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An investigation of potential carbon sinks within the city of Gothenburg

Master's thesis in Industrial Ecology

Alexander Helldal & Carl Laurell

Department of Space, Earth and Environment, Physical Resource Theory.

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Abstract

The IPCC has concluded that carbon sinks are necessary to reach emissions and environmental targets and is used together with the Paris agreement as basis for environmental targets set by the City of Gothenburg. For the CO_2 emission target regarding territorial emissions, the City has pledged to reduce the territorial emissions until 2030 from the current stage of 4.2 tonnes of CO_2 eq. per citizen and year to 1.1 tonnes of CO_2 eq. per citizen and year. By the year 2050 the City of Gothenburg has set a target of the emissions per citizen and year being zero. To meet the targets, mitigation of emissions as well as carbon sinks are necessary.

Based on those targets the aim of this thesis was set to investigate possible carbon sink technologies that would be suitable to utilize by the City of Gothenburg, to find the total potential carbon sink of those technologies and to estimate the associated costs for implementing the technologies. Where carbon sink technologies refers to both technical solutions as well as practical methods. The method used in this thesis is based on several steps of literature studies combined with interviews of professionals and experts. The first step of the literature study was to gather information about different kinds of carbon sink technologies and this step covers the technologies; Bioenergy with carbon capture and storage (BECCS), Biochar, Wooden houses, Agriculture strategies, Green spaces, Green roofs, Forests, Land Creation and Blue carbon. The next step was to discard the technologies that was found not to be suitable for the City of Gothenburg or if there existed sufficient data and information to calculate a possible potential carbon sink. Where the carbon sink technologies based of blue carbon and land creation were discarded based on the lack of data. Other technologies such as green roofs and improved forestry principles were mainly discarded based on the time constraints of the study. The last step of the literature study was to estimate and quantify the potential carbon sink for the chosen technologies and to compare the potential with the set targets. Where the technologies investigated in this step were: BECCS, biochar, constructing wooden houses, agroforestry and urban forestry (parts of agriculture strategies and green spaces).

The thesis provides a total carbon sink potential for the years 2030 and 2050, and a cost per tonne of CO_2 captured for each of the technologies chosen in the last step of the method. To evaluate the uncertainties for the different technologies a high and a low scenario for the carbon sink potential were assessed. Where the results from the high scenario shows that the total potential for the technologies as carbon sinks could be as high as 2.5 Mtonnes CO_2 until the year 2030. Where the estimated effects of the total carbon sink, from each technology, were 61% (of the total potential) for BECCS, 30% for Wooden houses, 8% for Biochar and 1 % for Agroforestry/urban forestry. The results for the low scenario shows that the potential carbon sink could be around 1.44 Mtonnes captured CO_2 by the year 2030. In the low scenario, BECCS had a higher share (83%) than in the high scenario, while wooden houses (11%), biochar (6%) and agroforestry (0%) and urban forestry (0%) had lower shares of the total potential than in the high scenario. When the results

are compared to the territorial emission goal, the high scenario showed that the total potential of all methods can contribute with an annual carbon sink representing 26% of the reduced emission target by 2030. For the low scenario the total potential was 15% of the 2030 target.

Finally, discussions and recommendations for each technology is provided. Where discussions around secondary benefits and uncertainties are provided to give the City of Gothenburg a good understanding for each of the recommended technologies.

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1
Introduction

In 2018, anthropogenic emissions has caused an increase of 1°C temperature over pre-industrial levels and the climate change is likely to reach 1.5°C between the years of 2030 and 2050 according to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2018) [1]. To keep the potential risks and impacts related to climate change at manageable levels there is a need to limit the global average temperature increase to well below 2°C. To reach the target, mitigation strategies of current greenhouse gas (GHG) emissions are needed but also to capture and store historical emissions [1]. The capture and storage of historical emissions from the atmosphere to the biosphere and the lithosphere would be counted as negative emissions in the IPCC scenarios. According to the IPCC pathways, there could be a need for up to 10 billion tons of net negative CO_2 emissions annually as early as the year 2050 to reach the climate target, see Figure 1.1.

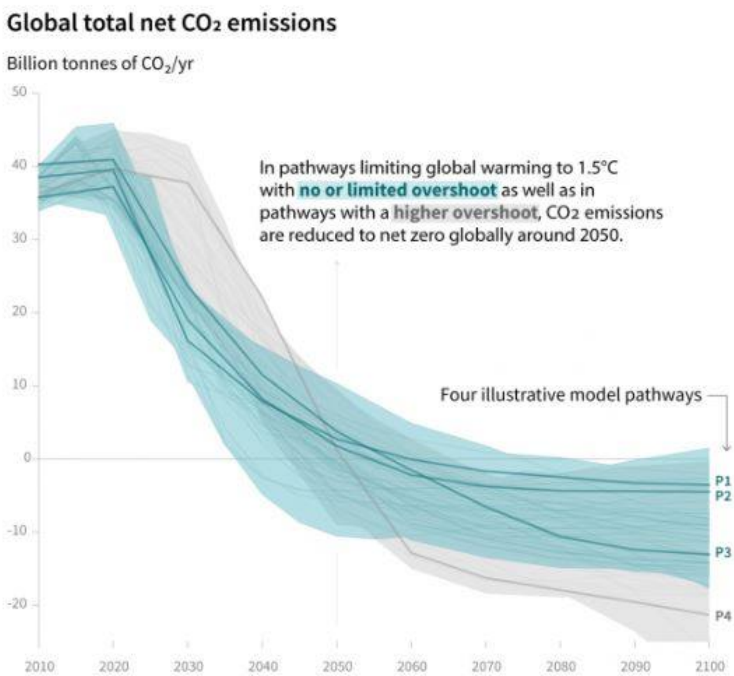

Figure 1.1: IPCC pathways for global net CO_2 emissions to reach the 1.5 degree target.

In all the possible climate sensitivity pathways, net negative emissions are necessary at the latest by the year 2090 to reach the 1.5 °C target [1]. Several negative emissions techniques require time to implement or are still considered immature technologies without a widespread use. Thus the process of implementing such technologies should be done as soon as possible to remove the maximum amount of carbon from the atmosphere before the target years set by the Paris climate conference (COP21) [2, 3].

The City of Gothenburg aspires to be one of the front runners in mitigating climate change and has set targets based on the COP 21 [4]. By the year of 2050 the city aims to reach "sustainable and fair" levels of greenhouse gas emissions while also keeping other hazardous gases at healthy levels [5]. The fair levels of emissions also includes increased emissions on a global scale for developing nations which would mean that developed nations will mitigate a higher share of the emissions while developing countries would not have the same requirements. To be in line with these targets the City of Gothenburg has developed a climate-program of which includes the different climate goals and strategies.

The IPCC report describes different carbon sink techniques that could be required to reach the climate targets. Among the techniques stated are bioenergy with Carbon Capture and Storage (BECCS), potential carbon removing methods of agriculture, forestry and other land intensive practises [1]. This thesis aims to evaluate the carbon sink technologies described by the IPCC and to further investigate other options of carbon sinks for implementation in Gothenburg. The method consists of two steps of literature study to determine which technologies to be investigated further, in regard to implementation in Gothenburg. The first step includes investigating previous research and by having discussions with experts within the field to find the best alternatives of carbon sink technologies with the highest potential today. To narrow down the alternatives, a decision was made to further investigate the carbon sink technologies of bioenergy with carbon capture and storage (BECCS), biochar, wooden houses and urban/agroforestry. The second step of the literature study was done to investigate and compare the chosen technologies by their carbon sink potential within the borders of the City of Gothenburg and to give an approximate cost per tonne CO_2 captured. Finally, the results, secondary benefits and barriers are discussed and recommendations based on the possible carbon sink strategy paths for the City of Gothenburg are presented.

1.1 Aim and research questions

This thesis aims to provide the City of Gothenburg with knowledge surrounding the cost and potential of different carbon sink technologies in terms of captured and stored CO_2 until the years of 2030 and 2050. A secondary aim is to evaluate and discuss potential uncertainties, disadvantages and secondary benefits related to each technology.

Research questions:

• Which potential carbon sink technologies can be applied within the City of Gothenburg?

• How much CO_2 could potentially be captured and stored from each technology until the years of 2030 and 2050?

• How large is the estimated cost (SEK) per tonne of CO_2 stored by using the different techniques?

1.2 Definition of carbon sink

The definition used in this report will be the same as in IPPC's:
"Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities." [1].

1.3 Limitations

The geographical boundary for this thesis will be limited to the City of Gothenburg, which implies that only the technologies that can capture CO_2 inside the borders of Gothenburg are reviewed as viable.

Examining and providing a potential carbon sink for every and any technology of capturing and storing CO_2 would cause a too large scope. This thesis will only consider carbon sink technologies where sufficient data exist and technologies that can be deemed viable and feasible for Gothenburg.

Further limitations selected to narrow the scope down includes:
• Exclusion of a discount rate from cost calculations.

• Exclusion of emission calculations from the construction of facilities, transport of biomass and CO_2 and the storage site of CO_2.

2
Background

In the environment- and climate program from 2021, the City of Gothenburg set targets of reducing the emissions per citizen by 10.3% per year in the City's pledge to reduce emissions by the year 2030 [6]. Between the year 2018 (reference year in the climate report) and 2030 the emissions per citizen (in Gothenburg) should be reduced from 4.2 tonnes of CO_2 eq. to 1.1 tonnes of CO_2 eq. in 2030. The targeted decrease in territorial emissions per year can be seen in Figure 2.1.

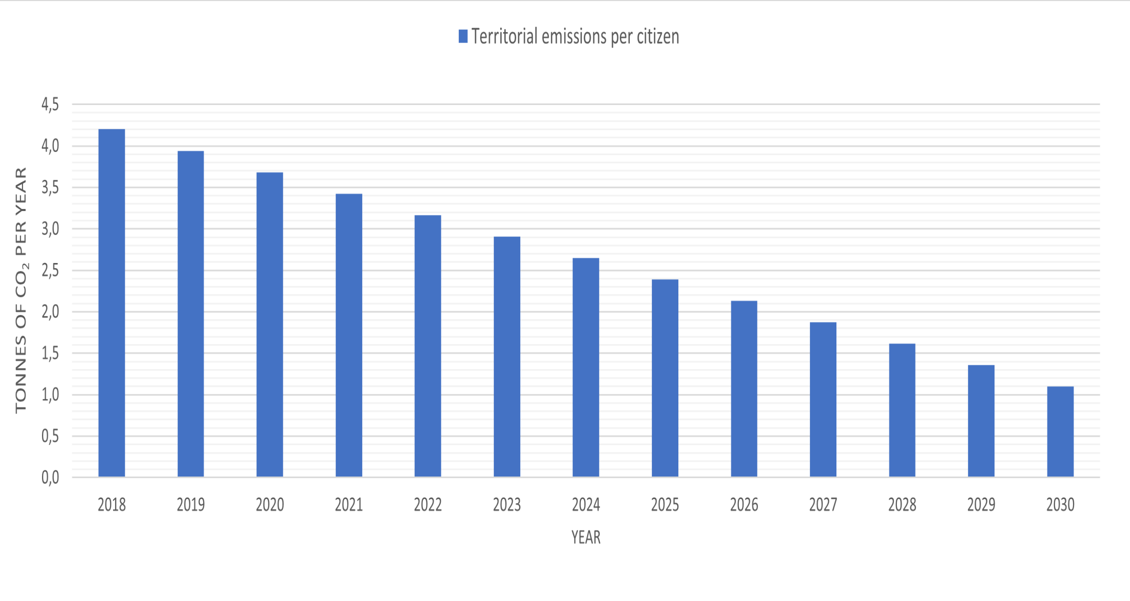

Figure 2.1: Targeted territorial CO_2 emissions per citizen and year in Gothenburg until 2030.

In total the territorial emissions of Gothenburg's 579 281 citizens are 2.4 Mtonnes annually [6, 7]. Until 2030 the territorial emissions are set to decrease to 0.64 Mtonnes annually, assuming the population size stays at a similar level. The targeted 12 year reduction of 74% would mean a significant acceleration of emission reductions from the previous decade where emissions fell by approximately 30% between the years of 2005 and 2017 for an average Swedish citizen [8]. Viewing the consumption based emissions, i.e. emissions taking placed outside of Gothenburg but where the end product is consumed by a citizen in Gothenburg, the reduction between the years 2008 and 2017 were 18% [4]. For the consumption based emissions the City of Gothenburg aims to reduce the emissions by 63% by the year 2030 compared to 2018 levels [6]. Thus, it is necessary to reduce emissions and to implement carbon sink technologies within Gothenburg to reach both the consumption based and the territorial targets.

2.1 Secondary targets

Carbon sink technologies can have several secondary benefits that align with local environmental goals. To showcase the feasibility and attractiveness of certain carbon sinks alternatives the positive externalities should be investigated. Impacts on air quality, bioenergy, biodiversity are examples of secondary benefits from carbon sink technologies. Those secondary benefits could potentially help the City of Gothenburg with targets outside the reduction of CO_2-emissions, for example, as one target set by the City of Gothenburg includes increasing green areas and sound reductions in the city for it's citizens. Carbon sink technologies where green areas are expanded would also fulfill such targets for example [9].

Several of the City of Gothenburgs targets include air quality and potentially dangerous greenhouse gases. The concept of GHG describes gases that trap heat and are generally measured on a global scale. Although the effects of some of the green house gases such as nitrous oxide (N_2O) or volatile organic carbons (VOC) are also local, including impacts on air quality and other environmental aspects [4]. To mitigate local effects, thresholds have been set by the City of Gothenburg which are based on recommendations by Public Health Agency of Sweden [10].

Secondary benefits or externalities are often complex and therefore it is important to evaluate all the technologies for potential trade-offs. When environmental targets are set both ecological and social aspects should be taken into account, where the social aspects are at risk of being forgotten [11]. For example, to integrate the challenge of biodiversity loss combined with climate mitigation targets [11]. If a carbon sink technology leads to significant biodiversity loss the net effect might be seen as negative. Also, many climate scenarios include technical solutions such as BECCS. Although BECCS facilities cause trade-offs such as the concern about lowering efficiency from the combustion plant, competition with food production and high costs [12].

2.2 Carbon tax

As "green" and environmentally friendly technologies can be relatively expensive compared to the fossil-based alternatives there exist policies and taxes to promote environmentally friendly technologies. Sweden has several political policies and subsidies to promote carbon neutral and green technologies. One system is the carbon tax, 2020 the tax was set at 1190 [SEK/tonne of emitted CO_2] [13]. The price of the tax can be used as a reference cost for carbon capture technologies investors when a potential cost analysis is done. There exist some exceptions for taxes if the fuel used is classified as carbon neutral. A facility can be exempt from the tax by using fuels that are classified as KN-nr 4401 or 4402 [14]. Fuels and the origins that are included in the KN-nr 4401 and 4402 standards are shown in Table 2.1.

Table 2.1: Fuels exempt from the Swedish carbon tax based on the origin of the input material.

Classification	**Type of fuel**	**Type of biomass**
KN-nr 4401	Firewood	Logs, twigs, bundles of rice.
KN-nr 4401	Wood	Wood chips or shavings.
KN-nr 4401	Wood	Sawdust and other wood waste.
KN-nr 4402	Charcoal	Including coal from nutshells, whether or not agglomerated.

Fuels that fulfill these criteria are thus excluded from carbon- and energy taxes and potentially become cost efficient compared to other fossil-based alternatives. The carbon tax has been rising historically and if the trend of continues fuels exempt from the tax could have a decreasing cost relative to fossil-based alternatives over time [13].

2.3 Development of carbon capture technologies

The City of Gothenburg wants to act as a front runner in a society striving to be sustainable and could have a higher willingness to accept ideas that are less established [6]. For example, technologies with high investment costs or ideas that are at an early stage of their development. As several carbon sink technologies are not established on a market, investing in niche products or processes that provide a carbon sink might hold the most significant potential in the future. The correlation of effort and technological progress can be described by an S-curve [15]. The S-curve shows how technological progress is quite rapid after a certain amount of effort is put into a technology. At a low effort stage it would mean the product or process is yet to have a technological breakthrough and investments in the product or process could lead to significant technological advancements. An S-curve can be seen in Figure 2.2 as a schematic by Becker and Spetz [15].

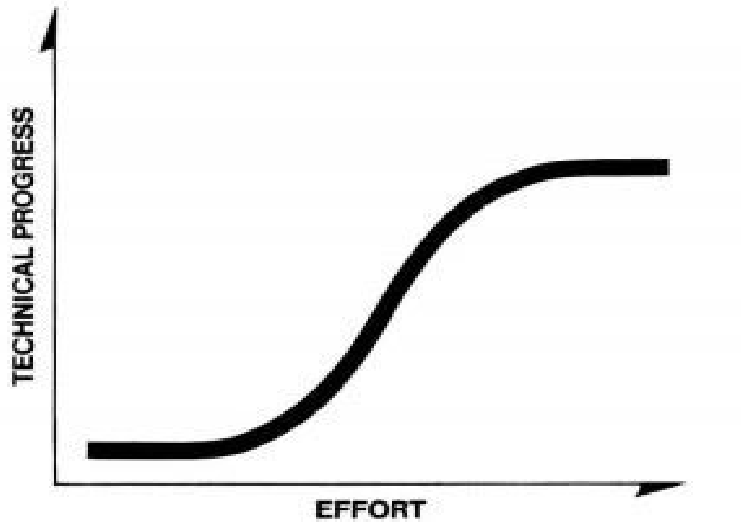

Figure 2.2: The S-curve showing the correlation between technological progress to effort.

It would align well with current climate goals to invest into technologies that are less proven while also having significant potential as carbon sinks with positive externalities. The most cost effective option will often be preferred but with a limited land area in the Gothenburg region there is a need for creative and less land intensive solutions [16].

2.4 Carbon capture technologies

Any carbon sink technology potentially considered for the thesis should fulfill the criteria and definitions, see Section 1.2. The definition excludes a technology that mitigates emission while not functioning as a carbon sink. For example, replacing fossil-based energy with renewable energy is not considered a carbon capture technology in this thesis. For an illustration of what the definition counts as a carbon capture technology, see Figure 2.3

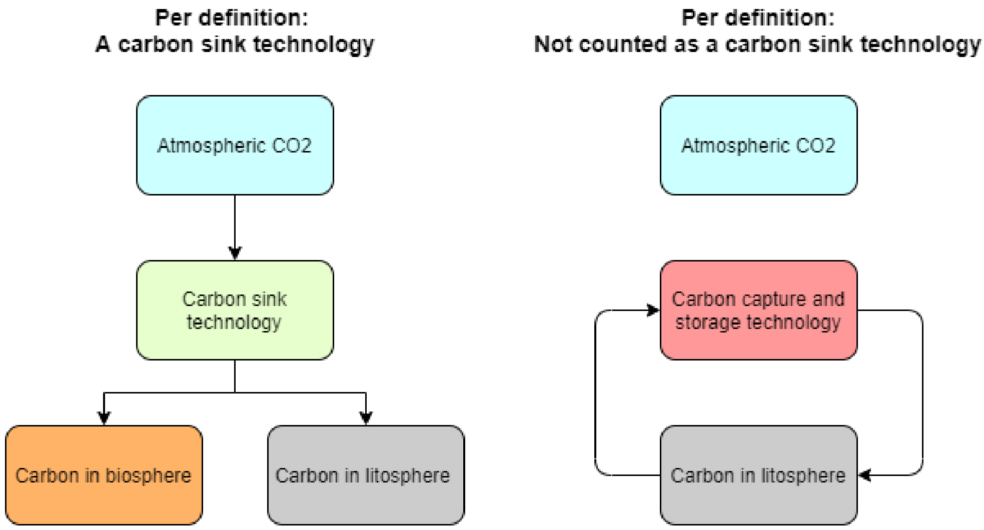

Figure 2.3: Illustration of the carbon sink technology definition.

Carbon capture is the procedure of binding inorganic carbon to form organic carbon and store it for a long time. A system can be considered carbon negative over a period of time if the operation of carbon capture leads to a decrease of total carbon in the atmosphere. Systems are thus considered if they have a net negative impact on the atmospheric carbon stock of a system over a set period of time.

2.5 Theory: further investigation technologies

In this section, a background theory for each carbon sink technology chosen for further investigation is presented.

2.5.1 Bio Energy Carbon Capture and Storage (BECCS)

Studies have shown that carbon capture and storage (CCS) and bio-energy based carbon capture and storage (BECCS) are necessary for Sweden to reach the future climate targets [17, 18]. Göteborg Energi, which is the owner of the energy plants in Gothenburg, has also acknowledged that CCS and BECCS technology is necessary for Gothenburg to reach the existing climate targets [19]. Today there is several initiatives within the area of CCS in Gothenburg, for example "CinfraCap" a joint venture between Göteborg Energi, Nordion Energi, Preem, St1, Renova, and Gothenburg Port Authority. Another project is a new planned bio-based thermal power plant in Ryahamnen [20].

Carbon capture and storage connected with energy production can be done with several different techniques at different stages of the process. One carbon capture technique already used in industry is the separation technique by using gas absorption with a solvent under high pressure to absorb carbon dioxide from a flue gas [21]. For existing equipment and existing plants, amine-scrubbing of CO_2 is a relative mature technique based of gas absorption with a wide amount of use within different industries, where an amine-based solvent is used to reduce the energy demand of the carbon capture [22]. The technique can also be attached to existing plants which is beneficial for large scale use on existing infrastructure and the technical aspects create up-scaling advantages. The technology has a high investment cost while the running costs are relatively low in comparison to the investment [23]. Although the heat requirement increases with the increased amount of CO_2 captured [22].

Bioenergy with carbon capture and storage (BECCS) is the principle of combining biofuels with CCS techniques. The bioenergy combustion facility is combined with a carbon capture technology and the carbon is then transported and deposed for long-term storage. Combining a carbon net zero technique such as biofuels, which uses carbon from the biosphere and creates a carbon net negative system [23]. The carbon captured from the combustion flow is transported to a site where it can be deposited underground into the lithosphere and thus decreases the carbon dioxide concentration in the atmosphere and biosphere. Although, it should be noted that the carbon captured will be lower than the total amount of carbon within the biomass combusted. Thus the carbon in the atmosphere will increase in the short-term. Over a longer time span the net-effect on atmospheric CO_2 will be negative.

The efficiency of the process is also dependent on the location of the storage and the BECCS facility. As the process of capture, transportation and storage of the carbon is energy intensive the net gain from BECCS could decrease depending on the scope of a study. The overall efficiency of a bio-based heat-plant has been reported to decrease by up to 37% due to the complex and energy intensive process of CCS, although Wienchol et al. (2020) state a possible 8-12% decrease [24, 25].

2.5.2 Biochar

In the biochar system the capture and sequestration of CO_2 from the atmosphere into the biosphere is from photosynthesis. The carbon is fixed either in crops, timber or in end products such as green waste and manure which can be utilized as input materials into the biochar process. The input material is then exposed to pyrolysis to produce the end products of process heat and biochar, although other secondary products such as bio-oils and syngas can also be produced [26]. The process heat provided from the pyrolysis could be seen as bio-energy and help to offset fossil-fuel based energy. The carbon sink is created by the carbon that is captured in the biochar and can later be applied to soils or be utilized in industries [26].

Generally, biochar can be produced from a variety of different materials that have a high organic fraction [27]. Therefore, production of biochar could be used as an utilization tool to handle waste flows as these resources potentially have limited competition from other businesses [28]. Although the different input materials might require different type of equipment to be utilized, such as a dryer being used to decrease the moisture of an input material etc.

Biochar has good long-term storage properties which are suitable for carbon sequestration. This is because the biochar can be considered to be resistant to chemical and biological decomposition. The stability can however be difficult to define. Although, results from Crombie et al. (2013) have shown that there is a correlation between the pyrolysis temperature and the increased stability of the carbon within the biochar [29]. This however creates a trade off, as higher pyrolysis temperature leads to decreased biochar yield but increases the carbon fraction and the aromatic condensation of the biochar. The result is that higher temperature will give less yield but higher recalcitrance [28]. The pyrolysis temperature is also mentioned in ”Vägen till en klimatpositiv framtid” where it is claimed that the pyrolysis should have a temperature of at least 450 °C in order to create stable biochar [30].

This stability is what makes biochar a technique viable as a carbon capture technology. But the biochar can also have other secondary benefits after its end use with the potential of improving yield and soil quality [28]. The recalcitrant form of carbon can increase the water- and nutrient holding capacities of soils, which can lead to enhanced productivity leading to an increased rate of carbon uptake in the plants from atmospheric CO_2 [26].

From a local perspective (in Gothenburg), the interest in using biochar have already been shown by the city and an investigation has been made by Gothenburg (together with consultants) regarding the potential to invest in a biochar production facility based on garden waste at Renova [31].

For a widespread use of biochar a certification and legalization would be necessary to create a regulated and safe market with a homogenized standard for biochar quality. The European Biochar Certificate (EBC) Foundation created a certificate for biochar for the purposes of safe biochar [32]. EBC consist of several requirements for biochar to be considered safe and sustainable. The requirements refers to thresholds for different harmful or toxic compounds in the biochar, such as the heavy metals: Zink, Copper and Cadmium. The requirements are primarily set to enable biochar reaching the requirements to be certified and thus potentially safe to be used for feed production or other agricultural purposes. The requirements for the certificates might become a hinder, especially for biochar from human wastes. One EBC requirement is that only plant biomass may be used to produce biochar [32]. Limiting the EBC certification to exclusively be based of biomass could reduce the potential and viability significantly.

2.5.3 Wooden houses

Houses completely or partly constructed in timber have been a part of the history of Gothenburg and one of the stand out house types of the city are the "Landshövdingshus". Between 1874 and 1994 there was a ban on constructing wooden houses higher than two storeys [33]. Instead the houses had a bottom storey in stone or concrete and top stories in wood. Today the houses hold historic value and serve as architectural trademarks for the the city.

The Swedish ban on constructing wooden houses rising higher than two storeys has since that time been lifted and the demand for wooden buildings and structures is continuously rising [34]. In 2016 around 12% of the input material into buildings were wood and 10% of all multi-storey buildings were constructed in wood [35, 36]. The construction of buildings, mainly housing, globally leads to emissions of approximately 39% of the total emissions from the process- and energy related sector [37]. Further, the construction sector also stands for around half of the steel demand globally. The increased structural risk of wood to weather- and less predictable events such as fires and storms has led to an extensive use of steel and concrete in structures but several of the material disadvantages can today be solved with modern techniques [34]. For example, selective choosing of planks and discarding planks with deficiencies can help the robustness of the structure.

For a structure to be used as a carbon sink the lifetime of the structure should outlast the time span required for the same amount of wood to regrow, also known as the rotation period of the forest. The construction wood stores the atmospheric carbon and creates a net sink in the biosphere, assuming the lifetime of the structure exceed the rotation period of a tree [38].

There is potential to construct timber buildings up to twenty storeys high [39]. Several multi-storey houses have already been constructed in Sweden [40] and more are planned. For example a project in Gothenburg the "BRF SLÅ ROT" which is a planned housing cooperative built in wood that will house 45 apartments of varying size, located in central Gothenburg [41]. Additionally a preschool named "Hoppet" built in cross laminated timber (CLT) has been constructed and the project aims to be carbon neutral [42]. The type of construction method chosen for these projects was a wooden frame in CLT as the main structural building material. CLT panels are produced from spruce boards that are dried, stacked crosswise and then glued together over their entire surface [43]. Mechanical benefits of the CLT are the reduced uncertainty of mechanical properties and has a relative light weight [44]. Further environmental benefits were also reported by Chen et al. (2020), which is based of the results from an LCA, using the Athena impact estimator to see the different CO_2 emissions from two alternatives, see Table 2.2 [44].

Table 2.2: Emissions of CO_2-eq for different construction and life time steps in the life cycle of a 12 storey building for two different building materials, reinforced concrete (RC) and CLT.

Kg of CO_2-eq emissions from steps in the life cycle			
LCA-steps	CLT [10^6 kg CO_2-eq]	RC [10^6 kg CO_2-eq]	Difference [10^6 kg CO_2-eq]
Production	1.32	1.84	-0.52
Construction	0.21	0.15	0.06
Usage	0.06	0.03	0.03
End-of-life	0.12	0.12	0.00
Total	1.71	2.14	-0.43

The results show that the emissions are 21% lower for the CLT option of construction than the reinforced concrete (RC) option. Additionally wastes from wooden houses can be used as input in other industries. By reusing and recycle as much as possible of the material from a wooden house; up to 84% of the CO_2 eq. emissions could be saved compared to a reinforced concrete house [39].

The increasing trend of constructing in wood is not only evident in Sweden. Hurmekoski [45] writes that the share of wooden multi-storey houses in Finland is increasing exponentially. If the environmental focus is to be fully implemented into the construction sector there is a need for willingness from the industry. From a survey conducted by Laguardo-Mallo and Ezpinosa (2016) regarding the importance of different factors when choosing building materials for houses it was evident that environmental factors were not highly prioritized [46].

2.5.4 Agricultural strategies

Climate change is impacting food and fiber production all over the world due to higher CO_2 concentrations, higher temperature, unstable precipitation. Although, if the damages of climate change could be more extreme in lower latitudes of the world it is still relevant for higher latitudes countries, like Sweden, to adapt [47]. Therefore there is a need to change our "modern monoculture agriculture management" to a more climate smart agriculture in order to have higher resilience against climate changes [47].

Climate smart agriculture is mainly about achieving adaptation to climate change and to lower the emissions per output product. One way of using our agricultural system to improve the mitigation and adaptation to the climate change is to increase the soil organic carbon (SOC) within the system [48]. Increasing SOC is to reallocate atmospheric CO_2 into the long-term organic pools and in that way offsetting the GHG emissions. SOC also has an important part as a driver of soil structure, nutrient cycling, microbial activity and biodiversity. There can be different strategies to increase the long-term soil C storage. One strategy is to increase it with organic inputs (cover crops, agroforestry etc) [48], and another strategy is to implement a "No-till management". But also to mix these strategies can be a climate-smart agricultural practice[49].

The No-till management (or reduced tilling) treatments idea is to promote carbon sequestration and to reduce CO_2 emissions and this strategy is one recommended component in climate-smart agriculture [49]. This can be questioned, as there are still no real proof that no-till management is increasing the carbon stock by itself and further investigation on type of climate and soils is needed [49]. The crop cover method can vary in increased SOC between what type of crops that are cultivated and which cover crops are included in the crop rotation. But in general there is a net increase of SOC [48]. However, it seems that the best potential is when a combination between the two practises are done and it exist results on creating a net sink of carbon during this practise [49].

Another promising agriculture management is to implement agroforestry. Agroforestry is done by increasing the amount of trees and bushes within the farming land or pasture land [30]. Tree-based inter-cropping systems are also often referred to as "alley cropping" and this method of using trees as "intercrops" can play a vital role of sequestering carbon both in the plants over and below soil components[50]. Agroforestry has also been proven to have a positive impact on the storage of carbon, increased biodiversity and having better resilience against dryer weather and erosion [30].

2.5.5 Green spaces

Green spaces is the collective name for urban areas that are covered by trees, grass or other nature based areas or infrastructure considered to be naturally green. Although green roofs are excluded and the green spaces will refer to ground level spaces. The city of Gothenburg has goals considering green areas such as parks and trees close to its inhabitants. For example to increase the amount of inhabitants that have a green area of at least 0.2 hectares within 300 meters, between 2018 the value of 93 % is targeted to reach 100 % in 2030. The level of maintenance of green spaces has a great impact on the amount of carbon sequestered. Cutting, mowing and other maintenance practises significantly lowered the annually sequestered amount of carbon as well as leading to further emissions [51]. The type of vegetation had a high impact on the carbon sequestration above and below ground, thus the choice becomes important for cities aiming to reach carbon net zero [5].

2.6 Theory: other technologies with potential

In this section, a background theory for each carbon sink technology not chosen for further investigation is presented. Observe that even if those technologies are not evaluated in this thesis they can still have potential to be large carbon sinks.

2.6.1 Green roofs

Green roofs describes the practise of growing plants and substrates on rooftops. Depending on what type of coverage used the effect of the green roofs differ. A green roof consists of a vegetation mat growing above a substrate which is provided with a water reservoir or provisioning system, as seen in Figure 2.4. There is also a roof slab to protect the underlying roof from damages. Green roofs leads to reduced

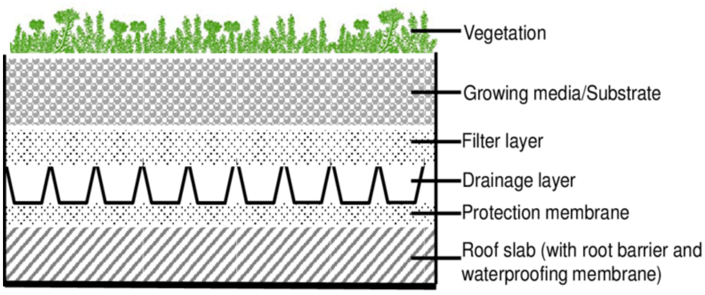

Figure 2.4: Green roof schematic by C. Pimentel-Rodrigues, A. Silva-Alfonso and M. Lima .

energy demand for the building and sequestered carbon from the atmosphere [9]. Green roofs also provides habitats for insects and small animals as well as having good water retention capabilities. As roof tops are the main "top area" of cities that sunlight reach it is also an ideal spot for plants that doesn't require extensive management other than sunlight and water to grow. For a green roof in Michigan the carbon sequestered in the above ground biomass cultivated was at an average of 162 g per square meter [52]. The energy savings based on simulations using the energy Green roof calculator (GREC) indicates annual savings of more than 3.4 kWh per square meter compared to conventional dark roofs [53]. The study was conducted on office roofs in Oregon, USA and the calculations are climate dependent and might alter in other climates.

The green roofs can be extensive or intensive depending of the substrate of choice. Extensive green roofs are shallow with a depth of less than 20 centimeters and often require no care while the thicker intensive (>20 cm of depth) roofs can support woody plants, but generally require more care [9]. The intensity also affects how much carbon is sequestered. The mitigating effects on air pollution and energy reductions [52] combined with the carbon sequestration means the green roofs could be of interest for municipalities and cities seeking environmental improvements to urban environments.

2.6.2 Forests

Forests have several different roles in supporting and maintaining ecological cycles and systems with their ecosystem functions and environmental services. Recycling carbon and water while also regulating water flows and protecting soils are just some processes a forest contributes with [54].

Forests also function as carbon sinks, sequestering CO_2 from the atmosphere. Forests approximately absorb one fourth of the anthropogenic CO_2 emissions and storing it in large carbon pools in both tree biomass and soils [55]. By utilizing the impact forests has on the carbon cycle, it can provide an important land-based mitigation option to capture and store carbon [55]. The implementation of more biomass is a target in several scenarios by the IPCC in order to reach the 1.5 °C target [1, 56]. Increased forestry can be achieved by planting forest on non-occupied land (afforestation) or by planting forest on recently deforested areas (reforestation). Also mitigating the trends of deforestation and forest degradation can be used to further reduce greenhouse gas emissions from the land [55]. The strategy of capturing carbon in forests and avoiding deforestation is seen as one of the most cost effective and safest way for large-scale mitigation of the climate change [56].

Some uncertainties exist surrounding the impact of these kinds of biophysical processes. For example, how the albedo changes, does to the energy exchange with the surface and how it affects the water vapor when planting a large scale forest [55, 56]. Another aspect to take into account when characterizing forest is to distinguish between planted and natural forest. As planted forest commonly is mono cultural plantations it may lead to low ecosystem resilience and the stresses from environmental change can lead to high mortality [57]. Also, high-yielding trees species often have a high water demand and can therefore reduce water flows to other native species or close by natural forests [57].

2.6.3 Land creation

Several methods of capturing carbon are based on the idea of freeing up land for biomass growth. By moving a carbon-inefficient practise that was competing with forests for land or simply to create land where it previously were no land such as on the ocean, can create opportunities for biomass growth. The effect of land creation or land sparring for biomass growth has a lot of potential but often rely on complex techniques.

One way to spare land from agriculture would be to grow crops underground. The technique is at an early stage of any potential development and there exists limited data. To potentially be cost and carbon effective, an abandoned area underground could be utilised where crops were to be grown with an artificial lighting system. The crops would substitute crops grown in traditional manners that occupy arable land. The land would then instead be used to sequester as much carbon as possible and if the carbon sequestered would out-weigh the additional emissions from growing crops in the altered way [58].

Another way to spare land is to create artificial islands and to move either practises that require arable land or to grow biomass directly on the islands. The artificial island would be built in wood or another material that floats. Limited research has been done and thus the data is scarce. An opinion piece by Siobhán Dunphy discusses an island safe from extreme weathers with solar panels [59]. The solar panel could then provide energy that catalyzes the reaction to form methanol from CO_2 in the water. However, collecting the methanol while still acting as a carbon sink or a renewable source of energy is one of several different issues.

2.6.4 Blue carbon

In coastal zones there exist sea grass meadows or other underwater biomass growth which can be highly productive from a carbon sequestration standpoint and provide the ecosystem with important services [60]. The underwater biomass, often named ”blue carbon”, stands for the organic carbon in the sea grass sediment that accumulates from the production and sedimentation in the meadows. These ecosystem can be used as a potential carbon sink in areas with high fractions of sub-surface land such as seabeds [61]. Research has showed that this storage can be of significant quantities and contribute to mitigate climate change. The point with this method of blue carbon is to try and conserve the aquatic biomass in order to avoid the carbon release from the system and by that contribute with a carbon sink.

3
Methods

3.1 Literature study

An extensive literature study was conducted to assess all possible options of carbon capture. Literature was obtained from personnel at the environment administration at Gothenburg city and Chalmers university of Technology, mainly by having email contact and online meetings. Online search engines such as Web of Science and Google scholar were used semi-systematically. Key words were used to search for information in various search engines. The search was conducted by the use of keywords such as "carbon sink technologies", "carbon capture" to find all possible ways of capturing carbon. Further, specifying a certain technology by using the specific method as key word, for example: "biochar" was done to find additional information. From the articles a wide variety of information was obtained. Articles that held particularly interesting information such as concrete numbers or ideas were thoroughly analysed. The articles of interest were critically assessed and where the findings were deemed to be quite uncertain another article with similar results indicating the same conclusion was found. The literature study was an ongoing process for the entirety of the master thesis as the need for new data emerges, to continuously learn and to ensure new thought processes are backed up by relevant literature.

3.2 Criteria table

In this step the literature study was analyzed, to investigate which of the carbon sink options that are viable and feasible to evaluate further. The viable and feasible argument of inclusion/exclusion in the study is based on critical parameters that are deemed essential for the technique and are not included in the other criteria. For example, an idea is considered not viable if, at an early stage of development or was deemed expensive whilst holding low potential as a carbon sink.

First a criteria table was done, to establish which carbon sink technologies fulfill the basic criteria of ”sufficient data, Suitable conditions in Gothenburg and Viable idea”. The criteria table can be seen in Figure 3.1. These criteria were chosen to match the thesis aim of viable and feasible technologies within Gothenburg and having results based on data that are considered reliable for the years 2030 and 2050.

	Sufficient data	Suitable conditions in Gothenburg	Viable idea
BECCS	Yes	Yes	Yes
Biochar	Yes	Yes	Yes
Agroforestry	Yes	Yes	Yes
Wooden houses	Yes	Yes	Yes
Green Areas	Yes	Yes	Yes
Forestration	Yes	Yes	Yes
Green roofs	Yes	Yes	Yes
Blue carbon	No	Yes	Yes
Carbon islands	Yes	No	No
Underground crops	No	Yes	-

Figure 3.1: Criteria table for the different carbon capture technologies.

Based on the result in Figure 3.1 a decision to not evaluate the carbon sink technologies of blue carbon, carbon islands and underground crops further was made. Blue carbon and underground crops was discarded on the basis of insufficient data. Carbon islands was discarded on the basis of the climate in Gothenburg not being suitable. See the result section 4. Although, these methods could still have potential to sequester significant amounts of carbon.

The technologies fulfilling the criteria was examined further based on acquired information to establish which carbon sink technologies that possibly could act as a carbon sink option. Although all technologies were assessed as possible carbon sinks, a decision to not further investigate forestation and green roof was done. This decision was done during this part of the project as only five technologies could be examined thoroughly due to time constraint, see result section 4. The chosen technologies for further investigation was: Bioenergy with carbon capture and storage (BECCS), Biochar, Wooden Houses and Agroforestry/Urban forestry.

3.3 Method for BECCS

CCS technology integration into modern cities requires a large point source of CO_2 emissions. For example, in combination with a solid waste incineration plant or industry facilities where a flue gas with high fraction of CO_2 exist, as per the definition and limitations of the report (section 1.3 and 1.4) the prevention of CO_2 emissions from fossil fuels are not considered in this report. A minimum value of 0.5 Mt per year was set based of Garðarsdóttir et al.(2018) [62]. Which means only plants that exceed the threshold from a point emission set at 0.5 Mt CO_2 per year will be considered as a potential CCS applicable site. To qualify as a bio-based energy facility it was chosen that at least 50% of the input material should be bio-based. To estimate the total potential of carbon capture, an efficiency factor for the CCS plant at 90% was selected, based of Fagerlund et al.(2021) [63]. A second scenario was also investigated, set at 70% capture efficiency, to establish how the cost calculation is affected by a drop in efficiency. The calculation of the annual CO_2 captured can be seen in equation 3.1. Where the CO_2 captured from a emission source is equal to the efficiency of the CCS unit (ξ) multiplied with the amount of CO_2 emissions and then multiplied by the bio-based fraction of the emissions (X_{bio}).

$$\mathrm{CO_2}\ Captured = \xi \cdot Emissions \cdot X_{bio} \tag{3.1}$$

3.3.1 Cost calculation for BECCS

The cost of the CCS technology will be evaluated in SEK per ton captured and stored CO_2. The cost for CCS implementation will be divided into four different parts; investment-, running-, transport- and storage cost. The investment and running costs are based of a study by Gassnova SF [64]. The study from 2019 gives estimated prices for the construction of CCS units at two sites of similar size to Sävenäs, one site named Fortum is based of a waste to energy facility and these numbers will be used for the investment and running cost. The study assumes an operational life time of 22 years with an additional three years of construction, which was the same for Garðarsdóttir et al. [62] and the Gassnova study [64]. Investment cost and running cost based of Gassnova are converted to SEK from NOK by a factor of 1:1 (1 NOK= 1 SEK [65]). Transport are as mentioned in section 4.1.2 based on the number from Karlsson et al. [30]. The storage costs is based on a Swedish case study from Garðarsdóttir and colleagues [62] and are only estimations for storage at Utsira (and possibly Falluden). The total cost estimation is calculated by equation 3.2.

$$Total\ cost\ (TC)\ [SEK] = Ic + Rc \cdot OT + TRc + Sc \tag{3.2}$$

The total cost is the sum of the investment cost (Ic), running cost (Rc) and OT is the operational time in years, transport cost (TRc) and storage cost (Sc). The cost is then split over all the emissions of CO_2 captured (bio-based and fossil-based) by equation 3.3.

$$Cost\ per\ tonne\ (SEK) = \frac{TC}{\mathrm{CO_2}\ captured} \tag{3.3}$$

A second calculation is also done viewing only the bio-based emissions as a product. Thus splitting the cost over the bio-based emissions instead of all the captured CO_2, using equation 3.3 but the CO_2 captured refers to the bio-based emissions.

3.4 Method for biochar

To identify what kind of input material that could be used for biochar production we followed literature principles mentioned in section 3.1 and had interviews with experienced people within the field.

The next step was to quantify the possible flows of input materials within the region of Gothenburg to see what volume of biomass that is existing and could be utilized. The input data presented and used in this study is produced by pre-studies done by consultant firms together with the city of Gothenburg, data presented by Gryaab and other documents produced by the city [31, 66]. As every flow could not be identified (for example seaweed and agriculture waste) the input materials examined are: sewage sludge, garden waste, wood waste and food waste. The four input flows will all qualify as "biochar feedstocks" in the study.

When a quantification of the input flows was done the next was to investigate the potential output of biochar production per year (BP). This started with a further more technical investigation on fast or slow pyrolysis and pyrolysis temperature with the help of scientific articles and meetings with company representatives. Then a chosen pyrolysis temperature was decided at (700 °C) in order to make a relatively stable and clean biochar [27]. The calculation on Biochar production for each material was done as described in equation 3.4. Where BP represent ”Biochar production”, IB represent ”Input of biomass” and BO represent ”% Biochar output per Input of biomass”. All values used for BO dependent on different materials was taken from the end report from ”Rest till bäst”[27].

$$BP\ [tonnes/year] = IB\ [tonne/year] \cdot BO\ [Wt - \%] \tag{3.4}$$

As the Biochar production could be quantified the next step was to relate this to the aim, how much sequestered carbon (CS) can potentially be capture within biochar until the years 2030 and 2050. The carbon sequestered per mass unit of biochar was calculated based of the "Rest till Bäst" report and the report on biochar from sludge by von Bahr (2016) [67, 27]. See Equation 3.5. Where the first parameter BP is the biochar yield per year calculated in Equation 3.4. The second parameter is years of production, which accounts for the years between installation of the production and the years 2030 or 2050. With an assumed installation time of 1.5 years we have accounted for 7 to 27 years until 2030 respectively 2050. The third parameter X_{Carbon} is the fraction of carbon within the biochar, which is based on weight and different input material. The carbon remaining in the biochar after application is set at 95% after 100 years based of Paulsson et al. (2020), therefore L=0.95 is to account for leaching and other events leading to reduced carbon captured within the biochar [27]. A factor for error is also added at 5% to account for other unforseen complications, EF=0.05. Also, as the biochar consists of the carbon atom and not the entire carbon dioxide molecule the weight from CO_2 to carbon is done by a factor of 44 (molar mass of CO_2) divided by 12 (molar mass of carbon).

$$CS[tonnes\ \mathrm{CO_2}] = BP[tonens/year] \cdot [years] \cdot X_{Carbon}[\%] \cdot (44/12) \cdot L \cdot (1 - EF) \tag{3.5}$$

An assumption that was made was that the installed capacity is matched to utilize all the amount of biomass that can be available, which can be seen as unrealistic but will determine the large potential of biochar.

3.4.1 Cost calculations for biochar

The cost calculations for biochar are adjusted on a cost per ton of CO_2 sequestered. A life time of 25 years is used for both a CCS unit and biochar unit [64]. For a biochar unit the construction time is estimated at 1 year with 24 years of operation. The parameters used in the calculations are investment cost (I) and annual operational cost (A), the values for those are from a study made by Turek et al. (2018) and can be found in table 4.5 (in Results) [68]. It is assumed that the City of Gothenburg uses all the 24 years of operation and therefore only a cost for the period of 2023-2048 is calculated. The equation used is presented in Equation 3.6. Observe that inflation or discounting is not considered in these calculations.

$$Cost\ [SEK\ per\ tonnes\ CO_2] = \frac{(I\ [SEK] + A\ [\frac{SEK}{year}] \cdot 24\ [year])}{CS[Tonnes\ \mathrm{CO_2}]} \tag{3.6}$$

3.5 Method for Wooden houses

Building a wooden house is not classified as a carbon sink by definition, the carbon is sequestered by biomass and to enable new biomass to grow the lifetime of the houses are a key element. As houses are not classified in this thesis to be as long lived as CO_2 storage underground or biochar the topic will be viewed in two separate ways. One way is by viewing Swedish forestry as a sustainable long term forestry that provides biomass without the carbon pool of the forest being degraded, this is based of the thinking introduced by Cowie ,Berndes and Smith (2013) [69]. The other way of viewing it is by taking the life time of houses into consideration and using the rotation period for trees to establish a net carbon sink based on the theory introduced by Guest et al. (2013) [38]. The ”Guest-theory” is also based on a sustainable forestry and that in the end of bio-based products (Wooden house) lifetime it is used for incineration for bio-energy production [38].

As 90% of houses with two storeys or fewer are already built in wood, the focus of this report will lie on houses higher than two stories, and will be refereed to as "multi-storey buildings". To establish a scenario of the quantity of new houses that will be built we based the results off statistics from Fastighetskontoret and SCB [70, 71]. The data used is the amount of built houses from 2016 to 2020 and planned construction of houses until 2050. Based on the information a decision to use the scenario of 4181 new apartments per year was made. For simplicity it was assumed that the increase in housing is constant until 2050. Which means that 4181 apartments (not complexes) are built every year until 2050. The construction, and thus emissions, of houses is also deemed as unavoidable as the city plans to construct new houses.

The next step was to choose the number of stories and material of the buildings. Based on Skullestad et al. (2016) the climate impact difference for a timber structure compared to a reinforced concrete building decreases after a height of 12 storeys. Thus, a decision to limit the study to 7 and 12 storey houses was made and to use cross laminated timber as building material [39]. The same study is used for the data of mass CLT per building which was later used for calculating the stored carbon.

First calculation was to quantify the amount of CO_2 that was captured per square meter for the 7 and 12 storey buildings referred to as ”CM2”. This was done as by Equation 3.7. $M3_{7,12}$ represent the amount of m^3 CLT per m^2 house area within the chosen house example, data for this parameter is gathered from Skullestad et al. (2016) [39]. KgCLT represent kg of CLT per m^3 of CLT, based on data from Robertsson et al. (2012) [72]. X_{tree} represent % of tree within a kilogram of CLT and X_{CO2} represent kg CO_2 that is captured within a kg of tree, data used is based on calculations made by Derome (2021) [42].

$$\begin{aligned} CM2_{7,12}\ [kg\ CO_2/m^2] = M3_{7,12}\ [m^3\ CLT/m^2] \cdot KgCLT\ [kg\ CLT/m^3\ CLT] \\ \cdot X_{tree}\ [\% - tree] \cdot X_{CO2}\ [kg\ CO_2/kg\ tree] \end{aligned} \tag{3.7}$$

When $CM2_{7,12}$ was calculated for the building the next step was to calculate the potential within Gothenburg. With a decision of 4181 new building projects finished every year, three scenarios was made based on % of the buildings built in CLT. Scenario A (100% is built with CLT), Scenario B (50% is built with CLT), Scenario C (20% is built with CLT). This is done in order to show how the potential of storing carbon shifts depending on how many wooden buildings the city of Gothenburg decides to build. New multi-storey houses built was split over 7 and 12 storey houses. This split is done to, in a simplified manner, to show the complete potential of CLT based wooden houses. For the calculations: 75% of the new buildings constructed was assumed to be 7 storeys and 25% to be 12 storeys.

Then to calculate the amount of stored CO_2 within the new buildings each year ($WH_{7,12}$) the Equation 3.8 was used. Where $B_{7,12}$ represent the amount of 7 respectively 12 storey apartments built and $M2_{7,12}$ represent amount of square meters within each building.

$$\begin{aligned} WH_{7,12}[TonneCO2] = B_{7,12}\ [Built\ apartments] \cdot CM2_{7,12}\ [kg\ CO_2/m^2] \\ \cdot M2_{7,12}[m^2/apartment] \cdot \frac{1}{1000}[kg/tonne] \end{aligned} \tag{3.8}$$

After establishing the amount of captured CO_2 within each building a second calculation step was done. Based of rotation time for growing trees in a forest and life time of houses, this method is referenced to as the ”Guest-theory”. A ”Guest-factor” (GF) was introduced by Guest et al. [38], which stands for the global warming potential (GWP_{100}) saved when using biomass in products over a specific storage time (life time of a house) and rotation time of a forest. Equation 3.9 describes the correlation. The rotation span for Norwegian spruce in Sweden is 45-65 years. To use the method presented by Guest and colleagues [38] an even number for GF is required. Thus the rotation time of 60 years was selected. For interpretation of the GF, data on the life time of a wooden house is also required which was set to 80 years based on Panojevic and Svensson (2019) [73].

$$GWP_{100} = WH_{7,12}[TonneCO2] \cdot GF_{60,80} \tag{3.9}$$

Last calculation was to integrate the time-span, where an assumed delay of at least three years between decision to construct a house in wood and finished constructed house was assumed. Which means the construction industry will contribute to carbon storage in buildings after the year 2025 and until 2050.

A cost analysis was not done as the literature is not unanimous and several different cost parameters means the issue has a high complexity. The issue will be handled in the discussion in the section: "Cost of wooden houses".

3.6 Method for Agroforestry

To establish the amount of arable land potentially available for agroforestry, the Swedish Board of Agricultures (Jordbruksverket) data was selected for agricultural land and pasture land within the city of Gothenburg [74, 75]. Both types were considered as possible options as both agriculture land and pasture land is mentioned in ”Vägen till en klimatpositiv framtid” as optional land for agroforestry [30].

For the region of Gothenburg the Boreal forest type is the dominating type according to Swedish forest agency (Skogstyrelsen) (2015) [76]. Within the boreal conditions silver birch is a common tree and has available data on carbon stored and was therefore selected to be used in the calculations for agroforestry. The data used is based on Uri et al. (2012) [77]. For the silver birch, data on carbon stored above ground for different ages in a habitat similar to Gothenburg was available, including carbon stored in stems, branches, shoots and leaves. The potential increase or decrease of SOC will therefore not be included, and instead be discussed as a potential ”secondary benefit”.

Based on the data gathered, the Equation 3.10 was used in order to find the potential of captured carbon. The calculation is done for three different scenarios, in order to show the difference on the amount of sequestered carbon based on the amount of land chosen to be utilized. The results will be based on three different fractions of the total area used for agroforestry. Scenario A is 60%, B is 40% and C is 20%. For a single case it would mean that a fraction of the total agricultural and pasture land in Gothenburg will be used for agroforestry, this fraction is then referred to $X_{Sc.Agro}$. The agroforestry land itself is later assumed to utilize silver birch on 5% of the land, which is referred to as $X_{Silverbirch}$. The total agriculture and pasture land is referred to as Land and is expressed in Hectare. The amount of tonnes biomass per hectare of silver birch is referred to BM. The carbon concentration varied depending on age of the tree. The lowest measured concentration was 47.8% and highest 50.2%, based on the span an average of 49% will be used for calculations. The carbon is then adjusted to CO_2 by the molar weight relationship between carbon dioxide (44g/mol) and carbon (12g/mol). ”n” is referred to the specific year the Silver birch is planted.

$$\begin{aligned} CS(n)[Tonne\mathrm{CO_2}] = X_{Sc.Agro}\ [\%] \cdot X_{Silverbirch}\ [\%] \cdot Land[Ha] \\ \cdot BM\ [tBiomass/Ha(n)] \cdot X_{Cfraction}\ [\%] \cdot (44/12) \end{aligned} \tag{3.10}$$

3.7 Method for urban forestry

Urban forestry will cover green areas within the city. The urban forestry is also based of the silver birch by the same principles as the agroforestry method section based on Uri et al. (2012) [77]. Green spaces of less intensive biomass such as bushes and green roofs will not be included in this section. This study will only consider parks within the City of Gothenburg, which has an area of around 2000 hectare [78]. The result will entirely be based of these 2000 hectares of parks around Gothenburg. Then an increase or addition of trees from three different scenarios, either 5, 10 or 20% addition to the current amount of forestry to the 2000 hectares (respectively Scenario A, B,C).

The carbon sequestered (CS) is dependent on the land used for biomass growth of birch for a selected year (n). Biomass grown (BM) is used to calculate the biomass grown per hectare above ground and the fraction of carbon in the biomass is then used to calculate the amount of carbon in the biomass grown.

$$CS(n) = Land[He] \cdot BM[t/He(n)] \cdot Conc\,C.[fractionC] \cdot (44/12) \tag{3.11}$$

3.8 Method for comparison of the carbon sinks

To show how the different methods relate to each other in terms of CO_2 stored different plausible scenarios of each method will be compared. A low scenario was done to compare the methods based of a "worst-case" type of scenario. For the low scenario, only garden and wood waste are considered viable input materials to a biochar plant. The CCS efficiency is set at 70% and for the other methods the scenario that result in least amount of carbon stored will be used. Then a high scenario was done to show the "best-case" scenario. All waste streams, not including food waste, are considered and the CCS efficiency is set at 90%. For scenario based methods the scenario that resulted in the highest amount of carbon stored will be used (Scenario A).

4
Results

After the initial stages of the literature study it was decided that "Blue carbon" and "underground crops" on the basis of there not existing sufficient data. For Gothenburg data exist on the condition of the ocean floor but are not sufficient for analyze at this moment [79]. Although new literature is coming out at the moment of this report such as the report "The coastal landscape affects seagrass meadows' ability to mitigate climate change" by Simon Ungman Hain [80]. The idea behind Underground crops is discarded on a similar basis, as the idea is not seen as mature enough with limited literature existing [58].

Carbon islands as a carbon sink is decided to not be used as a potential carbon sink technology after the literature review as the technology has too many uncertainties with little carbon sink potential and mainly discussed as a mitigation practise [59].

The carbon sink technologies identified as viable ideas with sufficient existing data and suitable for the climate of Gothenburg were further examined. Due to the time constraints of the report mentioned in section 3.2 the technologies were investigated to establish which were expected to have the most significant potential as carbon sinks for the City of Gothenburg. Forestry in Gothenburg is handled by the Lübeck-model which is seen as a good management method for forestry and thus little effects would be gained from altering the forestry methods [81]. Green roofs show significant advantages in several areas such as energy reduction, providing green areas in cities and potentially increasing biodiversity [9]. Although these effects would aid several climate and environmental targets the City of Gothenburg has established, the carbon sink aspect is uncertain [6]. According to Luronuma et al. the carbon sequestration per m^2 was shown to be as low as 336 g/year [9]. Thus, with several uncertainties and knowledge gaps existing it was decided that although interesting the green roof technology as a carbon sink for the City of Gothenburg was not investigated further in this thesis. The remaining technologies of BECCS, biochar, wooden houses and agro-/urban forestry were thus selected to have significant potential and are investigated further.

4.1 BECCS

The results will be presented on the basis that CO_2 captured and stored can be defined as "carbon sink" only if the fuel that lead to the emissions are bio-based. If the fossil-based share of emissions are considered it will be stated in connection with any graph.

4.1.1 Opportunities for BECCS in Gothenburg

For a CCS unit to be economically viable there is a need for a bio-based energy plant or industry that emits at least 0.5 Mtonnes of CO_2 annually where at least 50% should be bio-based. As no industry qualifies for the bio-based condition, only waste incineration for heat and electricity within Gothenburg could be applicable [62]. Waste incineration in Gothenburg is mainly done at the Renova power plant in Sävenäs. Combustible waste arrive at the plant every day and the annual input of waste is more than 500 000 tonnes [82]. The production of heat is 1506 GWh and 279 GWh of electricity for the year of 2018 [83]. Around 63% of the input waste is bio-based, based of 2020 numbers from the Swedish Environmental Protection Agency (Naturvårdsverket) (2012) [84]. The entire power plant facility in Sävenäs emitted more than 561 000 tons of CO_2 for the year of 2020, where the bio based share was around 355 000 tons (63%). The relative high share of bio-based input materials to Sävenäs with total emissions exceeding 0.5 Mtonnes annually leads to the plant qualifying as a reasonable site for implementation of CCS technology and to be counted as a BECCS facility in this thesis.

4.1.2 Carbon sink with BECCS

A previous study based of a waste to energy plant in Klemetsrud, Norway by Fagerlund and co-workers (2020) showed that 90% of the carbon dioxide can be captured [63]. The technique used was amine-scrubbing of post combustion flue gas flow, the same technique that was suggested applicable to Swedish infrastructure with a similar efficiency of 90% as reported by Johnsson and Kjärstad (2019) [23]. 90% efficiency of a CCS unit applied at Sävenäs would lead to over 500 000 tonnes CO_2 captured annually where around 318 000 tonnes would be bio-based. In Figure 4.1 the amount of CO_2 captured and stored based on the total amount of emissions (blue staple) and carbon sink emissions can be seen (green staple).

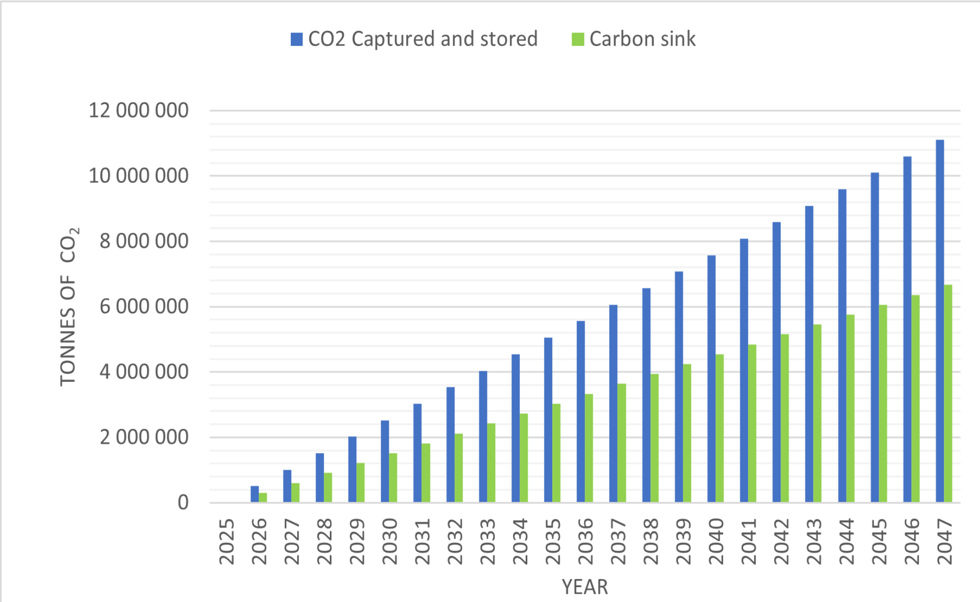

Figure 4.1: Accumulated tonnes of captured and stored CO_2 starting from the year of 2025 until 2047 based off 90% of CO_2 being captured from the emissions at the Sävenäs plant. Emissions that are fossil- and bio-based (blue staple) and exclusively bio-based (carbon sink, green staple) for the hypothetical lifetime of 22 years for a CCS unit connected to the Sävenäs plant.

Based on the hypothetical BECCS scenario at Sävenäs, an overview flowchart of how the system could look like is presented in Figure 4.2.

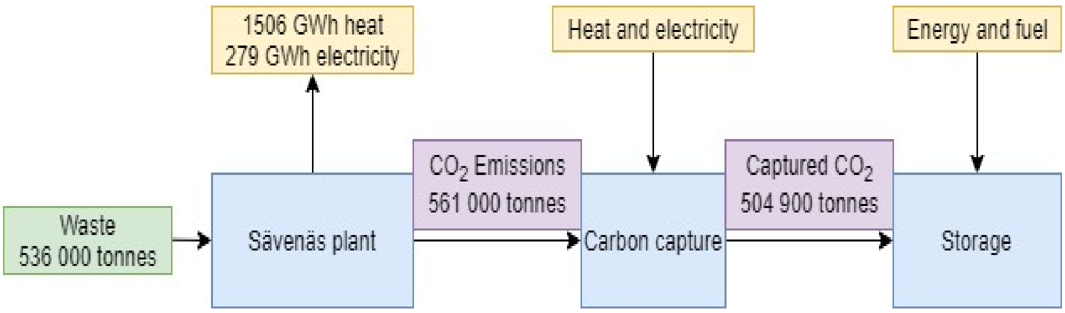

Figure 4.2: Flowchart illustrating the potential of a CCS unit in connection with Sävenäs power plant. Mass flows and energy units are stated on an annual basis.

The results for the specified years of 2030 and 2050, the territorial emissions target years set by the City of Gothenburg, can be seen in Table 4.1. The results show the contribution of captured tonnes of CO_2 and the amount of the carbon sink for the two target years.

Table 4.1: Potential of accumulated CO_2 captured until 2030 and 2050.

Potential captured CO_2 at Sävenäs until 2030 and 2050		
Target year	Captured [tonnes CO_2]	Carbon sink [tonnes CO_2]
2030	2 524 500	1 514 700
2050	11 107 800	6 664 680

4.1.3 Costs CCS/BECCS

The costs are presented by the different cost-steps: investment-, running-, transportation- and storage cost. The cost will be evaluated in SEK per ton captured and stored CO_2. The investment and running cost are based of a study by Gassnova SF [64]. The study from 2019 estimates cost for the construction of CCS units at Klemetsrud in Norway in connection to a waste to energy plant facility of similar size to Sävenäs. The study estimated the investment price of 4 715 MNOK for the facility at Klemetsrud. Assuming an operational life time of 22 years. Per ton of CO_2 captured, assuming the capacity of capturing at 90%, the investment price would be 424 SEK/tonCO_2. With a further operational cost of 473 SEK/tonCO_2. Transport cost are set at an interval of 150-250 SEK and are based of Karlsson et al. (2020) [30]. The storage cost are set at an interval of 100-200 SEK and is based on a Swedish case study from Garðarsdóttir and collueges (2018) which are estimations for storage at Utsira, Norway [62]. The result of the cost calculations can be seen in Table 4.2.

Table 4.2: Predicted costs Bio Energy Carbon Capture and Storage.

Costs [SEK/ton CO_2 captured]	
Specific cost	**Rya**
Investment	424 [64]
Running	473 [64]
Transport	150-250
Storage	100-200 [62]
Total	1147-1347

The span for transport and storage are due to uncertainties as stated by Karlsson et al. (2020) [30]. The difference between the low- and high scenario is visualized in Figure 4.3.

Figure 4.3: Cost in SEK per tonne of captured CO_2 based of the two cost scenarios.

The definition of a carbon sink as based of bio-based emissions and not fossil-based alter the results. As 40% of the CO_2 emissions from Sävenäs are fossil-based [84]. The alternative scenario of crediting all costs of the CCS-unit to the bio-based emissions (carbon sink) compared to crediting the cost to all the captured and stored CO_2 can be seen in Figure 4.4.

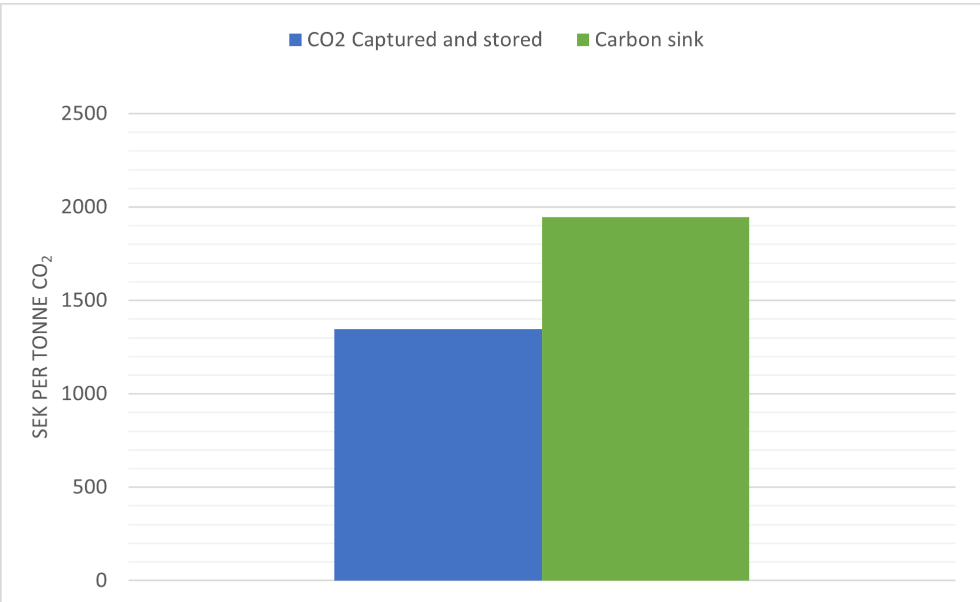

Figure 4.4: Cost per tonne of CO_2 captured and stored for the two alternatives ways of accrediting the cost.

The cost increases by approximately 600 SEK per tonne of CO_2 when accrediting all cost to the bio-based emissions. The scenario in 4.4 is based of the high cost scenario seen in Figure 4.3.

Another scenario was made at 70% efficiency of capturing CO_2 from the Sävenäs plant. The results can be seen in Figure 4.5. The low- and high cost scenarios are based on the same conditions as in Figure 4.3. The effect on the cost by the efficiency drop is an increase of the cost between 250 and 350 SEK depending on the preset conditions.

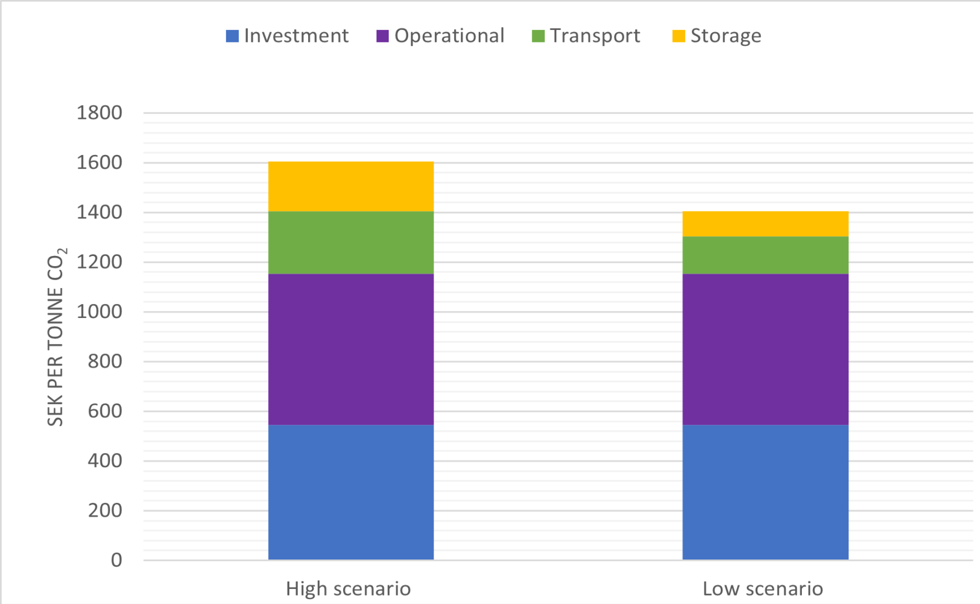

Figure 4.5: Cost in SEK per tonne of captured CO_2 based of the two cost scenarios.

4.2 Biochar

4.2.1 Input materials

Within Gothenbrug there exists plenty of different potential biomass flows that could be utilized for biochar production. The flows investigated in the thesis are: garden waste, other tree waste, sludge (dry) and food waste. These flows are quantified and presented in Table 4.3.

Table 4.3: Potential input material used for biochar production.

Input material	
Specific input	**Flows** [tonnes/year]
Garden waste	9 000-10 000
Other tree waste	12 000
Sludge (dry)	14 964
Food waste	22000

4.2.1.1 Garden and wood-waste

One potential flow in Gothenburg to utilize is the garden- and wood waste that is collected at Renova every year. Today these flows are mainly used in incineration to produce energy but could potentially be used in biochar production. It was found that around 6300 tonnes garden waste was annually collected in to Renovas sites. Besides those 6300 tonnes there is a potential for an additional waste bringing the total up to around 10 000 tonnes if all the surrounding city's also opted to commit their garden waste to Renova [31]. Another study from Eurosat claims that 9000 tonnes of twigs and other small sized fresh wood are collected annually which means the amount of collectable waste could be higher than 6300 tonnes within the city [85].

Further data on usable wood (unpainted, construction waste) that comes from different activities into Renovas facilities annually is estimated at around 12 000 tonnes. Thus, there is a potential of 22 000 tonnes of Garden and Wood waste (similiar input) that possibly can be used for biochar production [31].

4.2.1.2 Sewage sludge

For the citizens of Gothenburg and the nearby regions of Ale, Härryda, Kungälv, Lerum, Mölndal and Partille the waste water is treated at Gryaab's facilities. In 2020 around 52 766 tonnes of sludge was produced with a dry weight fraction of 28.4% (14 964 tonnes) [86]. Of the produced sludge around 46% (6 883 tonnes) was used as fertilizers and the remaining sludge from Gryaab is converted into plant soil

[87, 88]. However, as this flow could be utilized as biochar it creates an opportunity for the City of Gothenburg to use the sludge as a carbon sink in biochar production.

4.2.1.3 Food waste

In 2019 the average Swedish citizen contributed to around 44 kg per year of food waste and with 579 281 people living in Gothenburg the result is 25,5 tonnes of total food waste that potentially could be used for biochar production each year [66]. The city of Gothenburg has strategies in their climate program to try and reduce waste from its citizens and in 2019 a plan was done to try and reduce the amount of food waste from 44 kg to 35 kg per year and citizen until 2030 [66]. As this reduction implies a waste flow of 25,5 tonnes per year to 20,3 tonnes per year an assumed flow of 22 tonnes per year will be used as potential biomass for biochar production.

4.2.2 Carbon sink with biochar

As mentioned in Section 3.4 the calculations done for potential biochar yield and potential carbon sinks uses weight % of output biochar per input material and a %-carbon-content within the biochar. The values used are from ”Rest till bäst” and are presented in Table 4.4 [27]. Worth to notice are that there are a large variance between the different input materials (between 23-61 wt-%), which has a significant impact on the carbon sink results.

Table 4.4: Biochar yield Wt-% based on 700 °C pyrolysis. General carbon content ratios for different input materials from biochar analyses. *No exact data for food waste.

Biochar yield and carbon content ratios for further calculations.		
Material	**wt-%** [Biochar per input material]	**wt-%** [Fraction of carbon within the biochar]
Garden waste	29	66
Wood waste	29	66
Sewage sludge	61	58
Food waste	23	41*

The result of potential captured carbon within biochar from different flows of input material is presented in Figure 4.6. As seen in Figure 4.6 all flows have larger or smaller contribution to the carbon sink. This is explained by the magnitude of the flow but also the amount of ashes created in the pyrolysis. The fraction of ashes in the different biomass based biochar differs, especially for sewage sludge, the fraction is significantly higher than the other materials which leads to an increased rate of carbon captured [27].

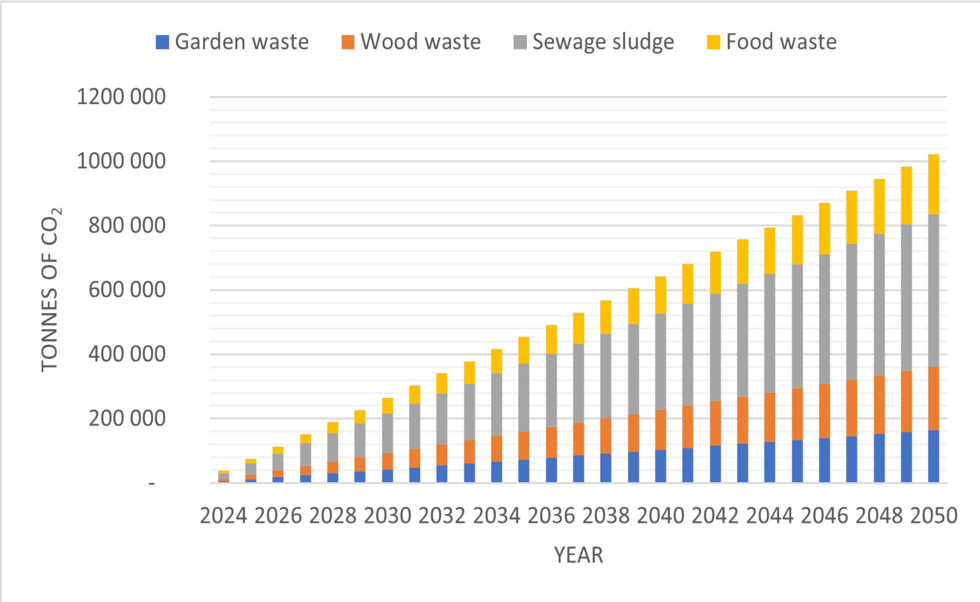

Figure 4.6: Tonnes of captured CO_2 accumulated over time within biochar by year and input material. Assumed production for all materials starting in 2023.

The output results are built on the scenario that all of the potential input material that exists are utilized from the year 2024 until the years 2030 and 2050. As the data on food waste is uncertain and the possibility to use food waste is uncertain the results for a scenario where food waste is included and one where food waste is excluded will be presented. The result is presented in Figure 4.7. A total of 216 813 - 264 870 tonnes CO_2 can be captured until 2030 and 836 280 - 1 021 641 tonnes CO_2 can be captured until 2050 (exclude-include food waste) with biochar production.

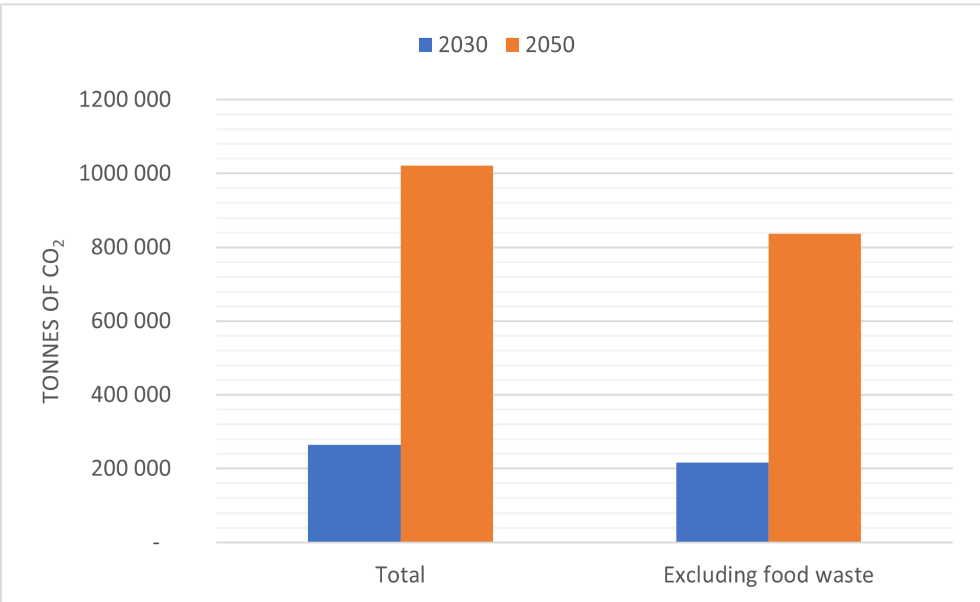

Figure 4.7: A comparison of the total tonnes of captured CO_2 within biochar between including food waste and excluding food waste.

4.2.3 Costs Biochar

The costs will be presented for a facility with a dryer and for a facility without a dryer, the costs can be seen in 4.5. Also, the cost approximation for the investment and operation costs for a PYREG biochar facility was dimensioned to handle up to 1 400 tonnes of input material per year. The data used as a base for the cost estimation are from an article by Turek et al. (2018) [68]. The numbers are presented in Table 4.5 and the cost are adjusted with a conversion rate of 1 Euro = 10.25 SEK [65].

Table 4.5: Cost for a PYREG plant.

Costs of biochar facility			
Type of facility	**Investment cost** [SEK/Unit]	**Annual investment cost** [SEK/year]	**Operational cost** [SEK/year]
Pyreg facility w/o dryer	8 405 000	350 208.3	190 547.5
Pyreg facility with dryer	14 467 875	602 828.1	1 062 617.5

The results from Table 4.5 were integrated with the results of input flows and potential captured CO_2 and the final cost results for each input material became, at an average, 743 [SEK per tonne CO_2] with no dryer and at average 2287 [SEK per tonne CO_2] with dryer. The result for each input material is presented in Figure 4.8

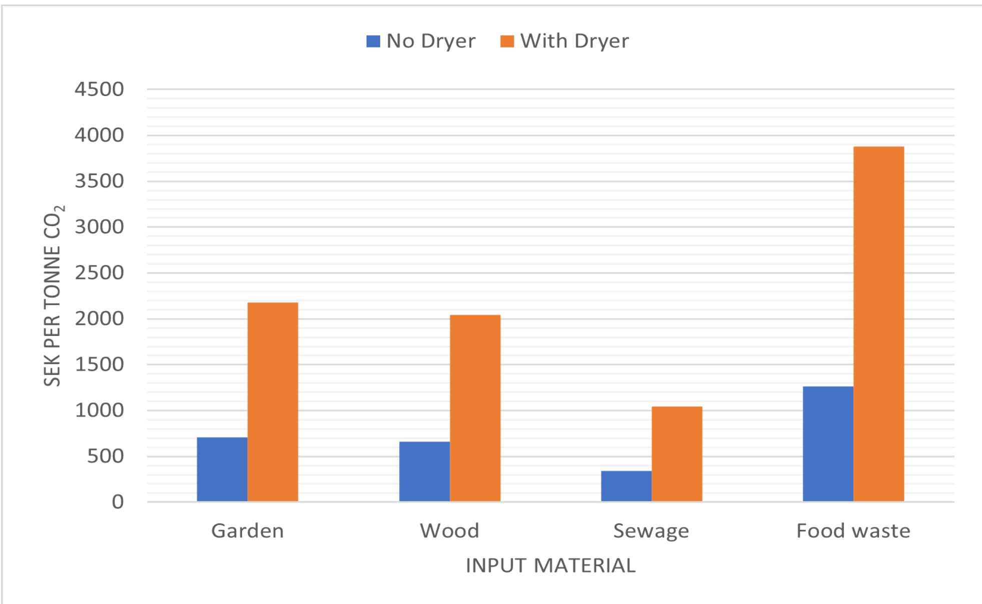

Figure 4.8: A comparison of the cost per tonne CO_2 when including and excluding a dryer, for the year 2048.

4.3 Wooden-buildings

4.3.1 Possibilities in Gothenburg

Gothenburg is expanding in houses and there exist no plans of decreasing the trend [70]. During the last five years the amount of newly built multi-storey houses have increased from around 2000 to 3800 [71]. The number of houses built for the last years can be seen in Table 4.6.

Table 4.6: Statistics from "Statistiska centralbyrån" regarding the amount of houses that have been built per year over the last years in Gothenburg. *Not specified but a total of 4500 houses was built.

Housing built per year in Gothenburg over the last 5 years.					
Building type	**2016**	**2017**	**2018**	**2019**	**2020**
Multi-storey houses	1 989	1 683	2 428	3 840	4100*
Small housing	415	349	310	345	*

To establish an approximate number of new houses that will be built the "2020 yearly report" from the property management committee in Gothenburg is used [70]. The report states that there exists a need of around 4000-5000 new houses per year in order to handle the increasing population within the city. So based on the result in table 4.6 and the report, the number of newly built apartments was set at 4181 each year, see section 3.5. This number of 4181 of newly built apartments are then split between 7-storey houses and 12-storey houses built each year, using a 75-25 % distribution between the two alternatives (also presented in method as $B_{7,12}$). Which then led to the results of 112 7-storey and 22 12-storey buildings is needed to be built each year to build a total of 4181 new apartments each year.

4.3.2 Carbon sink with wooden houses

The amount of wood used in the two different types of buildings and the parameters used for the calculations, 7 and 12 storeys high respectively, can be seen in Table 4.7. The values used is from Skullestad et al. (2016), Robertsson et al. (2012) and Derome (2021)[39, 42, 72].

Table 4.7: Data and values used for the 7 and 12 storey buildings.

Data for the 7 and 12 storey buildings		
	7 Storey	12 storey
M2 [m^2]	6097	10542
CLT [m^3]	1410	2792
M3 [m^3 CLT/m^2]	0,2312	0,2648
KgCLT [kg CLT/m^3]	409	409
X_{tree} [%-tree]	0,95	0,95
X_{CO2} [kg CO_2/kg tree]	1,57	1,57
CM2 [kg CO_2/m^2]	141	161
B [Apparments built]	112	22
WH [Tonne CO_2]	**96 327**	**37 088**

Based of the data in Table 4.7 and calculations in the Method, see equation 3.7 and 3.8 the carbon sink results could be calculated. Where the result is based on the 75/25% distribution of 7/12 storey building which lead to parameter B in Table 4.7 that shows how many buildings should be built each year. The results can also be seen in Table 4.7, and if the potential of both 7 and 12 storey building is summarized an annually amount of around 133 415 tonnes of CO_2 could potentially be stored within new buildings. By the year of 2050, up to almost 3.5 Mton of CO_2 could be stored in the new-built houses in Gotheburg. Based on the assumption that all multi-storey houses are built according to the method presented. Scenario A is set to 100% and Scenario B is set at 50% and C set at 20% of the buildings being built out of CLT. The results for all the scenarios can be seen in Figure 4.9.

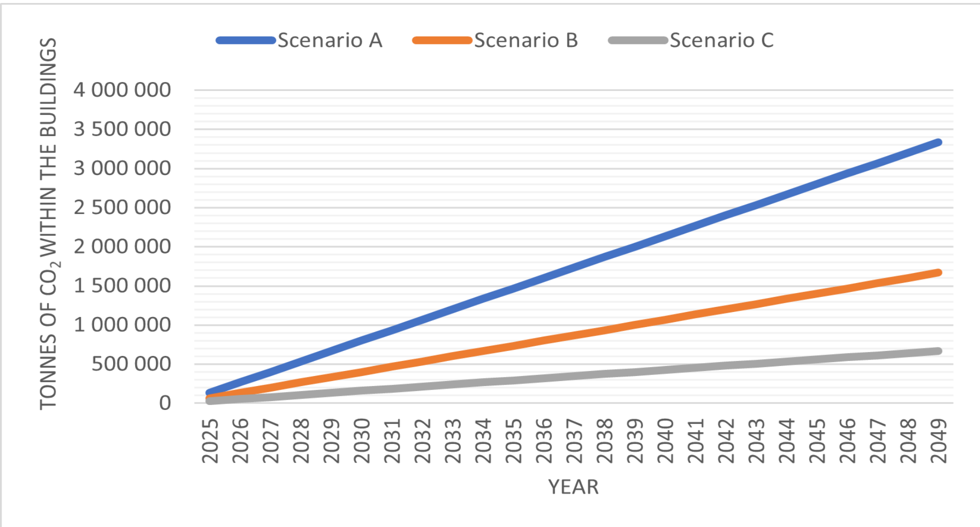

Figure 4.9: Tonnes stored of CO_2 integrated over the years 2025-2049 for different scenarios.

For comparison of the result between specific years and scenarios the result is also presented in Figure 4.10 in staple form.

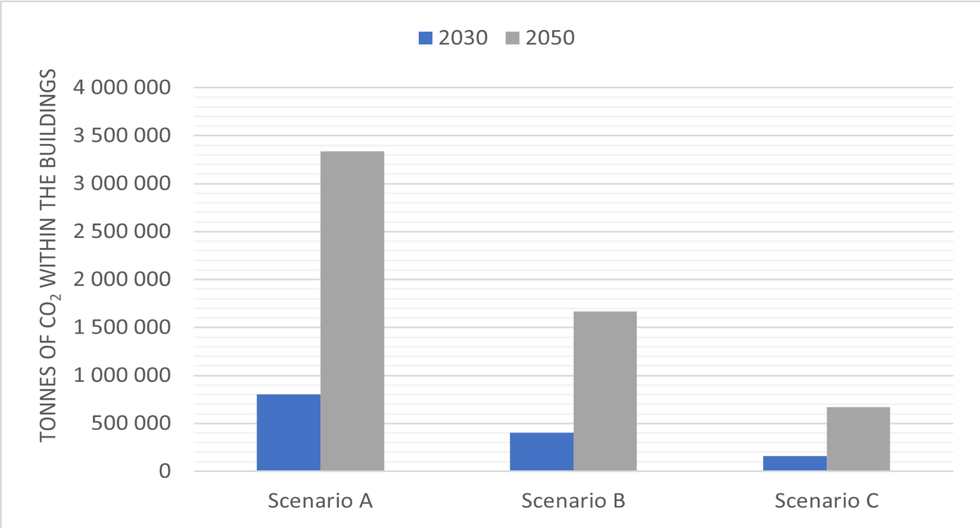

Figure 4.10: Accumulated tonnes of CO_2 stored within new built buildings, a comparison between years (2030,2050) and scenario A,B and C.

The calculations based of the theory presented by Guest et al., see equation 3.9, are presented in Table 4.11. The calculations are done with a GF of -0,47 which results in a decrease to the total saved GWP_{100} at 62 705 CO_2-eq. Which means a decrease of the carbon sink by 53%. The illustration is based of scenario A for one year.

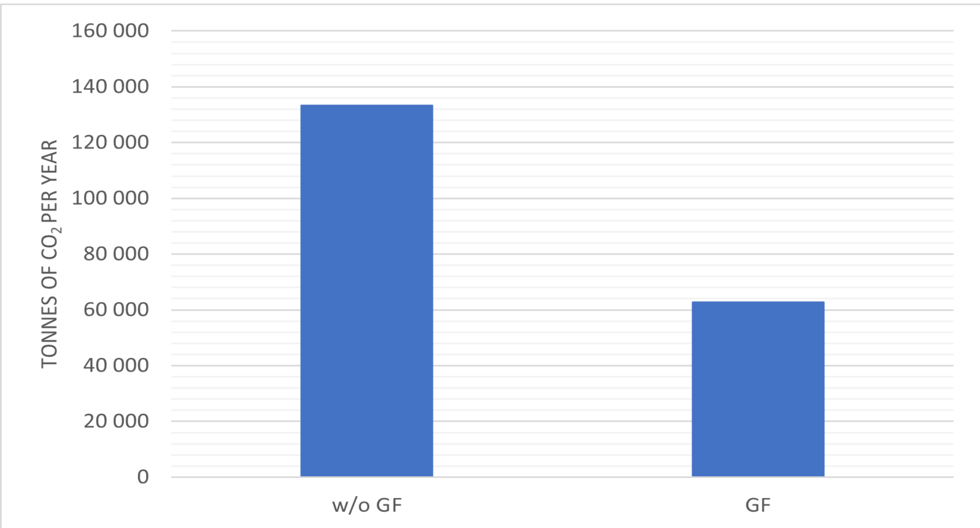

Figure 4.11: Result of stored CO_2 within the buldings each year. A comparison between the calculation using the Guest factor and the calculation without using the Guest factor.

For comparison of the result between specific years and scenarios the result are also presented in Figure 4.10 in staple form. When applying the GF on the results can be seen in Figure 4.12. As described a loss of 53% of the stored carbon counted as a carbon sink. This GF is calculated on the basis of a storage time (life time of a house) of 80 years and forest rotation time of 60 years, and to use the stored biomass for bio-energy production after its lifetime.

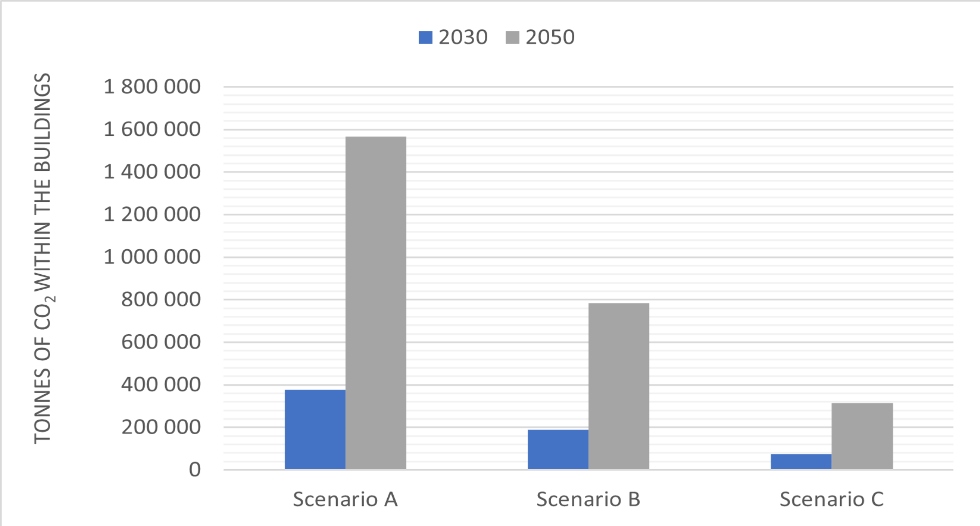

Figure 4.12: Accumulated tonnes of CO_2 stored within new built buildings, when applying the Guest factor. A comparison between years (2030,2050) and scenario A,B and C.

4.3.3 Cost wooden houses

The cost of wooden houses differ in some senses from concrete. For example, the maintenance cost is assumed to be higher for wooden structures due to the increased need for repairs but there is a high uncertainty. The construction cost however is often reported to be similar as the cost of concrete and steel frames [35, 46]. Thus a cost evaluation will not be done for wooden houses. Instead a discussion of benefits and down sides will be done in the discussion section.

4.4 Agroforestry

The agroforestry section will investigate the potential of altering the 4229 hectares of agricultural and pasture land within the city.

4.4.1 Agricultural areas for agroforestry

The statistics from the Swedish board of agriculture claims that the city of Gothenburg has around 2780 hectares of agriculture land and 1449 hectares of pasture land, which is split between private- and state owned [74]. The numbers will be used for the agroforestry scenarios and presented in Table 4.8.

Table 4.8: Agriculture and Pasture Land data from 2020, both for the region of Gothenburg City.

Hectares of agriculture and pasture land	
Land type	**Amount of land** [hectares]
Agricultural land	2 780
Pasture land	1 449
Total land	4 229

4.4.2 Carbon sink with agroforestry

The results for the potential captured carbon for the different Scenarios are presented in Figure 4.13. By the year 2030 around 2000-6000 tonnes of CO_2 can be captured and by the year 2050 around 7000-21000 tonnes of CO_2 can be captured, dependent on the set scenario.

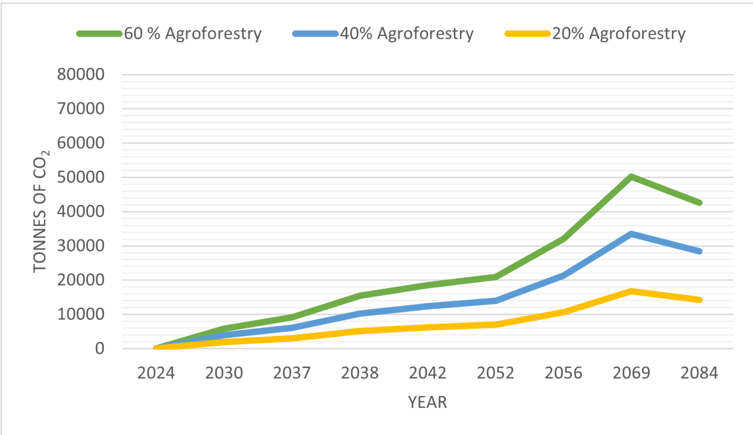

Figure 4.13: The potential CO_2 capture based of percentage area used for agroforestry of the existing agricultural and pasture land within Gothenburg. Scenario A: 60 %, Scenario B: 40 %, Scenario C: 20%.

4.5 Urban forestry

The results will be based of the 2000 hectares of parks around Gothenburg see section 3.7.

4.5.1 Carbon sink with urban forestry

The potential carbon sinks from the urban forestry is presented in Figure 4.14. By the year 2030 around 4600-18 500 tonnes of CO_2 can be captured and by the year 2050 around 16 400-65 800 tonnes of CO_2 can be captured.

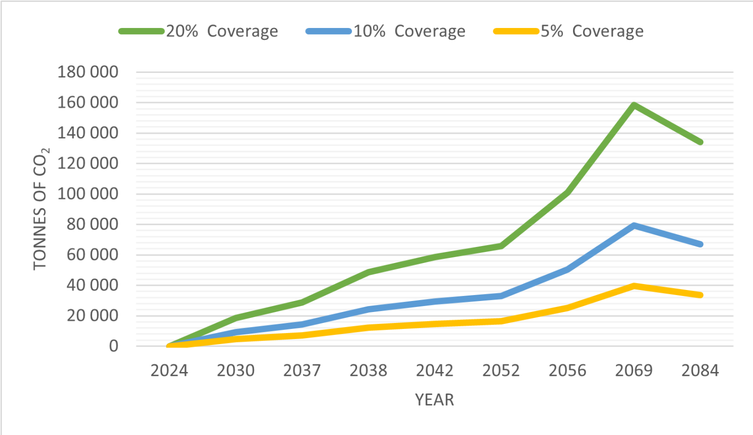

Figure 4.14: The potential CO_2 capture based of percentage area used for urban forestry of the existing parks within Gothenburg. Scenario A: 20 %, Scenario B: 10 %, Scenario C: 5%.

4.6 Comparative results

To show how the different methods relate to each other in terms of CO_2 stored two different figures can be seen in Figure 4.15 and Figure 4.16. The low scenario is based of the parameter with the lowest impact on CO_2 stored for all the technologies while the high scenario is based of the parameters with the highest impact on CO_2 stored. The low scenario parameters can be seen in Table 4.9.

Table 4.9: Low scenario parameters. Specified as either a Scenario (See previous results) or if only one parameter was altered the parameter is specified.

Low scenario parameters	
Technology	Scenario or specific parameter
Agroforestry	Scenario C
Urban forestry	Scenario C
Wooden houses	Scenario C
Biochar	Garden and wood waste streams considered.
BECCS	(ξ) set at 70%

The combined potential of the carbon sink technologies by 2050, assuming the low scenario is seen in Figure 4.15. The total share of the 6.24 Mtonnes of captured and stored CO_2 are split between the different techniques. BECCS is shown to be the most significant technique with 83% of the total carbon sink potential. The potential carbon sink from Agroforestry was 0.1% of the total share.

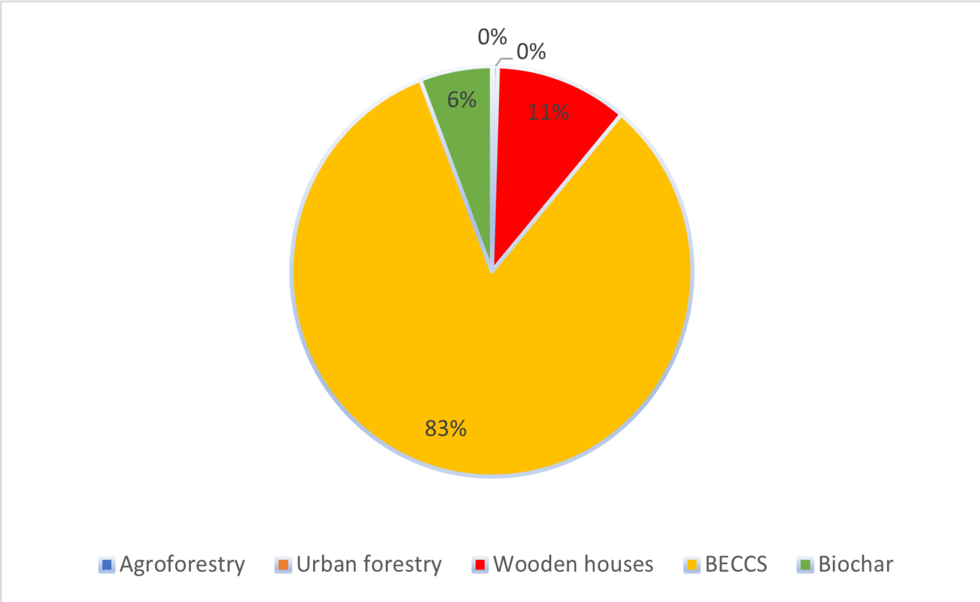

Figure 4.15: Low scenario comparison between the different carbon sink technologies by 2050.

For the high scenario the specific parameters for the scenario is specified in Table 4.10. For biochar, the food waste is excluded as the numbers are deemed too uncertain. Thus the potential from wood waste, garden waste and sewage sludge are considered in the high scenario.

Table 4.10: High scenario parameters. Specified as either a Scenario (See previous results) or if only one parameter was altered the parameter is specified.

High scenario parameters	
Technology	Scenario or specific parameter
Agroforestry	Scenario A
Urban forestry	Scenario A
Wooden houses	Scenario A
Biochar	Garden- and wood waste and sewage sludge.
BECCS	(ξ) set at 90%

The combined potential of the carbon sink technologies by 2050, assuming the high scenario is seen in Figure 4.16. The total share of the 10.91 Mtonnes of captured and stored CO_2 are split between the different techniques. BECCS is shown to be the most significant technique with 61% of the total carbon sink potential. The potential carbon sink from Agroforestry was 0.2% of the total share.

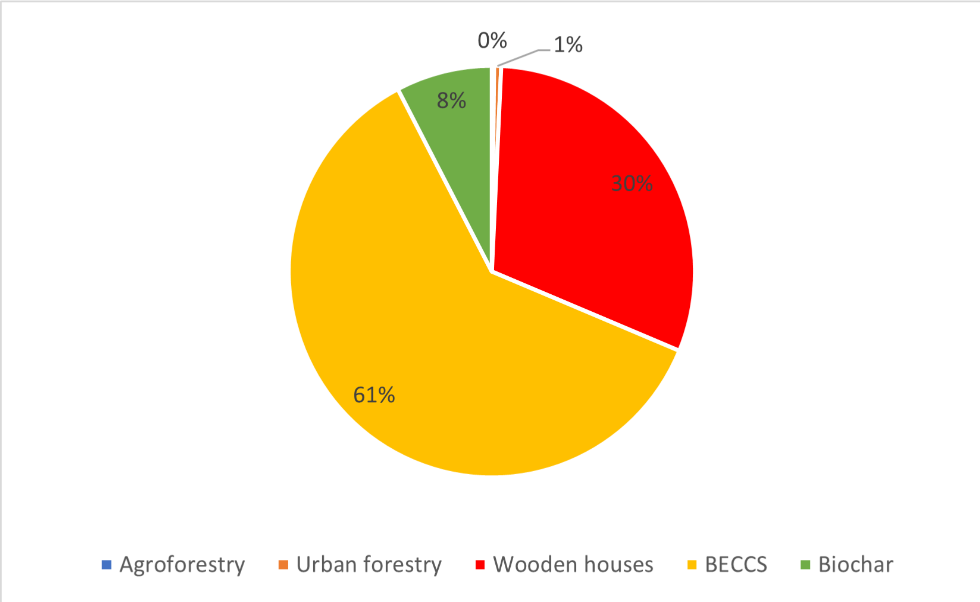

Figure 4.16: High scenario comparison between the different carbon sink alternatives by 2050.

Between the high- and low scenario the most significant change in the carbon sink potential is BECCS, with an increase of 1.48 Mtonne. In relative terms, based on the change in fraction of the total, wooden houses sees the most significant increase rising from 11% of the total carbon sink potential in the low scenario up to 30% of the total in the high scenario.

If all technologies were installed at full capacity the annual stored CO_2 can be seen in Table 4.11. Assuming the same parameters for low- and high scenario as specified in Table 4.9 and Table 4.10.

Table 4.11: The annual emissions from each carbon sink technology for the low and high scenario, based on the result for the target year 2030.

Annual carbon sink effect by technology. [Tonnes of CO_2]		
Technology	**Low scenario**	**High scenario**
Agroforestry	372	976
Urban forestry	880	3078
Wooden houses	26 683	133 416
Biochar	13 453	30 973
BECCS	235 620	302 940
Total	277 008	471 383

Some comparisons based on the total annual carbon sink potential results to the annual territorial emission targets of the City of Gothenburg by 2030 based on the results seen in table 4.11 can be done. The result shows that the total potential of the carbon sink technologies is equal to around 26% of the emissions reductions necessary on a yearly bases, based on the high scenario and assuming all technologies are used at the full potential by 2029. On a citizen basis the carbon sink would be equal to every citizen emitting 0.86 tonnes of CO_2 eq. per year. For the low scenario the same number is 15.4%. If the fossil-based emissions from Sävenäs were to be included as negative emissions the total of the high scenario would be: 37.5% and for the low scenario: 24.2%.

5
Discussion

BECCS represented the most significant technology as a carbon sink and the potentially high cost could prove to be worthwhile as no other technology can reach a similar magnitude of carbon stored according to the results. The technique could potentially lead to an accumulated carbon sink of 1.51 Mtonnes by 2030 out of the total potential of 2.55 Mtonnes, based on the high scenario seen in Figure 4.10. Although this number could be just a little more than 1 Mtonnes for BECCS out of a total of 1.44 Mtonnes, assuming the low scenario seen in Figure 4.9. For both the scenarios BECCS stand out as the most significant method, while agroforestry and urban forestry contribute by relative small margins. Although, the carbon sink potential for urban forestry and agroforestry was found to be insignificantly small both technologies could still serve other secondary benefits and pose as a cost effective options. Wooden houses was also judged to not have any cost (compared to its alternative) and could roughly contribute to 30% (3 Mtonnes) of the total carbon sink potential by the year 2050, being the largest carbon sink option with the potential of not having any additional costs. Biochar had a potential of 8% (0.2 Mtonnes) of carbon sink in the high scenario by the year 2050, with an average price of 743 SEK per tonne CO_2 captured between all the input materials.

From a emissions budget perspective the incorporation of all methods would be suggested if the city aspire to reach the climate targets set. A reduction of 80% of the territorial emissions by the year of 2030 require both mitigation actions as well as carbon sink technologies. Taking an optimistic stance on the carbon sink estimations and assuming the high scenario is valid for all technologies, would mean negative emissions of totally 2.55 Mtonnes and on an annual basis be equal to around 26% of the emission reduction target of a decrease by 3.1 tonnes of territorial CO_2 eq. emissions per citizen.

Although, during the literature study uncertainties, possible solutions and secondary benefits have been discovered. Those are described and discussed for each technology in the following sections.

5.1 BECCS

The results indicates that BECCS has the highest potential as a carbon sink of all the selected technologies and a higher total potential than all the other investigated methods combined. Installation of a CCS unit in connection with the Sävenäs plant could lead to more than 10.6 Mtonnes of CO_2 stored by 2050 (fosil- and biobased). Annual emissions captured and stored could be up to 0.5 M tonnes of CO_2 eq. which is equal to the territorial emissions of more than 120 000 citizens in Gothenburg [6]. Although roughly 40% of the offset emissions are fossil-based, the transition of the district heating system to be bio-based would mean the total amount of the mentioned emissions could be counted as a carbon sink in the future. Decisions makers would have to weight the huge potential of CO_2 emissions captured and stored from the Sävenäs site against the several uncertainties and costs. The significant uncertainties and problematic details surrounding different parameters together with the cost aspect will be handled in this section.

5.1.1 Cost

Combining bio energy with CCS technology could potentially have one of the highest cost per tonne CO_2 stored of all the technologies investigated. The cost for all steps were estimated to be between 1100-1600 SEK per tonne CO_2, see Table 4.2, however the cost is within the same cost-range as the Swedish carbon tax at 1190 [SEK/tonne CO_2] [13]. The cost calculations does not account for a loss of efficiency or the cost structure of a potential investment and although this study does not investigate all the possible cost parameters thoroughly the cost range corresponds well with other literature [30].

The most significant risk of investing in CCS technology is the cost structure of the investment. Around half of the cost is tied into investment costs. Instead of paying per captured tonne of CO_2, as would be the case with a carbon tax or other methods of carbon sinks, the majority of the costs occur before any emissions are captured. Potential scenarios such as a higher cost scenario combined with other potential downsides could become problematic for the investor and decrease the economic viability.

Further, if the carbon tax would increase by a similar trend as historically the relative price of BECCS facilities might decrease [13]. As several climate targets, including the targets set by the City of Gothenburg, are projected to not be met there could be a need to take a higher financial risk to reach the targets [5]. The cost might decrease as the technology is getting more widespread and additional R&D work is done, similar to the theory of the S-curve [15]. Based on the assumptions that the cost per tonne CO_2 captured and stored were to decrease, following the S-curve, while the carbon tax increase following historical trends. The CCS technology in connection with bioenergy could be an attractive carbon sink technology from a cost perspective.

5.1.2 Efficiency

The overall efficiency of a bio based heat-plant is reported to drop when installing a CCS unit. The efficiency drop could have a significant impact on the economic and technical viability. A drop by up to 37% is stated by Levihn et al. (2019) due to the complicated and energy intensive process of CCS units [24]. The efficiency loss is not represented with a monetary value in the results. Thus, it is important to bring up the complications a significant efficiency drop would have for the technology. The potential of 37% drop could lead to fossil emissions replacing the carbon neutral emissions lost from the bio-energy plant. An increased use of fossil-based emissions would complicate the process of achieving targets the city have of transitioning the district heating to being completely bio-based. The potential drop also imply that both the territorial and consumption based emission targets would be difficult to reach. Although the S-curve argument of increased efficiency after investment could be done, the demand for heat from a CCS unit would still exist as the heat requirement for the amine reaction is high. The implementation of CCS technology would put a greater demand on the energy sector and ideally CCS would be done when there is an excess of heat available.

5.1.3 Storage of CO_2

To be able to store CO_2 in a effective way the CO_2 density needs to be as high as possible. To achieve the right temperature and pressure conditions the CO_2 should be injected around 800 meters deep to the ground [23]. The conditions can be met at some locations in Sweden (Faludden etc.) and investigation has been done in having storage locations within the Swedish boarders. However, some uncertainties exist and there is a need for more development and investigations before a large project could be done in Sweden. In Norway the situation is different, as well documented storage possibilities exist [89]. Also, as plans for capture and storage of CO_2 are developed and are at an advanced stage, such as the Northern Lights Project [23, 89].

Therefore,in the case of BECCS within Gothenburg, the carbon storage would likely be located in Norway as stated by Fuss and Johnsson (2020) [89]. The requirement would be purchasing storage possibilities from Norway and which then would be dependent on foreign companies and infrastructure.

5.1.4 Transportation of CO_2

After the carbon dioxide is captured there is a need for transportation to a site that is safe for storage (as mentioned in last section). An infrastructure for transportation is necessary or a transport chain using current infrastructure. Based on Nordi CCS vision for 2050 and ongoing discussion within the field the most likely transportation method within the nordic countries to the storage site is by ship [90]. As the storage sites most likely will be at sea it implies that transportation can be divided into two steps [23]. First step is from the CO_2 capture facility to the Gothenburg harbour (or potentially Lysekil) and the second step will be from the Gothenburg harbour to the storage facility (probably Norway).

The most likely transportation method for the first step (relatively short distance) would be by road or by train, although the transportation could potentially also be done by a pipeline in order to reduce costs [23]. The second part of the transportation of CO_2 would be between the harbour and Gassum or Utsira which could be done by either pipeline or by ship. The difference between the two alternatives is that for the pipeline alternative the bulk of the cost are the capital investment, while for the ship alternative the majority of the cost are the running costs. For both of the alternatives the cost is mainly based on the amount transported CO_2 per year and the distance for the transportation [23]. Although, an issue with investing in pipeline is the low ability for adjustment or up-scaling, which implies that if there is a need for larger flows of CO_2 a completely new pipeline with larger dimensions would be required to be installed [30]. Alternatively, the pipelines could be overdimension for the purpose to create flexibility for the pipelines which would increase cost.

Transporting and storing the CO_2 in Norway should be the first choice in order to establish CCS infrastructure. From Gothenburg the distance is relative short and the storage techniques and availability is to be assumed reliable. Possibilities to cooperate with other corporations in Gothenburg seeking to use similar CCS systems could lead to scaling benefits and such collaborations should be investigated.

5.1.5 Uncertainties

There exists technical and in other ways problematic uncertainties when evaluating BECCS or CCS units. For example the volume flow of the flue gas and the flue gas concentration of CO_2 is of high importance [62]. The cost estimation model is dependent on different parameters that might be technically difficult to achieve. One example is the assumption that the flue gas leaves Sävenäs from a single point source. If this assumption is not the case, there might be a need for further investments in the Sävenäs plant. Such investments would then be to redirect all the CO_2 emissions through one flue gas stream, if it is possible at all, are deemed outside the scope of the study. Additionally there are little room for error in the cost calculation and if a harsh and cold winter for example would complicate technical aspects it could alter the cost scenario.

It is mentioned in 'Vägen till en klimatpositiv framtid", that it is complex to evaluate the real cost in Sweden for a BECCS implementation as the experience and practical implementation within BECCS is lower than for CCS connected to other industries [30]. The study also mentions that the costs is difficult to define for a CCS unit connected to a bio-based energy plant. As several details are uncertain there might be a need to expand on the cost analysis to create room for the uncertainties. Together with the efficiency loss it could potentially mean that the cost analysis performed might be misleading and a further in depth analysis combined with field experiments are necessary.

5.1.6 Future outlook

Göteborg Energi has acknowledged that CCS and BECCS technology is necessary to reach the climate targets [19]. Although the main obstacle being economical aspects, it is thus important that sufficient investments and policies are put in place to stimulate the growth of CCS technologies. There are also projects in place by Göteborg Energi to construct a new bio-based facility where a CCS unit could be considered as an addition. The new facility discussed by Göteborg Energi would produce 620 GWh heat and 210 GWh electricity [20]. The planned output of heat and electricity is smaller than Sävenäs and might not reach the limit of 0.5 Mtonnes of emissions of CO_2 to be considered viable. Thus, it could be beneficial to examine the possibilities to adjust the technical parameters to be able to include a CCS unit in the planned construction.

As the CCS infrastructure is at an early stage of development and there exist industrial, including refinery, facilities that reach the minimum value of emissions to be CCS applicable but are either not state owned or do not qualify as bio-based at the moment[84]. In a study made by Johnson and Fuss (2020) on marginal abatement cost for CCS applied in connection with the largest industrial emissions sources in Sweden a total potential of 23 $MtCO_2$ could be captured annually [89]. The authors further stressed the need for an integrated system for both CCS and BECCS for cost effective development. This could potentially mean that an established infrastructure for CO_2 could enable additional industries to invest in carbon capture technologies. Which leads to the most reasonable option for transport is to develop transportation by ship to not exclude sites not located in Gothenburg for the second transport (from Gothenburg to the chosen storage location) [23]. Gothenburg can contribute by working towards removing barriers and potentially boost the CCS trend among industries.

5.2 Biochar

Based of the results, biochar can potentially contribute with a carbon sink of up to around 264 000 tonnes of CO_2 until the year 2030 and up to around 1 000 000 tonnes of CO_2 until the year 2050. Based on the assumption that all flows of input material found in this thesis is utilized by the City of Gothenburg. The amount of flows are vital as being one of the key parameters (together with the pyrolysis output and storage time) that decides upon the magnitude that becomes a carbon sink. It could however be argued that it can be difficult for the City of Gothenburg to utilize all flows of input materials. Assuming not all flows can be utilized results in the low scenario, from that scenario biochar would only contribute with a relatively small fraction of carbon capture when comparing with the results from BECCS but have potentially larger impact than agroforestry and urban forestry, see Figure 4.15. Also, the costs to utilize biochar production was estimated between 340-1260 SEK per tonne of CO_2 captured when no dryer is installed and 1046-3881 with a dryer installed for the different input materials. The large variety is due to the difference in output per input and the carbon content within the different biochar from the input materials.

All these factors make the City of Gothenburg compelled to weight the relative small carbon capture with a significant price against the secondary benefits and end use possibilities from the biochar production, which could make biochar a more attractive option for the City of Gothenburg. To make this weighting easier for the city, further discussion for the flows, end use options and uncertainties can be found in the following sections.

5.2.1 Input materials

Biochar can be used to utilize ”waste flows” and create a path for the City of Gothenburg to establish more circularity of material flows within the city. As mentioned in the theory (Section 2.5.2) for biochar every input needs different pre-pyrolysis treatment, but there is also other uncertainties and possibilities that can be discussed for each of the flows in this thesis.

When considering garden waste and especially the 12 000 [tonnes/year] ”other tree waste” it is critical to also evaluate its value as input for bioenergy production. As there are results showing a net energy production loss of around 38% when comparing biochar production to incineration. This implies that the total benefits of the bio energy alternative might out weigh the carbon sink and other secondary benefits from producing biochar [91]. Another aspect of the wooden material flow is the pre-treatment, which often consists of a first step of shredding and sieving to get the input material to the right size followed by a drying-step [91]. One example from the Skånefrö facility, the shredding was done to a size of 15 mm pieces and was after dried by a batch-dryer [27]. The steps mentioned is one of the reasons for the loss of efficiency and should be considered when looking at producing biochar from wooden materials. Nevertheless, if the City of Gothenburg is going to reach the carbon neutral goal there will be a need for all the possible carbon sink technologies to be utilized. In the case of tree based input material it would be reasonable to investigate the benefits of utilizing the material for biochar production versus the indirect effects of not using the input material for other purposes. Especially, to weigh the possible mitigated emission from producing bioenergy against the possible carbon sink from biochar.

The input flow that contributes to the highest carbon sink, sewage sludge, which alone stands for around 46 % of the carbon sink potential by the year 2030 (including food waste). Today, this flow from Gryaab is used as fertilizer and compost (made of sewage sludge) because of the abundance of nutrients, with an approximate 50 % split between the two options [88]. If all the flow of sewage sludge instead was used for biochar, because of its soil-improving properties, the biochar from sewage sludge could potentially be used in agriculture and at the same time contribute to a carbon sink.

There can also be a risk when using sewage sludge as it can consist of toxic compounds which can have negative effects on the end use [28]. This can create problems, as for right now, biochar from sewage sludge is not approved from EBC (mentioned in Section 2.5.2). Which could lower the attractiveness for the City of Gothenburg when considering making biochar from sewage sludge. On the other hand, there already exist an interest of approving biochar from sludge and there is indications that biochar from sludge could meet the standards set [27].

The pre-pyrolysis treatment of sewage sludge is mainly done to reduce the water content of the sludge and increase the dry weight percentage to at least 85% [68]. This can be done by well developed dryer systems, but this step can be seen as quite expensive as sludge often has a large wet fraction [27]. In order to avoid costs and emissions linked to transportation of the sludge, it should be considered that the sludge should be dried at the Gryaab facility before the transportation to the biochar production site. However, as of today the sludge goes through de-watering and thickening processes. It is therefore uncertain whether if further drying is necessary, and this should be investigated further. With all this in mind the results from the thesis show that biochar produced from sewage sludge is an opportunity as a carbon sink for the City of Gothenburg, and should therefore be in consideration by the City of Gothenburg.

The next and last potential input flow in this report might also be the most uncertain one, the food waste. Just as sewage sludge food waste are generally richer in nutrients (N,P and K) which could make it an attractive option for biochar production [28]. However, to utilize this resource can be a hard as the captured food waste is today used for biogas and bio-fertilizer production [92]. But there is also many different methods of utilizing food waste as animal feed and thermochemical processes which can increase the competitiveness for this resource [93]. Even if there exist studies investigating food waste for biochar production it is not mentioned as a potential waste flow to be utilized in ”Rest till bäst”[27, 94]. If food waste was to be utilized, the pre-pyrolysis treatment should also consist of drying as food waste generally has a high content of moisture and in some cases even shredding of the food waste is needed [93]. Thus, food waste is not considered to be a likely input for biochar production, but is however an alternative.

5.2.2 Biochar enduse

If a large production of biochar is done by the city of Gothenburg there also exists a need to consider where and how to use the biochar. Either by selling the biochar to other cities/farmers or to utilize the biochar within the city. As the market for biochar have not been predicted in this thesis, the option of selling the biochar is only given as an alternative and not included in cost calculations. Further, other ways of using the biochar in the city is considered.

As mentioned in the biochar background segment, the most likely end use is to apply the biochar to soil, because of the water- and nutrient holding capacities. The 4229 hectares of agriculture and pasture land within Gothenburg could be a potential end use alternatives for the biochar. This has also been mentioned in "Vägen till en klimatpositiv framtid" as a suitable place for carbon sequestration and for contributing to better soils, but it is also mentioned that there are uncertainties with that statement and more research is needed [30]. There also exist an uncertainty for soils at a temperate climate as the effects of biochar have showed to be small with both negative and positive results on yields in agriculture [28]. Looking into how much biochar that could be applied, results have shown that over 50 tonnes of biochar per hectare in temperate soils has lead to statistically negative results. Therefore,a general number for application is somewhere between 20-50 tonnes biochar per hectare [28]. Notice that this is not a yearly input of biochar, rather this amount (20-50 tonnes) is applied during a range of years. A recommendation to the City of Gothenburg is to consider to utilize their agricultural and pasture land for biochar application.

Another end use possibility that is discussed is to apply biochar on football fields. The biochar addition leads to more resistance to dry periods, reduces the need for water from the grass and to makes the field more durable. In an experiment done in Granäs in southern Sweden a tryout with 2 kg biochar per square meter (20 ton per hectare) was done. The experiment showed good results and applying biochar on football fields is therefore potentially something that could be done by the City of Gothenburg [27].

Another possibility for the City of Gothenburg is to apply the biochar together with trees within the city. As "city-trees" often is exposed to extreme environments which can lead to a water and nutrient stress. An interesting thought is that this could potentially be exploited together with our "Urban forestry" suggestion in order to create a larger carbon sink.

So, more or less any place that needs good soils is a possible alternative for application of biochar. As seen, the options can vary and if the City of Gothenburg wants to utilize the (possibly) produced biochar a further investigation within Gothenburg should be made to see the exact amount of biochar that could be applicable within Gothenburg.

5.2.3 Secondary benefits

As mentioned in section 2.5.2, one of the main products from biochar production is the bioenergy produced, which can be connected to the heating system in Gothenburg [31]. This is one property that makes the biochar system unique as it will give the City of Gothenburg an option to both produce green energy and at the same time contribute to a carbon sink. Unfortunately, a possible value for the energy output possibly gained with the flows in this thesis has not been calculated, but would be recommended for further research.

As described in the last section, a secondary benefit of contributing to better soils is a interesting possible benefit from application of biochar. Thus, the biochar could potentially play a part as an input in the city's agriculture, or in rehabilitating degraded land and at the same time sequestering carbon dioxide from the atmosphere [95]. Which gives the City of Gothenburg large application alternatives as it can be applied both within the city and in agriculture, or maybe create new possibilities for collaborations with local farmers. Such a possibility could for example be to trade biochar for agricultural waste as an input material etc.

Another secondary benefit is that biochar creates a way for the City of Gothenburg to create more circularity with its resources. As biochar can utilize more or less any kind of biomass, it creates new possibilities for waste flows to be utilized in a better way.

5.2.4 Uncertainties

When considering the results for biochar it is important to acknowledge that the output results in this study are built on the scenario that all of the potential input material flows that exist is utilized. Even if the scope is to investigate the potential it might be reasonable to argue for that this a potential is not very realistic. To create a more realistic scenario it may be more reasonable to assume a step by step development for each input material.

Another uncertainty is the biochar stability in soil over long terms, as the soil environment might lead to increased leaching and the circumstances could differ over time. Wang, Xiong and Kuzyakov argue that the biochar decomposition rate is dependent on several factors [96]. Among these factors are climate, soil organic carbon (SOC) content and addition of plant residues. The addition of further carbon to the soil leading to a more rapid decomposition of biochar and leading to a decrease in the viability of the technology as an assumed 95% of carbon is counted as long term storage. Thus, the City of Gothenburg should investigate the soils in the region if they have the suitable conditions for biochar as a long term carbon sink.

The output and carbon sink values could also be discussed. As this report values for biochar per input material and carbon content per biochar is based on fast pyrolysis and a pyrolysis temperature of 700 °C as this is the general way of producing biochar by companies in southern Sweden today [27]. This should be investigated on the local input materials to see what settings is beneficial for the end use chosen by Gothenburg. Although the result from this study will give an indication of the magnitude of the carbon sink.

The costs is a large uncertainty in this thesis, as it is only based of one source. As the pyrolysis machines in the costs calculation is based on only managing 1400 tonnes of input material per year a round off was needed. For example, if one flows needed 8,34 pyrolysis machines, a round off to 9 was done. Which leads to an increased price. Also, as the drying in the source was based on sewage sludge and the same intensity of drying may not be needed for tree materials this might give a larger cost for the drying for other materials than sewage sludge.

5.2.5 Future outlook

During this study the impression have been that biochar is a technology on the rise based on the discussions in seminars with ”Klimatkommunerna” and the from the ongoing research that is being done by different companies (Skånefrö and Göteborgs Energi). Therefore a recommendation for the city of Gothenburg is to follow and help the development of biochar in order to make the development as good (and fast) as possible and to contribute to the S-curve. As there is quite a lot of uncertainties but at the same time also many possibilities that needs to be investigated.

One thing to investigate is that it might be necessary to expand the view of biochar, and to include waste water sludge in biochar certificates. This could be done either by diverting from EBCs standards for biochar certificates or by creating a new type of product for biochar from waste. If the biochar from sewage sludge would not meet the standards within agriculture to be used as a soil enhancer there might be other markets or opportunities. For example, Callegari and Capodaglio (2018) argue that the bio availability of the heavy metals in the biochar is low and that it could be used at contaminated soil to absorb other contaminants [97]. Other uses were reported in cement industry where biochar concrete composites have shown interesting properties in increased strength and sound isolation compared to other concrete formulas [98].

This thesis has shown that there exist input materials that can be utilized within Gothenburg. However, there exist other potential flows that this thesis has not covered, for example seaweed and agricultural waste. As the result have shown, the biochar production is not the most impactful in terms of carbon sink. So, it might be reasonable for the City of Gothenburg to look around for other possible flows to expand the biochar production in the future.

An area that this study has not covered is the possible market value for biochar. However, the recovery of valuable end products as well as a stabilization of the carbon could potentially create new value chains and also new markets [97]. This can possibly create a larger demand for biochar in the future, as biochar is a way to utilize ”waste flows” and produce a stable carbon product.

5.3 Wooden houses

With a projected plan to construct 4000-5000 multi-storey houses per year in Gothenburg there exist a large quantity of emissions that will occur in all predictable scenarios and are classified as "unavoidable emissions". The incorporation of wooden materials at a larger scale than today could lead to a carbon sink of almost 3.5 Mtonnes of CO_2 until 2050 assuming all multi-storey houses where built in wood from 2025. This is equal to the annual territorial emissions of more than 31 500 citizens. Although quite unlikely that all houses can be constructed in wood it shows that the carbon sink benefit of wooden houses. Assuming 50% of houses are constructed in wood and emissions reach the target of 1.1 ton of CO_2 eq. per citizen by 2030, which the City require to comply with the set environmental targets [4]. The carbon stored in the houses from this scenario would then be equal to the annual emissions of more than 60 000 citizens.

Wooden houses have historically held material disadvantages and to avoid another ban on wooden houses higher than two storeys in Sweden, the development of wooden houses should be carefully executed. When selecting materials for house constructions of various sections the alternative corresponding to the least amount of CO_2 emissions was not selected at times due to preconditions of the ground or specific demands by Lokalförvaltning in Gothenburg [99]. To avoid the issue of houses being built on unsuitable conditions, subsidies as a policy instrument promoting the use of wooden building material in projects where wood is feasible could be one direction to go forward with for decision makers.

5.3.1 Cost

An cost evaluation was not done due to the complexity of costs associated with building houses. The main cost issue for wooden houses arise from the unpredictability of the wooden material. For example the water resistance and the lower durability of wooden materials could prove to be problematic and costly. The corrosion of screws in wooden structures has been one problematic factor in American wooden structures and Hodgin (2018) argues that the progression and advancements in wooden housing is too quick and might end up causing additional issues [100]. These factors could result in increased maintenance costs compared to steel and cement houses. However Gustafsson (2019) argues, concerning wooden foundations, that the wooden alternative when produced at a large scale is cost competitive with a cement foundation [99]. Additional studies on the long term effects might be necessary, where all the material costs over a life cycle are considered.

5.3.2 Secondary benefits

The potential carbon sink is distinguished from the mitigated emissions from construction, production and usage in this study. The mitigated emissions have an impact on the total carbon budget although the mitigation of carbon emission does not count as a carbon sink by definition this can create a misleading picture of what the total carbon budget impact would be for a wooden house. From an environmental perspective and working around carbon budgets the mitigation of emission is as valuable as creating a carbon sink. Thus, a comparison of emissions when building a 12 story mass timber building with a similar concrete building can be seen in table 2.2, seen in section 2.5.3. The results showed that the emissions are 21% lower for the CLT option of construction than the reinforced concrete (RC) option. The increased mitigation effects of the CLT house shows that there are additional mitigating benefits from constructing in wood than to just to create a carbon sink. This adds further weight to the argument of constructing houses in wood from an environmental stand point.

The wood used in the buildings can be reused for other purposes such as biochar production or bioenergy production after the house is demolished [44]. Wastes from production can be used for regional heating or other carbon sink methods according to Skullestad, Bohne and Lohne (2016) [39]. The mitigation varies between different reports and projects and is also influenced by the limitations of the individual study. However, the building waste management and end of lifetime uses for the components of the house can significantly improve the total environemntal aspect of a wooden house compared to a reinforced concrete house. Reuse and recycling could lead to up to 84% of the CO_2 eq. emissions being saved compared to a reinforced concrete house which would aid the city in creating a more circular society [39].

5.3.3 Uncertainties

Although the recycling would be ideal, in many cases Andersson (2019) argues that recycling and re-usage of materials from modern houses could be an expensive practise [99]. As the complexity of houses increases, separation of different materials also become more complex. The construction of wooden houses leads to complex mixtures of materials and thus the high emission reductions for wooden houses might be too simplified or come at a high cost. A potential solution is to construct houses where parts can be replaced and separated with as little effort as possible.

The amount of sequestered carbon is based on the literature of sustainable forestry by Cowie, Berndes and Smith (2013) [69]. When calculating the presented numbers it is done on the basis that the wood input is harvested in a sustainable manner. Resulting in the carbon pool of the harvested forest not decreasing over time. If the assumption can not be made for the total carbon budget, that the total carbon pool of a forestry is decreasing over time, the construction of houses in wood could potentially become a net increase in atmospheric carbon compared to a steel and concrete option. The issue arise if the area where the wood was harvested from can not be used for new biomass equal or greater to the reference point. Thus the City of Gothenburg or other decision makers should take the origin of the wood and the supplier of the wood into consideration before using the numbers reported in the results of this thesis.

Another way of viewing the issue of sustainable wood production for wooden houses is the the Guest factor, see Figure 4.12. The Guest factor calculations is also based of the assumption that new trees are planted but the theory takes the individual house and tree into consideration aswell as the enduse of the wooden products. The GF does increase transparency for the calculations by taking an individual house as an individual case from a carbon sink perspective. The age of the tree and the life time of the house plays into the calculations and a net carbon sequestration is obtained dependent on these parameters. For the results seen in Figure 4.12 the life time of a house is set at 80 years and rotation time for the forests of 60 years was used. There are two ways of increasing the carbon sink effect according to Guest et al (2013) [38]. One way of increasing the GF would be by decreasing the rotation period which would result in a higher net effect as a carbon sink. The option is not seen as viable as a shorter rotation period than 60 years could mean less sequestered carbon by the forests [77]. The other option is by increasing the life time parameter of the building which would mean an increase of the carbon sink effect. As is the case for the other carbon sink methods, the long time storage is a vital parameter and the relative low life time of houses means that the carbon in fact is not stored for a long time in a wooden house. The Guest factor highlights this issue where the average life time of the house is considered. Applying the Guest factor to the house building scenarios seen in Figure 4.12 and Figure 4.10, means that the net carbon sink for the wooden house alternative decreases with around 53%. Thus the importance of constructing long lived houses is highlighted.

5.3.4 Future outlook

As concluded by the survey done by Laguardo-Mallo and Ezpinosa (2016) regarding the importance of different factors when choosing building materials for houses it was evident that environmental factors were not highly prioritized [46]. Although environmental topics might be discussed to a greater extent in Sweden today than in the US at the time of the survey the economic performance and availability was scored higher. As the general uses of wood in Europe has been relative low for the start of 21st century, a shift towards constructing buildings in wood might increase prices and decrease availability which would slow down the trend of constructing wooden houses and shift the development towards other materials [45]. Thus, it could be problematic if the expansion of constructing in wood would be too rapid for the forestry industry to handle which could cause a snow ball effect of an over saturated market.

An increasing trend of constructing in wood and the potentially high need for maintenance of such houses combined with the need to replace various parts could be high [35]. Which might cause a situation where the price of wood could increase and pose a threat to the long-term stability of constructing wooden houses. Hurmekoski (2016) further argues that the market for bio energy and other wood based products are to increase as well [45]. Combined with this the city of Gothenburg has decided that the district heating should be "fossil-free" by 2025 [4]. The district heating systems is also put under pressure tops at certain times of the year which could create an unstable market for wood products.

The need for sustainable forestry for the wood supply might prove to be a barrier for wooden houses. Gustavsson and colleagues (2006) argues that a saturation point will be reached for the demand of wood [101]. At the saturation point the soil organic carbon should not deteriorate and the stock should be kept at a stable level. The amount of wood provided at the saturation point is not specified but at this point a cause could be that the use of wooden houses or other products are not beneficial from an environmental perspective. The issue highlights the need for environmental symbioses. The re-use and end use of wooden products as well as circular flows of resources. Symbioses could therefore become the key to long-term construction in wood. An example of a potential symbiosis is the completely bio-based district heating system, a target for the city, and construction of houses in wood [4]. To transform the district heating to be bio-based there is need for additional bio-based waste streams. If the building sector started to construct more wooden houses it would lead to more bio-based waste that could ensure additional supply to the district heating system. The symbiosis would provide added circularity and thus contributing to the goals of an increased circular economy.

As the environmental burden of the construction sector is arguably not going to stop the construction of new buildings, as the demand for housing is high and a major political topic. The city of Gothenburg should instead aim to guide the construction sector towards building in sustainable manners and contributing towards all the possible climate goals the city has set. The unavoidable emissions from society bearing practises could be the toughest challenge facing modern societies.

5.4 Agroforestry

Agroforestry has the lowest potential as a carbon sink with a value of around 2000-6000 tonnes captured CO_2 until the year 2030 and 6900-21000 tonnes CO_2 capture until the year 2050 between the presented scenarios. The results are showing a clear picture that this method is dependent on mostly two parameters, area size and time. The time parameter stands out as looking at the result seen in Figure 4.13, the peak for the silver birch carbon storage is around the year 2069 which is not considered in this study. This however implies that a longer time perspective will probably be needed by the City of Gothenburg if they choose to start working with agroforestry as a carbon sink. The agroforestry method is better suited to long term projects and should be taken into consideration for projects that have a longer time span set. As the established potential carbon sink in this thesis is more or less negligible compared to the other alternatives other benefits from agroforestry should be taken into account if an implementation is to be considered by the City of Gothenburg.

5.4.1 Secondary benefits

As described in theory (section 2.5.4), the main goal with agroforestry is to create a sustainable climate smart agriculture. Where agroforestry could play a role as it has positive effects on biodiversity and resilience against the environmental changes that may occur in the future. As Jordon et al. (2020) describes it, the trees contributes to biodiversity by creating a suitable habitat for other species than the field does [102]. Therefore, as seen from our results the carbon sink may not be the most important, but if agroforestry could help with an increased biodiversity (and other ecosystem services) it might make agroforestry a more interesting option for the City of Gothenburg as it fits well with the other goals set. Such as having a high biodiversity within the City of Gothenburg [6]

One significant parameter that arguably should be included in the result, but as described in method chosen to be a secondary benefit is the potential increase of SOC when using agroforestry practises. The SOC is an important aspect, as in various ecosystem this is the largest reservoir of carbon that interacts with the atmosphere, both with negative and positive emissions [103]. By adding agroforestry, the systems will have the ability to sequester carbon within both trees and the soil. This is a subject that have been discussed in several reports, but the amount of potential carbon stored as SOC is dependent on many factor such as the original carbon stock within the soil and climate [30, 48]. The thesis is limited to above ground biomass and even if there is a potential of an increased carbon captured and stored from above ground biomass as the results of this thesis show, the soils should be further investigated if that potential carbon sink is wanted when also including the SOC [30, 103].

Other secondary benefits that is mentioned from having a well designed and managed agroforestry is the reduced soil erosion and the lowering in loading of nutrient to waterways. But also the economic value that this kind of system can produce with wooden products [50]. So there exist several possible secondary benefits that can be utilized by the City of Gothenburg, however the possible positive effects of agroforesty should be further investigated for the local conditions of the soils within Gothenburg and the forestry selected to be incorporated into the agroforestry.

5.4.2 Uncertainties

One uncertainty with the method used for the potential of agroforestry is the amount of agriculture and pasture land that can be utilized. As our numbers are acquired from the Swedish board of agriculture, which includes both private and state owned land. It is therefore uncertain of the amount of agricultural land the City of Gothenburg has ownership over. In their document with proposed goals, it is mentioned that the city have ownership over most of the city's land but there is a need for a collaboration between private land owners and authorities [6]. The collaboration is of importance as the more land area that can utilize agroforestry the more carbon can be captured and then an inclusion of private sectors would definitely be helpful but will for now be an uncertainty. However, as different scenarios is created (see Figure 4.13) to work around the uncertainties of land usage the result is still valid and could be useful for the City of Gothenburg.

One key parameter in the method is the choice of silver birch as the tree selected. It is important to emphasis that the result would probably be different if another tree type was chosen. The magnitude of difference is difficult to estimate, but as mentioned in the method, silver birch is a common tree in boreal climate and should therefore give a representative results. Other trees that have been used is agroforestry studies is hybrid poplar (clone-DN-177) and silver maple (Acer sacharrinum) which also could be investigated [50]. A recommendation to the City of Gothenburg is therefore to evaluate the most well suited tree for their purpose and the environment.

The choice of leaving costs out is an uncertainty, as there is a need of work for planting and probably also for maintenance of the agroforestry. The cost of labour, seeds and maintenance are assumed to be negligible and there is no investment cost as in for example BECCS. However, one argument could also be that if the agroforestry is implemented the possibly gains from the secondary benefits could save (or adapt) the agriculture (in the long term) from environmental changes such as heat and drought. Which then could lead to saved monetary value from yields of products etc in the future [47].

5.4.3 Future outlook

As seen in the discussion, it is quite many parameters that needs to be investigated. What kind of trees (or other plants) are optimal for agroforestry, how is the quality and carbon storage of the soils in Gothenburg etc. A recommendation connected to this is discussed in ”Vägen till en klimatpositiv framtid” where they recommend to have an dialogue together with the Swedish Board of Agriculture and the Swedish Environmental protection agency to make the right decisions when implementing the agroforestry [30]. As those agencies may have better knowledge of the land in Sweden and Swedish climate than the City of Gothenburg this is also something recommended in this thesis.

A second recommendation is to make an investigation on how much agricultural and pasture land that the City of Gothenburg has ownership over and thereby can be used for agroforestry should also be done. This also includes to reach out to private owners to see if an possible collaboration in implementing agroforestry can be done. If this is done, the City of Gothenburg will be able to match the possible usable land to the most fitting scenario from this thesis and then know the possible potential of agroforestry.

Also, it is important for the City of Gothenburg to have a long time perspective when thinking of agroforestry as a carbon sink (and for the secondary benefits). As described, the peak for the carbon capture is by the year 2069 when implementing the agroforestry in 2024. This implies during all these years, always keep a sustainable management of the agriculture/pasture land. Otherwise, the potential carbon storage from agroforestry can potentially be lost and go back to the atmosphere.

5.5 Urban Forestry

Urban forestry could potentially contribute to 4600-18500 tonnes of captured CO_2 until the year 2030 and 16400-65700 tonnes of captured CO_2 until the year 2050 depending on the different scenarios. Which also is more or less negligible compared to the other alternatives. Thus, the secondary benefits should be of higher importance when the City of Gothenburg consider urban forestry. As the method for the urban forestry in this thesis is based on the same reasoning as agroforestry, the same parameters is of importance here; area, time and tree species.

5.5.1 Secondary benefits

The addition of trees in the city can contribute to targets the City of Gothenburg has to establish a green area no further than 300 meters from the home of any individual citizen [16]. Although this target is reached by 99% today, with the construction of new housing and densification of the city, new areas could be required to reach the target.

Ecosystem services are also discussed in the climate report of 2019, where the city aims to have a "rich animal and plant life" [4]. The increased accessibility to forests and green areas is also mentioned among other things to have positive health effects for citizens. It could be of consideration if smaller forest areas should be incorporated to not only sequester carbon but to increase the accessibility and intensity of green areas for citizens and thus improving the mental health [16]. Other secondary benefits from the increase of trees is that they can provide several benefits to water, air and soil quality in the city[102]. Also, create natural corridors for animals and decrease the risk of flooding. The residues from the urban forestry can later be used as input materials for other techniques that mitigate climate change effects (such as BECCS and biochar production). Which may add further incentive for decision makers.

5.5.2 Uncertainties

As the area used is based on the hectares of parks owned by the Gothenburg the uncertainty of private ownership is not existing in this case. However, the fraction within the existing parks that is usable for plantation of new trees is an uncertainty. This is solved (just as in agroforestry) by creating the different scenarios for the City of Gothenburg to be able to apply the most likely scenario in the future.

The choice of tree and the uncertainty around that is the same as for agroforestry. However, in the case of using trees within the city, the social dimension might play a role. As parks and tree corridors within a city can be considered visually pleasing by the citizens. This is not something that was taken into consideration in this thesis but might be of importance for the City of Gothenburg.

5.5.3 Future outlook

There is a need to investigate the actual area of the parks that potentially can be used for an increase of trees. After that the City of Gothenburg will be able to apply the most fitting scenario to estimate the potential. The City of Gothenburg could also consider utilizing other areas beside the available park areas to further utilize urban forestry within other areas. To create plantations in areas that is not utilized at the moment. This could for example be besides roads, besides parking spots or in connection with larger industries. This thesis uses the parks as a base but there is potentially under-utilized areas within the city where urban forestry can be used.

Also, the same principle of sustainable management over a long time period is needed in urban forestry. So, if the City of Gothenburg wants to utilize urban forestry as a carbon sink it is of high importance to keep the biomass growing and being healthy for a long time period.

6 Conclusion

This thesis has provided an overview of different carbon sink technologies for the City of Gothenburg. The technologies of land creation and blue carbon requires additional investigation and data, and is suggested as technologies for further studies that could potentially lead to an increased amount of biomass within the city. Forests and green roofs are still viable alternatives as carbon sinks options and is recommended options for the City of Gothenburg to investigate further on a detailed level as carbon sinks technologies similar to the urban forestry example, where the secondary benefits could benefit several environmental targets.

From the results of this thesis the technology with the highest potential in terms of providing a carbon sink potential for the City of Gothenburg was BECCS. With a total of around 500 000 tonnes of CO_2 captured and stored annually, whereof 63% are bio-based. Based on the assumptions of the high scenario presented in this thesis, using BECCS will result in captured CO_2 of around 2.5 Mtonnes of CO_2 by the year 2030 and around 11.1 Mtonnes of CO_2 by the year 2050. Resulting in a cost between 1147-1604 SEK per tonne CO_2 captured and stored. Because of the high potential of CO_2 captured and stored estimated in this thesis, it is recommended from this thesis that the city initiate work on establishing CCS infrastructure.

Biochar could possibly contribute with a carbon sink of around 0.2 Mt CO_2 until 2030 and 0.8 Mt of CO_2 until 2050. As a carbon sink technology, biochar might not be the alternative with the highest potential. However, by producing biochar the focus is also on utilizing waste flows such as sewage sludge and garden waste, which gives the City of Gothenburg an opportunity to create circularity while also storing carbon. Although the trade-offs should be investigated further. The costs estimated in this thesis varies significantly and are estimated between 340-1260 SEK per tonne CO_2 for the different input materials without a dryer and 1046-3881 SEK per tonne CO_2 for the different input materials with a dryer. For biochar it is recommended that further studies are initiated to establish a cost-benefit analysis of investing in biochar and to resolve uncertainties. Such as the trade-offs associated with the input material, opportunities for increased input streams from other regions and the potential usages are some of the uncertainties that should be investigated further.

Wooden houses has a relatively large potential for storing carbon within newly constructed buildings. If all the new projected apartments were to be built in wood (Scenario A) around 0.9 Mt CO_2 can be stored within the buildings until 2030 and almost 3.5 Mt CO_2 can be stored until the year 2050. The City of Gothenburg has to ensure that the wood used for these buildings comes from a sustainable forestry that does not contribute to a decreasing carbon pool within the forest. A cost estimation was not done for this technology as the cost was assumed to be similar to the compared alternative ways of constructing houses. The recommendation to the City of Gothenburg is to investigate all possible ways of incorporating additional wood into the construction sector and to construct as high of a share of new houses in wood as possible.

Agroforestry and urban forestry showed the lowest results in terms of carbon sink potential. If added together a potential of 24.5 ktonnes captured CO_2 by the year 2030 and 86.8 ktonnes captured CO_2 by the year 2050 can be reached for the highest scenarios. Those results is based on alley cropping of silver birch, thus, the City of Gothenburg should look into alternative ways of agroforestry/urban forestry before a potential decision should be made. The recommendation to the City of Gothenburg is to initiate the incorporation of more forestry into agricultural and urban environments to store carbon. The additional trees within agroforestry/urban forestry would also help the city to reach other goals, such as better agriculture and improved air quality.

As a final conclusion from this thesis, the implementation of carbon sink technologies can potentially contribute to between 15-37% of the territorial emission goals for the year 2030, depending on what scenario chosen. Thus, carbon sink technologies combined with mitigation strategies should be implemented by the City of Gothenburg to reach the emission goals and to pave the way for a sustainable society.

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