with a reduction of 10 MSEK/MW in investment cost.

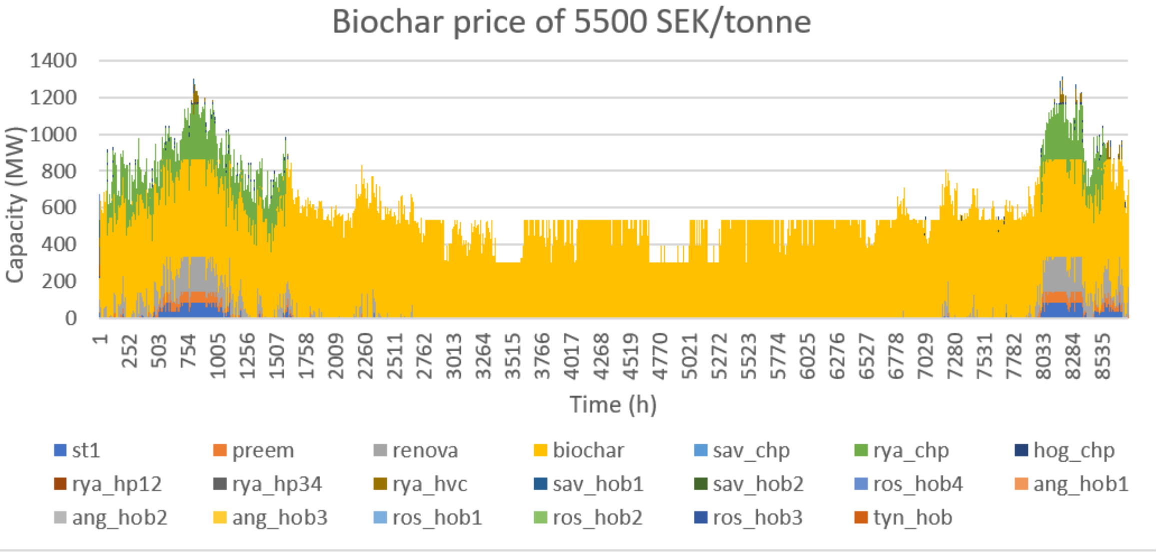


Figure E.4: The DHS when the price of biochar was set to 5500 SEK/tonne.

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