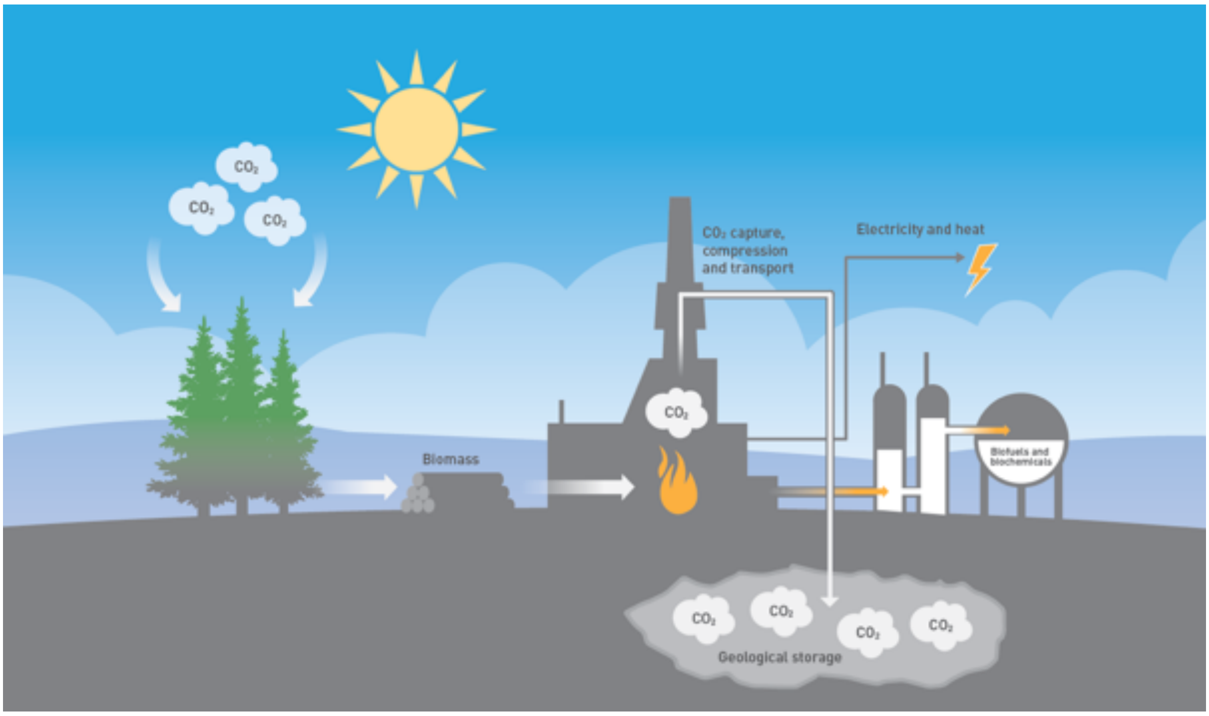
The Netherlands' Potential to Use Negative Emissions Created by BECCS Until 2050



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Executive Summary

Due to the posing threats of climate change and the newly formed Paris agreement, carbon mitigation becomes more and more important. BECCS, which is the application of CCS on the production of bioenergy resulting in negative emissions due to the carbon uptake of biomass, is one such technology. Additional advantages of BECCS is that carbon roof overshoot can take place and that BECCS allows for low amounts of fossil fuel use in a net zero carbon society. The aim of this research is to discover how many negative emissions the Netherlands is able to achieve between 2015 and 2050. Three different scenarios have been developed for this. The scenarios differ in the amount of biomass available to produce bioenergy. One scenario assumes only biomass input from the Netherlands, the second scenario assumes that the global biomass supply is equally divided per person, and the last scenario assumes that the Netherlands becomes an expert in handling biomass for bioenergy production purposes. The results of this research shows that the Netherlands can achieve annual negative emissions between 2.8 and 24.0 megatons of negative CO_2 emissions in 2050, depending on the scenario. The cumulative amount of negative emissions equates to 102.3 – 556.7 megatons CO_2. This allows the Netherlands to delay the implementation of other carbon neutral energy conversion technologies with 0.5 to 2.9 years while still achieving the same net carbon emission savings. However, this study was performed with a base year of 2015. We are currently almost in the year 2018. This means that if we wish to benefit as much as possible from BECCS, implementation must start rapidly. Regardless of the starting point, the results of this research show the significance that BECCS can play in mitigating carbon emissions in the Netherlands. It's a technology that should not be ignored.

Content

1 Introduction

In 2015, countries all over the globe met in France at the UN Climate Change Conference (also known as COP 21) to discuss the pressing threats of climate change. This conference resulted in the Paris Agreement, a treaty that states to hold global average temperature increases well below 2 °C compared to pre-industrial values, even vowing to pursue efforts to limit this temperature increase to 1.5 °C (United Nations, 2015). Currently, 194 parties signed the Paris Agreement. 129 of those parties also ratified the treaty (United Nations Treaty Collection, n.d.). However, evidence keeps building up to show just how much of a challenge this might turn out to be. The atmospheric level of CO_2, one of the main causes of temperature rise, keeps increasing every year due to anthropogenic carbon emissions (IPCC, 2013). Figure 1 shows the tremendous increase in anthropogenic carbon emissions over the past centuries, especially since the second half of the 20th century.

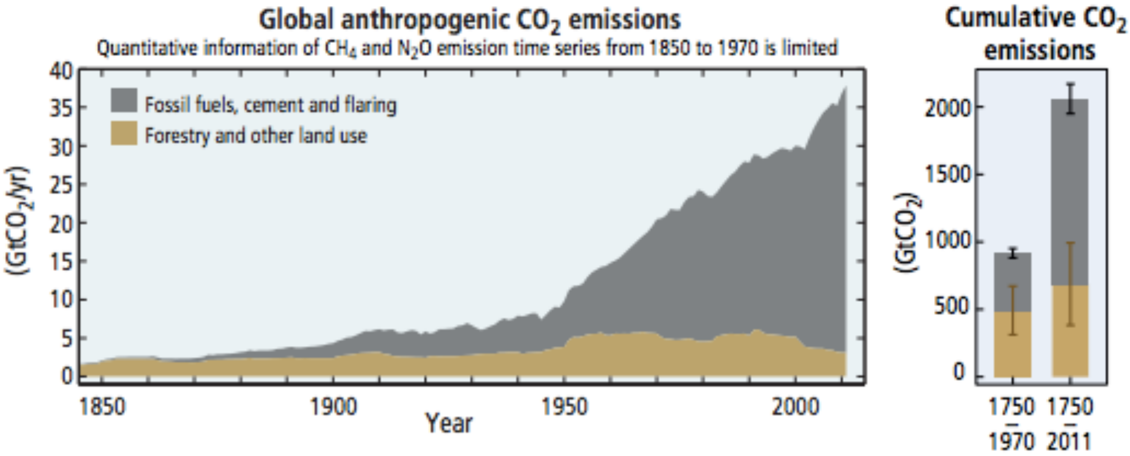


Figure 1.1 – Annual global anthropogenic CO_2 emissions (left) and cumulative anthropogenic CO_2 emissions (right) (IPCC, 2014)

In 2016 a new milestone was reached. For the first time in human history, the global average atmospheric CO_2 concentration hadn't gone below the value of 400 ppm between the period from January to October (WMO, 2016). Between 2000 and 2012, about 420 Gt CO_2 was emitted (PBL, 2012). Meinshausen *et al.* (2009) calculated that if the global cumulative CO_2 emissions between 2000 and 2049 reaches 1,437 Gt CO_2, there is a 50% probability that the 2 °C threshold will be exceeded. Without immediate action to cut carbon emissions, the outlook doesn't look promising.

As part of the Europe 2020 strategy, the European Union has set targets regarding climate change and energy. These climate change and energy goals are known as the European 20 20 20 targets. The targets aim to reduce greenhouse gas emission by 20% compared to 1990, increase the share of renewable energy sources in the final energy consumption to 20%, and to improve energy efficiency by 20% (European Commission, n.d.a). This European target has been translated in several national targets. For the Netherlands, the targets are to reduce greenhouse gas emissions by 16% compared to 2005, increase the share of renewable energy sources in the final energy consumption to 14%, and use no more than 60.7 Mtoe of primary energy (which is roughly 2,541 PJ of primary energy) (European Commission, n.d.b). The Netherlands is on track towards its greenhouse gas emissions target. However, this is only a first step. The European Union has already set targets to reduce greenhouse gas emissions by 40% compared to 1990 in 2030 (European Commission, n.d.c), and is committed to reducing emissions to 80 – 95% below 1990 levels by 2050 (European Commission, 2011). The Netherlands has already declared that it has committed itself to achieve the goal of reducing its greenhouse gases by 40% compared to 1990 in 2030 in order to stay in line with the goals of 2050 (Rijksoverheid, 2011).

These are very ambitious goals. If the Netherlands wishes to achieve these goals, it will need to decrease greenhouse gas emissions quickly. A concept that might aid herein is Bioenergy with Carbon Capture and Storage (BECCS). This concept combines bioenergy and carbon capture and storage (CCS) to generate negative emissions. Since bioenergy uses biomass that grows by consuming atmospheric CO_2, the CO_2 that is emitted by generating electricity, heat or biofuels is offset. This results in net zero carbon emissions. CCS is a technology that captures CO_2, and decreases the amount of carbon that is emitted into the atmosphere. When, for example, fossil fuels are used to generate electricity, CCS could capture and store 90% of the accompanying emissions. If bioenergy and CCS are combined, CO_2 originating from the atmosphere can be transferred into storage sites while generating either electricity, heat or fuels in the mean time. This is what is meant with “negative emissions”. This is schematically shown in figure 2.

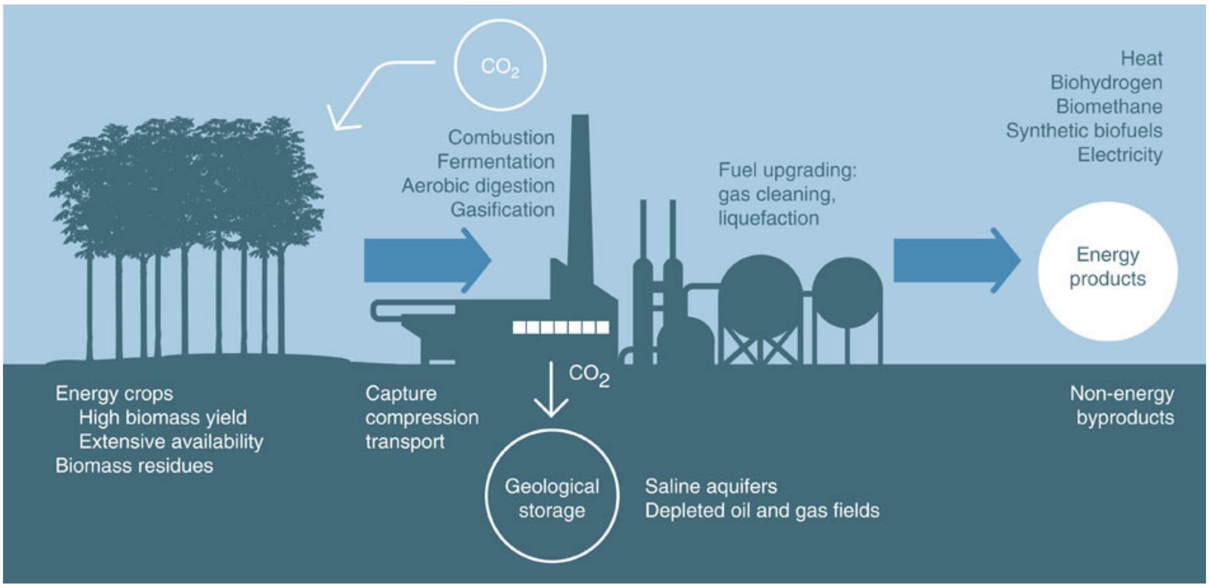


Figure 1.2 – A schematic representation of BECCS (Berkeley News, 2015)

A major advantage that accompanies BECCS is the fact that it gives the possibility to overshoot the CO_2 roof a little. Emitting a little more CO_2 isn’t as bad as without BECCS. Additionally, extra time to adjust to and implement other renewable energy technologies becomes available. Studies also identified that this helps driving down future carbon mitigation costs ((Azar *et al.*, 2010), (Azar, Johansson & Mattson, 2013), (Kriegler *et al.*, 2013), (Klein *et al.*, 2014), (Fuss *et al.*, 2014)).

This research aims to investigate the potential contribution BECCS can have in producing negative emissions for the Netherlands up until 2050. This is dependent on three factors. The first being how much biomass is used to create (bio)energy, and how much CO_2 is emitted when creating this energy. The second factor is the amount of CO_2 that can be captured by CCS technology. Finally, the capacities of storage sites might be very influential for the amount of negative CO_2 emissions the Netherlands can achieve.

This paper has been divided as follows. Section 2 looks into the basics of CCS. This section answer what CCS is, which technologies are used and what is important. Section 3 analyzes the current implementation of CCS in the Netherlands. Section 4 analyzes the total amount of CO_2 storage capacity in the Netherlands. Section 5 looks into the infrastructure needed for CCS and how much CO_2 could be transported and stored in the Netherlands until 2050. Section 6 looks into the basics of energy conversion technologies for biomass, describing the different ways that bioenergy can be produced and analyzing the different types of technologies that are used in the conversion process. Section 7 analyzes the current use of bioenergy in the Netherlands. Section 8 looks into the possible development of biomass use for bioenergy production in the Netherlands until 2050. Three scenarios for production of bioenergy have been formulated and will be explained here. In section 9, the net total of bioenergy that is produced and amount of negative emissions for all three scenarios will be presented. Finally, the discussion and conclusion are presented.

2 Carbon Capture and Storage

CCS is a concept that aims to prevent CO_2 from being emitted during electricity, heat and/or fuel generation as much as possible, thus reducing the increase in the atmospheric CO_2 level. Using CCS in combination with biomass even results in a transit of CO_2 from the air towards the ground, reducing the atmospheric CO_2 level in the process. This section will look into the technologies that are involved with CCS. This will result understanding how CCS works, which biomass conversion technologies are best suitable for CCS, how large its potential is to capture CO_2, and at what cost.

CCS has three steps that need to be followed. First, the CO_2 needs to be captured. The second step is the transportation of CO_2. The final step is storing it underground, making sure it doesn't flow back into the atmosphere.

2.1 Carbon Capture Technologies

The carbon capture step of CCS can be categorized into three technologies. These are post-combustion capture systems, pre-combustion capture systems and oxy-fuel capture systems (Pires *et al.,* 2011).

2.1.1Post-Combustion Capture Systems

Post-combustion capture systems are systems that capture CO_2 after the fuel (be it fossil fuels or biomass) has been combusted to generate power or heat. Post-combustion systems are well suited for (existing) power plants generating electricity and/or heat, and post-combustion systems are currently the most established system with proven pilot projects and commercial scale plants ((Leung, Caramanna & Maroto-Valer, 2014), (Theo *et al.*, 2016)).

One of the main disadvantages of post-combustion systems is the low concentration of CO_2 in the combustion flue gas of power plants. For coal-fired power plants the concentration is around 7 – 14%, while for gas-fired power plants the concentration goes as low as 4% (Leung, Caramanna & Maroto-Valer, 2014). It is most likely that co-firing of coal and biomass won't have any influences on the post-combustion system. However, dedicated firing of biomass in fluidized bed combustion systems (which are popular technologies used for biomass combustion) will have even lower CO_2 concentrations in the combustion flue gas (IEAGHG, 2011). For a qualitative transport of CO_2 through pipelines, the concentration of CO_2 should be at least 95.5% (de Visser *et al.*, 2008). Because of this, the energy requirement and costs increase significantly (Leung, Caramanna & Maroto-Valer, 2014). Additionally, post-combustion systems require the compression of CO_2, which is quite energy intensive, and has extensive water consumption (Theo *et al.,* 2016).

2.1.2 Pre-Combustion Capture Systems

Pre-combustion capture systems are systems that capture CO_2 before the fuel has been combusted to generate power. A process known as gasification is able to produce a gas (either producer gas or syngas) existing of mainly CO and H_2 from coal, natural gas or biomass ((Twidell & Weir, 2015), (Leung, Caramanna & Maroto-Valer, 2014)). Using the water-gas-shift reaction, it's possible to create H_2 and CO_2 from the CO in the producer gas or syngas and H_2O according to the equation $\mathrm{CO} + \mathrm{H_2O} \xRightarrow{\text{water-gas-shift}} \mathrm{H_2} + \mathrm{CO_2}$ (Naik *et al.*, 2010). This will result in a larger amount of H_2 and also a certain amount of CO_2. This CO_2 can then be captured, turning the fuel into pure hydrogen. Pre-combustion systems are thus only usable in gasification plants that aim to produce H_2. However, there are plants that immediately burn the gasses gained after gasification to produce power (known as (biomass) integrated gasification combined cycle plants (IGCCs)). Pre-combustion systems can also be applied in these plants. The concentration of CO_2 in the H_2/CO_2 fuel gas exceeds 20%, which makes it more concentrated than in the flue gases of post-combustion systems (Leung, Caramanna & Marato-Valer, 2014). Additionally, the output stream has, when compared to post-combustion systems, a relatively high pressure, making the compression of CO_2 to the preferred pressure less energy intensive (Pirest *et al.*, 2011).

Besides capturing CO_2 from the generation of hydrogen through the water-gas-shift reaction, it's also possible to capture CO_2 during the generation of biofuels such as ethanol or Fischer-Tropsch fuels ((Möllersten, Yan & Moreira, 2003), (Luckow *et al.*, 2010)). For ethanol production less than half of the carbon from biomass feedstocks end up in the ethanol product, while for Fischer-Tropsch fuels this amount can be around 30.2 – 32.2% (when biomass is used) ((Luckow *et al.,* 2010), (Larson *et al.,* 2009)). While the remaining carbon can be vented into the air, capturing and storing as much as possible will decrease the life cycle emissions of these biofuels.

Both ethanol production and Fischer-Tropsch fuel production have stages in which high purity streams of CO_2 are present. These high purity streams make it relatively easy to capture the CO_2 using pre-combustion capture systems. For ethanol production, 26% of the carbon that doesn't go into the ethanol is present in a high purity stream of CO_2 (Luckow *et al.*, 2010). For Fischer-Tropsch fuels the high purity stream of CO_2 is 81.1% of the carbon that isn't embedded into the final product (Luckow *et al.*, 2010).

IEAGHG (2011) makes two additional notes on the application of CCS in the generation of bio-bioethanl and FT-biodiesel. First, the (almost) pure stream of CO_2 in the fermentation process only needs to be dried and compressed. No capture process is required. The second note is that syngas already needs to be cleaned before it is converted into biofuels. This means that capturing the pure CO_2 stream from syngas will not result in any additional energy costs compared to a situation where CCS is not applied (besides compressing the CO_2).

Pre-combustion capture systems have a less energy intensive CO_2 separation process than post-combustion capture systems and also have consume less water than post-combustion systems. Although having lower energy requirements for the CO_2 separation process, the amount of energy lost this way is still significant (Theo *et al.*, 2016).

Pre-combustion capture systems are already well established in process industries and establishment of full-scale CCS plants is currently under progress (Theo *et al.,* 2016).

2.1.3 Oxy-Fuel Capture Systems

Oxy-fuel capture systems are systems that capture CO_2 by first conducting combustion in pure air instead of air. Oxygen gets separated from the other substances present in air before combustion. The largest advantage of this is that nitrogen, which affects separation processes and is a major heat sink, doesn't interfere in the process anymore ((Pires *et al.*, 2011), (Leung, Caramanna & Maroto-Valer, 2014)). The flue gases that are a result of the combustion with oxygen exist mainly of CO_2, water, particulates and SO_2. After removal of particulates and SO_2, the remaining gas exists for 80 – 98% of CO_2, depending on the fuel that has been used (Leung, Caramanna & Maroto-Valer, 2014).

The main advantages of using oxy-fuel capture systems are the low amount of pollutants that are emitted, the high CO_2 concentration in exhaust gases and its high compatibility with conventional steam cycles without large changes to the system (Theo *et al.,* 2016). Disadvantages are mainly the energy-intensiveness and high costs of oxygen separation and increased corrosion problems due to higher SO_2 concentrations in the flue gases ((Pires *et al.*, 2011), (Leung, Caramanna & Maroto-Valer, 2014), (Theo *et al.*, 2016)).
There currently aren't any full-scale oxy-fuel capture systems operational. They are limited to pilot-scale operations (Theo *et al.*, 2016).

Figure 2.1 summarizes the different capture systems schematically, leaving out only the possibilities of pre-combustion capture in ethanol and Fischer-Tropsch production (Pires *et al.*, 2011).

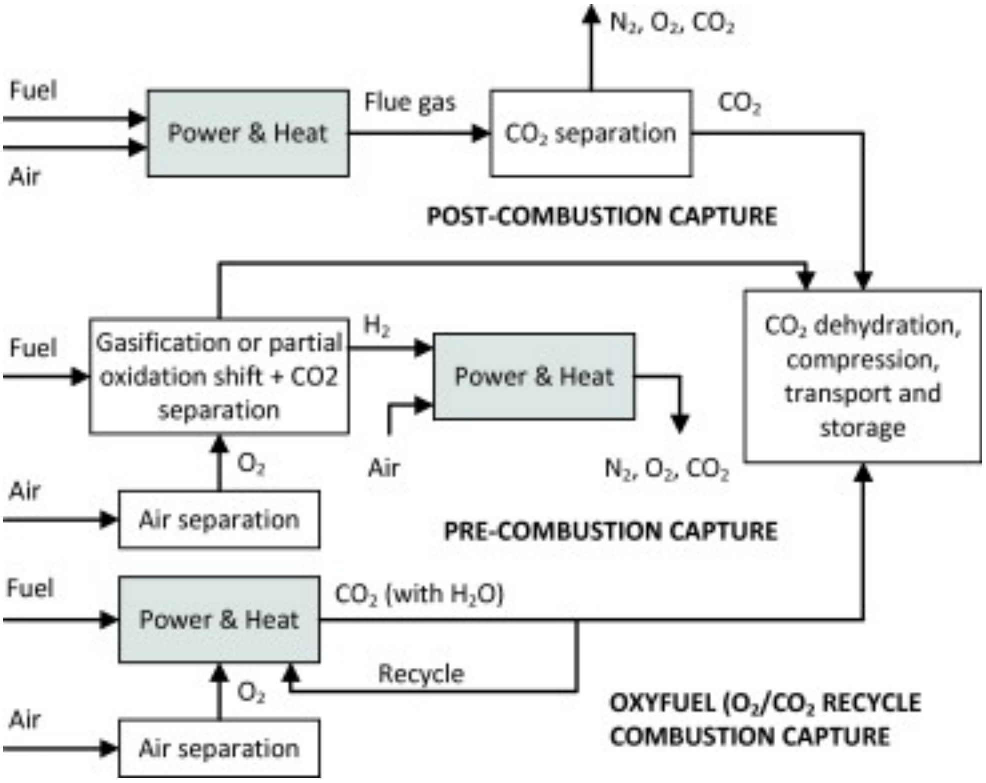


Figure 2.1 – A schematic representation of the different CO_2 capture systems (Pires *et al.*, 2011)

2.2 CO_2 Separation Technologies

The main principles of the three carbon capture technologies have been discussed above. But the actual separation of CO_2 from other substances in liquids or gases is performed by CO_2 separation technologies. When discussing the potential for BECCS, IEAGHG (2011) talks about four types of CO_2 separation techniques; absorption, adsorption, separation membranes and cryogenic distillation. Leung, Caramanna & Maroto-Valer (2014) bring forward two additional CO_2 separation technologies; chemical looping combustion and hydrate-based separation. All six technologies will be addressed below.

2.2.1 Absorption

Absorption is the process of letting flue gas pass through a liquid sorbent that will only absorb the CO_2, but let the other substances in the flue gas be. The mix of sorbent and CO_2 is then brought to an area where the desorption process (also known as stripping) can take place. Here the sorbent heated so that it can be compressed and transported to storage sites, while the sorbent (now free of CO_2) can be reused again in the absorption process.

There are two types of absorption. Physical and chemical absorption. Physical absorption focuses on absorbing CO_2 by making van der Waals or electrostatic bonds with it while chemical absorption focuses on absorbing CO_2 by making chemical bonds with the CO_2 molecules (Theo *et al.*, 2016). Figure 2.2 shows a schematic representation of applying absorption to separate CO_2.

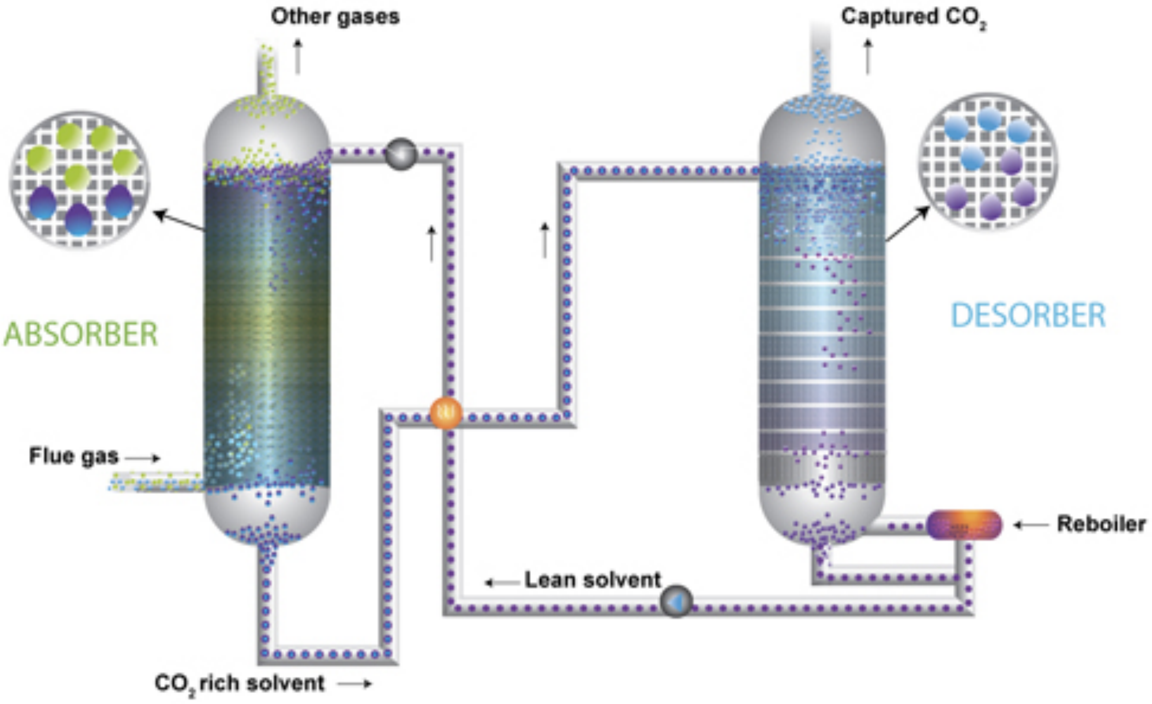


Figure 2.2 – A schematic representation of applying absorption the separate CO_2 from flue gases (CO2CRC, n.d.).

Sorbents that are most commonly used are monoethanolamine (MEA), diethanolamine (DEA) and potassium carbonate, with MEA having the highest absorption efficiency (Leung, Caramanna & Maroto-Valer, 2014). Piperazine is an amine that was discovered to react faster with CO_2, but is still under development since the use of piperazine is still more expensive than MEA ((Pires *et al.*, 2011), (Leung, Caramanna & Maroto-Valer, 2014)). Besides using amines as a sorbent it is also possible to use ammonium salts in a process called chilled ammonia process, which has energy advantages over amine sorbents due to lower temperatures in the desorption process (Leung, Caramanna & Maroto-Valer, 2014). Finally, calcium oxide can be used in a process called carbonation/calcination cycles and amino acid salt solutions can also be used as sorbent (Pirest *et al.,* 2011).

Advantages of applying absorption include absorption efficiencies that exceed 90%, the regeneration of sorbents, the maturity of the technology, and the reusability of sorbents

(Leung, Caramanna & Maroto-Valer, 2014). The disadvantages of absorption include the dependence of efficiency on the CO_2 concentration of the flue gas, corrosion problems, energy intensive desorption process, the loss of sorbent due to evaporation, sorbent degradation in oxygen rich atmospheres, and the human and environmental hazards that sorbents can prove to be ((Pires *et al.*, 2011), (Leung, Caramanna & Maroto-Valer, 2014)).

2.2.2 Adsorption

Adsorption is the process of letting gaseous or liquid mixtures pass by a solid sorbent which is able to bind only the CO_2 in the gaseous or liquid mixtures to its surface. Just as with absorption, the sorbent and CO_2 can be separated from one another by increasing the temperature or decreasing the pressure in a reactor that is meant for desorption. Depending on the method used to separate the CO_2 from the sorbent, the adsorption process can either be categorized under pressure swing adsorption (PSA) or temperature swing adsorption (TSA).

Common sorbents for adsorption are carbon molecular sieves, zeolites, activated carbon, hydrotalcities, lithium zirconate, calcium oxide, solid amine sorbents, and metal-organic framework materials (MOF) ((Leung, Caramanna & Maroto-Valer, 2014), (Theo *et al.*, 2016)).

A major drawback of TSA is the time it takes to regenerate the sorbent. The regeneration time can take hours for TSA, while PSA merely needs a few seconds (Pires *et al.*, 2011). Nevertheless, TSA is preferred in situations where the CO_2 concentration is low (Theo *et al.,* 2016). Further disadvantages of adsorption include high energy required for the desorption process (although they are lower than for absorption) and the high energy penalty for PSA due to the pressurization of CO_2 (Pires *et al.*, 2011). Advantages include capture efficiencies exceeding 85% (PSA), and the reusability of sorbents (Leung, Caramanna & Maroto-Valer, 2014). Another advantage is that during the water-gas-shift reaction the conversion of carbon monoxide increases from 55% to 100% when an adsorbent is present (Leung, Caramanna & Maroto-Valer, 2014).

2.2.3 Separation Membranes

Separation membranes are membranes that can be used to separate gases through making use of a membrane that selectively lets certain gases pass through while blocking others. This doesn't necessarily only have to be for separating CO_2 from flue gases, but could, for example, also be applied in oxy-fuel combustion to separate O_2 from the N_2 in air (Leung, Caramanna & Maroto-Valer 2014). There are two ways separation membranes can be applied. The first is letting either flue gas or the products of the water-gas-shift reaction pas past the membranes once. However, it's also possible to let the separated gas pass past a second membrane, aiming to make the captured CO_2 purer (Aaron & Tsouris, 2005). This set up is, however, also twice as expensive. Two-stage separation is shown in figure 2.3.

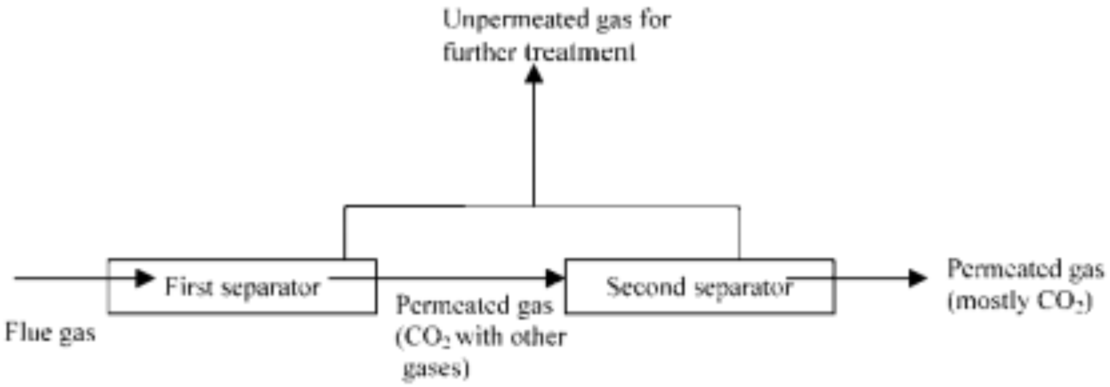


Figure 2.3 – A schematic representation of a two-stage separator using separation membranes (Aaron & Tsouris, 2005)

Membranes that can be used are ceramic membranes, metallic membranes, and polymeric membranes ((Aaron & Tsouris, 2005), (Brunetti *et al.*, 2010)). Polymeric membranes are the most popular separation membranes of the three (Yang *et al.*, 2008).

Advantages of using separation membranes to separate CO_2 include low costs, separation efficiencies exceeding 80%, simplicity of the equipment, and no use of sorbents (which might have a slight environmental impact due to its use) ((Pires *et al.*, 2011), (Leung, Caramanna & Maroto-Valer, 2014), (Brunetti *et al.*, 2010), (Theo *et al.*, 2016)). A major disadvantage of membranes is the trade-off it has between permeability and selectivity. Selective membranes aren't very permeable, and permeable membranes let other gases besides CO_2 pass through them ((Aaron & Tsouris, 2005), (Brunetti *et al.*, 2010)). Other disadvantages are cooling the gases to protect membranes, membranes should be able to resist the possible chemicals in flue gases (or chemicals should be removed before letting flue gases pass the separation membranes), and relatively high energy penalties associated with gaining a higher purity of CO_2 capture ((Pires *et al.*, 2011), (Theo *et al.*, 2016), (Yang *et al.*, 2008)).

2.2.4 Cryogenic Distillation

Cryogenic distillation is a process that makes use of the different boiling points of the substances that are present in the gas that is fed in. The temperature of flue gas is brought down to -100 – -135 °C and the pressure is increased to liquefy the gaseous CO_2 (Leung, Caramanna & Maroto-Valer, 2014). After this has been done, the liquefied CO_2 can be quite easily separated from the other gases.

Cryogenic distillation has several advantages. It avoids the use of large amounts of water, the chemical agents that can be expensive, corrosion problems, and pollution issues that accompany the use of sorbents, while having a carbon capture efficiency of 90 – 95% and being a technology that has already been used for quite some time in the industry to collect CO_2 for other processes ((Leung, Caramanna & Maroto-Valer, 2014), (Theo *et al.*, 2016)). However, the use of cryogenic distillation also has some significant disadvantages. Due to the low temperatures and high pressure, cryogenic distillation is an energy intensive process which will result in lower plant efficiencies and higher operational costs (Theo *et al.*, 2016). Additionally, ice formation can cause blockages of the piping system and pressure drops in the equipment, while frost can accumulate on the heat exchanger, decreasing its efficiency (Theo *et al.*, 2016). Thus, the level of moisture should be decreased prior to the cryogenic distillation process, resulting in an even more energy intensive and expensive process. Finally, cryogenic distillation can only be applied if concentration of the CO2 in the mixture gas has a concentration that exceeds 90% ((Leung, Caramanna & Maroto-Valer, 2014), (Theo *et al.,* 2016)).

2.2.5 Chemical Looping Combustion

Chemical looping combustion is a process that is nearly identical to oxy-fuel combustion systems. The main idea is that either biomass or fossil fuels are oxidized by pure oxygen instead of air. Air enters a reactor and oxidizes a metal. The metal oxide is then brought to an other reactor, where the oxygen can be used for the combustion of biomass or any other fossil fuel, leading to high concentrations of CO_2 in the exhaust gas. This process is shown schematically in figure 2.4.

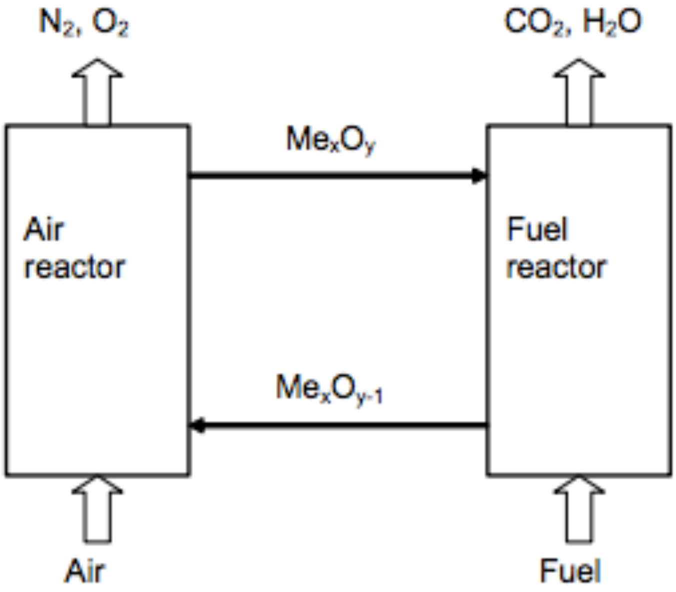


Figure 2.4 – A schematic representation of chemical looping combustion (Lyngfelt & Leckner, 2015)

Metals that can be used for chemical looping combustion are nickel (Ni), copper (Cu), iron (Fe), manganese (Mn), cobalt (Co) and some mixed oxide metals such as Fe-Mn-mixed oxides, Ni-Mn-mixed oxides, and Fe-Ni-mixed oxides (Adanez *et al.*, 2012).

The advantages of using chemical looping combustion include the high concentration of CO_2 in the exhaust gas and reaching CO_2 capture efficiencies of 98% (Lyngfelt & Leckner, 2015). The disadvantage of the technology is that it is still under development and hasn't been proven to be effective in an operational plant (Leung, Caramanna & Maroto-Valer, 2014).

2.2.6 Hydrate-Based Separation

Hydrates-based separation is a process that focuses on the ability of substances to form hydrates in different environments. The flue gases are exposed to water under high pressure. CO_2 can form hydrates easier than gases such as N_2 in such circumstances, making the process a good method to capture CO_2 from other gases (Leung, Caramanna & Maroto-

Valer, 2014). Using additive mixtures as tetrahydrofuran (THF) helps the hydrate-based separation process by letting hydrates form easier at lower temperatures (Zhang *et al.*, 2014).

Advantages of hydrate-based separation include small energy penalties (6 – 8%), an energy consumption that can be as low as just 0.57 kWh/kg-CO_2, and no use of sorbents that might have slight environmental impact (Leung, Caramanna & Maroto-Valer, 2014). A disadvantage is that the technology is novel and requires more research to become applicable (Leung, Caramanna & Maroto-Valer, 2014).

2.3 Capture Efficiencies and Energy Costs

This paragraph will look into the capture efficiencies and (energy) costs of using different capture and separation technologies. However, not all of the previously discussed technologies will be included in this analysis. From the three main carbon capture technologies, only post-combustion capture systems and pre-combustion capture system will be taken into account in the continuation of this research. The reason for this choice is the diffusion of oxy-fuel combustion capture systems. While post- and pre-combustion capture systems are already established at full scale or nearly at full-scale, oxy-fuel combustion capture systems are limited to pilot studies. The main (economic) barrier is the oxygen separation process, which makes the whole system both expensive and energy intensive. Gas separation techniques are already pretty mature technologies, making it unlikely that their degree of energy and cost reductions are at the same scale as newer technologies. Thus it is assumed that the use of post- and pre-combustion capture systems will be much more used in the future as a CCS technology than oxy-fuel combustion capture systems.

A good step before looking at the capture efficiency and costs of separation is categorizing separation technologies into the capture technologies in which they are used. IEAGHG (2011) gives a division for absorption, membranes, adsorption and cryogenic distillation. Post-combustion capture systems make use of absorption, adsorption, and separation membranes. The same applies to pre-combustion capture systems. Only oxy-fuel combustion capture systems make use of cryogenic distillation according to IEAGHG (2011). Also APEC (2012) states the use of absorption, adsorption, and separation membranes for post- and pre-combustion capture systems. Cuéllar-Franca & Azapagic (2015) mention only the use of absorption and adsorption in the case of pre-combustion capture systems, while assigning absorption, adsorption and separation membranes to post-combustion capture system. The reason for this categorization isn’t explained in the article. Thus it still will be assumed that absorption, adsorption and membrane separation are techniques useable for both post- and pre-combustion capture systems.

APEC (2012) also mentions cryogenic distillation under post-combustion capture systems, but emphasizes that cryogenic distillation needs a supply that has a pure concentration of CO_2 that exceeds 90%. Since it was already established that post-combustion capture systems generally have to capture CO_2 from flue gases that have a CO_2 concentration that is well below 20%, and pre-combustion systems that capture CO_2 from concentrations far below 90%, it can be safely assumed that cryogenic distillation is not a process that is applicable in post- and pre-combustion systems.

In theory, chemical looping combustion seems as a very promising technology with a high CO_2 capture efficiency. However, due to the fact that test mainly have been performed in small research pilots and modelling, this separation technology will not be further considered in this research ((Lyngfelt, 2014), (Lyngfelt & Leckner, 2015)).

Hydrate-based CO_2 separation also shows a lot of potential with its low energy penalty for power plants and low energy consumption. However, the technology is really immature and still needs more research to optimize the technology to become fully operation and commercialized ((Leung, Caramanna & Maroto-Valer, 2014), (Dashti, Yew & Lou, 2015), (Babu *et al.*, 2015)).

Thus the separation technologies that will be considered in this research are absorption, adsorption, and separation membranes.

Although the technologies that were discussed under “Carbon Capture Technologies” and “CO_2 Separation Technologies” have carbon capture/separation efficiencies that lie close to one another, there are still differences. The literature seems to more or less agree towards most separation efficiencies of several of the CO_2 separation technologies. Brunetti *et al.* (2010) reports CO_2 recovery rates of 80 – 95% for absorption and 60 – 80% for membrane separation. Leung, Caramanna & Maroto-Valer (2014) report separation yields of >90% for absorption, 80% for TSA, 85% for PSA, and 82 – 88% for membrane separation. Theo *et al.* (2016) reports separation yields of 90 – 98% for (physical) absorption, 80 – 95% for adsorption, and 80 – 90% for membrane technology. Brunetti *et al.* (2010) and Theo *et al.* (2016) also report on the energy requirements of these separation technologies. These numbers are shown in appendix 2.1.

There are some papers that connect post- and pre-combustion capture systems with capture efficiencies without specifying the exact separation technologies used in the system. The values of capture efficiencies for both CO_2 capture systems range between 85 and 90%, but most agree on 90% ((IEAGHG, 2007), (IEAGHG, 2009), (Congressional Research Service, 2010)). This is similar to the CO_2 separation efficiencies from absorption, adsorption and membrane separation.

Instead of talking about energy requirements it’s also possible to look at the efficiency penalty that accompany the use of CCS. Efficiency penalties simply are the reduction in plant efficiency due to the energy requirements of CCS. Reports on efficiency penalties range from 6% to 15.9% ((IEAGHG, 2009), (Congressional Research Service, 2010), (Goto, Yogo & Higashii, 2013), (Leung, Caramanna & Maroto-Valer, 2014)). For this research the energy requirements of the separation technologies will be used to calculate the lower energy output instead of the energy penalties.

IEAGHG (2011) built a scenario in which the CCS capture efficiency of post- and pre-combustion capture systems have a 90% capture efficiency in 2030 and a 95% efficiency in 2050. For this research the assumption is made that the generally used technology will be slightly better then the current highest efficiencies of the separation technologies, gradually increasing from now until 2050. Only for absorption it will be assumed that it won’t exceed its current state of the art efficiency values in 2050. IEAGHG (2011) states that when advanced bio-ethanol production is applied, approximately 11 – 13% of the total CO_2 can be captured. For the years 2030 and 2050 IEAGHG (2011) uses the values 11% and 13% capture efficiency respectively. These will also be used in this research. For the current capture efficiency, a value of 11% (thus the same as 2030) will be used. Larson *et al.* (2010) found that 51.4 – 53.6%

of the CO_2 that accompany the production of biodiesel from the Fischer Tropsch process can be captured. IEAGHG (2011) use capture efficiencies of 54% in their scenarios for both the years 2030 and 2050. These values will be used for this research. The current capture efficiency will be the exact middle of the range found by Larson *et al.* (2010). Markewitz & Bongartz (2015) state that currently adsorption and absorption is used for capturing the CO_2 during biogas upgrading treatment, but that there are alternatives such as membrane separation that are interesting for the future. Thus it is expected that currently and until 2030 adsorption will be used to capture the CO_2 in biogas upgrading treatment, but in 2050 this will have shifted to membrane separation. The CH_4 mass content in biogas is between 45 and 70%, while the CO_2 mass content in biogas is between 25 and 55% (Markewitz & Bongartz). It will be assumed that on average the content of CH_4 will be 57.5%, while the content of CO_2 will be 40%. This means that, based on weight, the ratio CH_4/CO_2 will be approximately 1.438. But to clearly analyze the amount of CO_2 that might be captured from biogas upgrading, the molar mass should be taken into account. For CH_4 this is 16.04 g/mol, while for CO_2 it is 44.01 g/mol. So the weight of 1 mol of CO_2 equals the weight of 44.01/16.04 = 2.744 mol of CH_4. So in biogas there will be on average $1.438 \times 2.744 \approx 3.95$ more CH_4 molecules than CO_2 molecules. If 100% combustion of CH_4 can be expected, approximately 20% of the CO_2 that will be eventually be emitted by the biomass/biofuel is present in its own form in the biogas. If adsorption capture is assumed for 2015, 2030 and 2050, the capture efficiencies will be approximately 17%, 18%, and 19% in 2015, 2030, and 2050 respectively. The assumed current efficiencies, efficiencies in 2030 and efficiencies in 2050 are shown in table 2.1. It is assumed that between 2015 and 2030, and between 2030 and 2050 the increase is linear.

Table 2.1 – CO_2 separation efficiencies in 2015, 2030 and 2050

Separation Technology/Biofuel	CO_2 Capture Efficiencies		
	2015	2030	2050
Absorption	93%	95%	98%
Adsorption	87%	91%	94%
Membrane Separation	85%	88%	91%
Bio-ethanol	11%	11%	13%
Biodiesel	52.5%	54%	54%
Green Gas	17%	18%	19%

Figure 2.5 was taken from Theo *et al.* (2016) and shows how much scientific attention the separation technologies have received in terms of published papers (it should be noted that this is focused on the separation technologies for pre-combustion capture systems). Here it is clearly visible that adsorption and separation membranes have received more attention than absorption in the past few years. Theo *et al.* (2016) explain the low interest in absorption due to the maturity of the technology. Taking into consideration that absorption also has higher energy requirements for its application, it is expected that eventually adsorption and separation membranes will be much more used than absorption is used (despite the higher separation efficiency). The exact division of how much CO_2 is captured by absorption,

adsorption, and membrane separation in 2015, 2030, and 2050 is shown in appendix 2.1. The energy requirements of absorption, adsorption, and membrane separation in 2015, 2030, and 2050 are shown in table 2.2. The periods between 2015 and 2030, and 2030 and 2050 are expected to increase in a linear fashion. Although the separation efficiencies of biofuels and green gas are lower than regularly is the case with pre-combustion capture, they are captured using the pre-combustion capture method. It is assumed that the division of CO_2 captured by these application is equal to those in appendix 2.2.

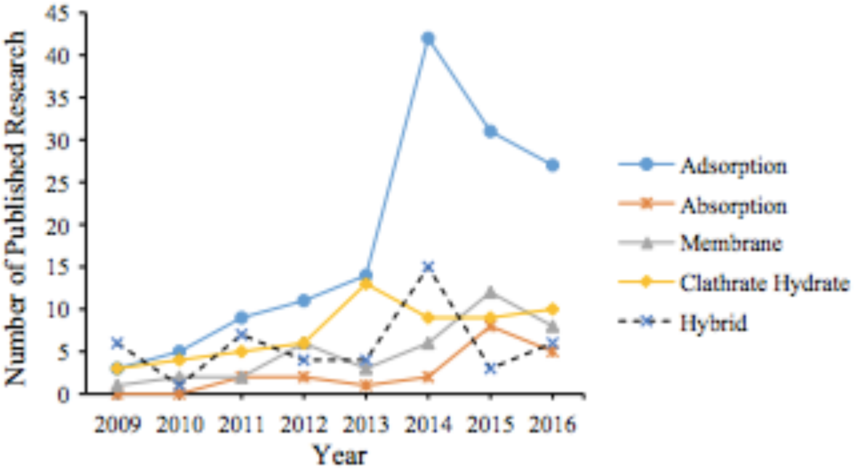


Figure 2.5 – Amount of published papers concerning separation technologies in the past years (Theo *et al.*, 2016)

Table 2.2 – Energy requirements for absorption, adsorption, and membrane separation in 2015, 2030, and 2050 (data used from Theo *et al.* (2016))

Year	Energy Requirements (MJ/kg CO_2)		
	Absorption	Adsorption	Membrane Separation
2015	5	2.5	3
2030	4.5	2	2
2050	4	1.5	0.5

In most cases, CO_2 is compressed to supercritical phase before transport, making it easier to transport through pipes. For CO_2 this is reached above 31.1 °C and 74 bar, but because of long pipe lengths (where pressure can drop easily) and impurities that are present at relatively high levels, the pressure is generally kept between 85 and 210 bar (Boot-Handford *et al.,* 2014). APEC (2012) talks about industry preference of pressures in pipelines greater than 10.3 MPa at the inlet, which equals 103 bar. Goto, Yogo & Higashii (2013) analyzed 27 different researches and the pressures they used as target pressure for CO_2 compression. The pressures ranged from 100 bar to 200 bar, with the majority being close to 100 bar. The most studies used 110 bar as a target pressure. Since 110 bar seems to be within agreement of the above mentioned articles, 110 bar will also be the target CO_2 pressure for this research.

Eva Fernandez (2013) found that, generally, before CO_2 separation the flue gas has a pressure of 1.01 bar and the syn-gas has a pressure of 38 bar for post-combustion capture systems and pre-combustion capture systems respectively. It is assumed that the pressure of CO_2 after separation in the case of post-combustion capture systems will be (or rather remain) 1 bar. In the case of pre-combustion, however, it is expected that the pressure will drop to a lower level than 38 bar after separation. Using a simulation, Erlach, Schmidt & Tsatsaronis (2011) found, while programming the use of an integrated gasification combined cycle (IGCC) plant with pre-combustion capture system and chemical looping, three different pressures just before the CO_2 entered the compression stage: 30% at 23 bar, 25% at 9 bar, and 45% at 3 bar. When all the CO_2 comes together, the gas will find an equilibrium at 10.5 bar. This will be the assumed pressure of CO_2 before it is compressed in a pre-combustion capture system.

Approximately 0.34 MJ/kg CO_2 is needed for the compression of CO_2 at atmospheric pressure to 110 bar (Bolland & Undrum, 2003). The graph provided by Bolland & Undrum (2003) only provides the compression work needed to compress CO_2 at atmospheric pressure to pressure ranging between 50 bar and 150 bar. However, using 3 points in the graph (0.285 MJ/kg CO_2 at 50 bar, 0.34 MJ/kg CO_2 at 110 bar, and 0.36 MJ/kg CO_2 at 150 bar) in excel and using a power trend line gives the equation

$$CW = 0.1232\, p^{0.2148} \qquad (1)$$

where CW is the compression work in MJ/kg CO_2 and p is the pressure in bar. Using this equation, it is possible to get an approximate number for the work needed to compress CO_2 to 10.5 bar. This is approximately 0.20 MJ/kg CO_2. Thus the work needed to compress CO_2 from 10.5 bar to 110 bar equals 0.34 – 0.20 = 0.14 MJ/kg CO_2.

Fermentation takes place at atmospheric pressure (America's Energy Future Panel on Alternative Liquid Transportation Fuels, 2009), thus the CO_2 from the production of bio-ethanol will consume approximately 0.34 MJ/kg CO_2 for compression of CO_2. It is also assumed that the pure stream of CO_2 originating from the production of syn-gas (in the situation of FT-biodiesel production) will reach a pressure of 10.5 bar during the cleaning process, which means that the energy consumption of compression of this CO_2 will be approximately 0.14 MJ/kg CO_2. In a study by ECN (2016), a pressure of 40 bars for coal gasification was used for the production of hydrogen. This will also be assumed in this study. According to the equation resulting from Bolland & Undrum (2003), this requires 0.08 MJ of energy per kg of CO_2 that needs to be compressed. CO_2 capture from biogas upgrading to green gas can occur through pre-combustion processes such as the adsorption (Petersson & Wellinger, 2009). Thus it is assumed that the captured CO_2 will be at the same pressure as normally is the case with pre-combustion processes, and will also cost the same amount of energy to compress to 110 bar.

Table 2.3 shows all the assumptions concerning the compression of CO_2 from different capture systems/biofuel.

Table 2.3 – Pressure before compression, desired level of pressure and energy requirements for the compression of CO_2 (calculated with help of Bolland & Undrum, 2003)

Capture System/Biofuel	Pressure Before Compression (bar)	Pressure After Compression (bar)	Energy Requirement (MJ/kg CO_2)
Post-Combustion	1	110	0.34
Pre-Combustion	10.5		0.14
Bio-Ethanol	1		0.34
FT-Biodiesel	10.5		0.14
Hydrogen	40		0.08
Green Gas	10.5		0.14

2.4 Carbon Transport

After being compressed, the CO_2 is transported to the storage site. There are several possibilities for this. Using pipelines is the most favored way of transport, followed by shipping, which mainly gets used when the CO_2 needs to be transported over very large distances ((Boot-Handford *et al.,* 2014), (Pires *et al.*, 2011)). Via rail or truck is also possible, but this is generally less favorable for the transport of large amounts of CO_2.

As previously mentioned, the CO_2 is transported in supercritical phase because of the ease of transporting CO_2 in this phase. This is done by increasing the pressure to values between 85 and 210 bar. With +6,000 kilometers of CO_2 pipes in the United States and experience with transport through off-shore pipes in places such as Snøhvit and Sleipner (both connected to Norway), transport of CO_2 is the most technically mature stage within CCS (IEA, 2013).
Although the transport of CO_2 through pipes seems as a currently well established process, it isn’t without any (potential) problems. One of the largest problems of CO_2 transport is corrosion of the transportation pipes. In the presence of water, CO_2 can dissolve and be converted into carbonic acid. Carbonic acid is very corrosive to carbon steel, which is typically used for the construction of existing CO_2 transport pipelines (Boot-Handford, 2014). This is why it is important to make sure that the water content in the CO_2 stream to be transported. De Visser *et al*. (2008) reports that keeping the water content beneath 500 ppm is safe enough for the transport of CO_2. Impurities might also have effects on the rate of corrosion (Boot-Handford, 2014). Because of the corrosive properties of water and different impurities and the health and safety issues that accompany certain impurities (which might become harmful in case of a blow-out), de Visser *et al*. (2008) made recommendations to assure high quality CO_2 transport. This is visible in appendix 2.3.

Other problems associated with the transport of CO_2 through pipelines are the formation of gas hydrates and ice (Boot-Handford, 2014). Because of the formation of gas hydrates and ice, it’s possible that obstruction of the pipelines occurs. The formation of gas hydrates can be avoided by lowering the water content to below 250 ppm (Boot-Handford).

2.5 Carbon Storage

Finally, the CO_2 needs to be stored. This is done underground, and generally happens in depleted oil and gas reservoirs, saline formations, and coal beds (Benson & Friedmann, 2014). It’s also possible to store CO_2 in oil, gas or methane fields that aren’t fully depleted yet as to enhance the recovery of these raw materials. Figure 2.6 shows all the possible storage alternatives.

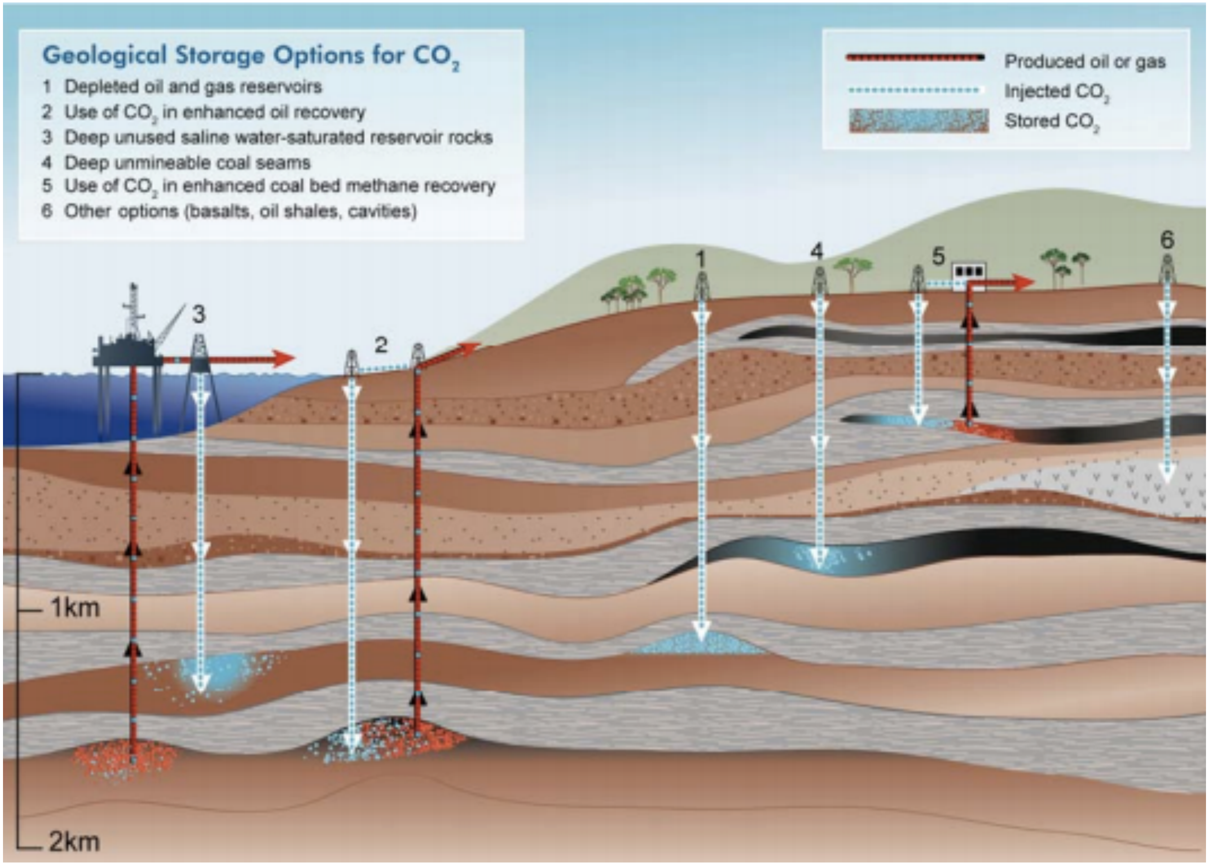


Figure 2.6 – The different alternatives for storing CO_2 (APEC, 2012)

Boot-Handford *et al.* (2014) describes four mechanisms through which the CO_2 remains trapped. The first is physical trapping. In this case, the CO_2 just remains trapped underground and can't escape upwards to ground levels. The second is dissolution trapping. Here, the CO_2 dissolves in the brine and then sinks through the storage aquifer. The third is mineral trapping. When this mechanism is applied, the CO_2 reacts with the host rock. This will result in the formation of carbonate. Finally, there is capillary trapping. In this case the CO_2 at the edges of the stored amount are trapped as pore-space bubbles.

There are some conditions to which the storage sites must comply to be regarded as a good storage site. These are a high enough porosity and thickness, which determines storage capacity, high enough permeability, which determines how easy the CO_2 can be injected, a sealing rock that will let no CO_2 rise back to ground levels, and a geological environment that is stable and won't easily form cracks through which the CO_2 can escape (Pires *et al.,* 2011).

Although capturing, transporting and storing CO_2 deep into the ground forms the largest part of the process, it doesn't mean the end of the matter. After injection it is important to keep monitoring the storage site. Research beforehand must make sure that the site is a safe storage site. However, due to unforeseen circumstances or human errors, stored CO_2 still might seep back to ground levels and up into the atmosphere. Through monitoring these cases should be recognized and rectified in an early stage, aiming to prevent atmospheric CO_2 levels to start rising again.

3 The Current Use of CCS in the Netherlands

Obviously, the potential of BECCS is largely dependent on the appliance and infrastructure of CCS in a country. This section looks into how diffused CCS currently is in the Netherlands, since a good understanding of the starting point is of importance. The next section will look into the possible development of a better (integrated) infrastructure for CCS.

The Netherlands had nearly realized the implementation of several onshore CCS storage demonstration projects between 2000 and 2010, including projects at Barendrecht, Geleen and several places in the northern part of the Netherlands ((CATO2, 2014), (IEAGHG, 2014)). In 2006 there were several pilot and demonstration projects for carbon capture and/or storage in development in the Netherlands such as CATO Catcher, Zero Emission Power Plant, the Buggenum power plant, CRUST (which focused on the continuation and expansion of the K12-B project), and the de Lier project (CATO3, 2015). However, due to public resistance and the falling of the then installed government, the (new) government chose to cancel all on-shore demonstration projects. The focus now has been put on storing CO_2 offshore. As the Dutch government states on its site (in Dutch) "*The government doesn't have any plans for onshore CO_2 storage (yet). There is sufficient capacity under the sea.*" (RVO, n.d.a).

Current CCS projects under operation or preparing for operation are the K12-B project and the Rotterdam Opslag en Afvang Demonstratieproject (ROAD). Besides these projects there's the use of carbon capture and utilization (CCU). This is performed by the company OCAP, which stands for Organic Carbondioxide for Assimilation of Plants, which transports captured CO_2 to greenhouses for the cultivation of plants. Although OCAP doesn't perform CCS, there are possibilities to connect their business to the (temporary) storage of CO_2 (TNO, 2015). Additionally, OCAP does have experience with the transport of CO_2 through pipes. Finally, OCAP was also involved with the Barendrecht CCS project before it was cancelled (OCAP, n.d. a), which indicates that OCAP could be an important partner regarding CCS in the future.

3.1 K12-B Project

The K12-B project is a project where the CO_2 from a natural gas field in the North Sea is directly re-injected back into the same reservoir from where it came (IEAGHG, 2014). The CO_2 is thus used for Enhanced Gas Recovery (EGR). Production of natural gas has been ongoing since 1987. The reinjection of CCS started in 2004 through a collaboration between Dutch Ministry of Economic affairs, TNO, and GDF Suez (now Engie) (GDF Suez, 2010). The stream of natural gas that is pumped up has a CO_2 content of 13% (TNO, 2007), and the depth of the storage site is at approximately 4,000-meter depth. The cumulative amount of CO_2 injected is somewhere between 90 and 100 kilotons (Global CCS Institute, 2015) and the injection site has an average injection rate that can reach up to approximately 20 kilotons of CO_2 per year (CATO3, 2015). Figure 3.1 shows the location of the K12-B project.

Figure 3.1 – The location of the K12-B project

3.2 ROAD

ROAD is a project that was set up by E.ON Benelux (now Uniper Benelux) and GDF Suez (now Engie) in 2009 ((Zero Emission Resource Organisation, n.d.), (CATO3, 2015)). The goal of the project is to capture 1.1 megatons of CO_2 annually from a 1,070 MW_e coal-fired power plant built by Uniper in 2008 using amine absorption in a post-combustion capture system (Global CCS Institute, n.d.). Initially it was the plan for ROAD to store CO_2 in an empty gas field called P18, which lies 20 kilometers from the coast, at a depth of approximately 3,500 meters, and with a capacity of about 35 megatons of CO_2 (Road CCS, 2015). However, due to financial problems, the new plans are to store in a gas field called Q16 Maas, which is still producing natural gas (CE Delft, 2016a). This means that ROAD also will be used for EGR. Q16 Maas is approximately 3.5 kilometers offshore, about 3,000 meters deep, and has the capacity to store between 2 and 4 megatons CO_2 ((Road CCS, 2016), (Global CCS Institute, n.d.)).

3.3 OCAP

OCAP is a company that delivers around 400 kilotons of CO_2 to some 580 greenhouses between Rotterdam, The Hague and Amsterdam (OCAP, n.d. b). OCAP has two sources from which it receives its CO_2. The first is from a hydrogen production plant that is located in Pernis and owned by Shell, while the second source is from a bioethanol production plant owned by Abengoa Bioenergy (TNO, 2015). Transport of CO_2 happens through pipe that is about 85 kilometers (OCAP, n.d. c). Figure 3.2 shows the current infrastructure of the source, pipes and greenhouses that receive the CO_2, as well as the planned expansion of pipes, greenhouses to deliver CO_2 to and also storage sites for CO_2.

Figure 3.2 – The current and planned expansion of OCAP's suppliers of CO_2, pipe infrastructure, greenhouses receiving CO_2, and areas for CO_2 storage (OCAP, n.d. b).

During the summer period (April to September) the demand for CO_2 is larger than the supply. Conversely, during winter periods the supply of CO_2 is larger than the demand (TNO, 2015). TNO (2015) looked into the possibility of off-setting this misbalance by temporarily injecting CO_2 into a CO_2 storage site. Using a buffer near the Maasvlakte could increase the supply of CO2 to greenhouses from 400 kilotons to 900 kilotons per year (Global CCS Institute, n.d.). Although TNO (2015) concluded that the connection of OCAP to ROAD for temporary CO_2 storage is not technically or financially feasible on the short term, TNO states that the temporary storage of CO_2 in CO_2 storage sites might be feasible in other expended gas field in the Netherlands.

It can be concluded that the use of CCS within the Netherlands is at a low level. The K12-B project has been ongoing for approximately 13 years, but the amount of CO_2 captured and stored is low. All the other projects were either cancelled or haven't even started. This means that the implementation of BECCS still has a long way to go before it can be realized.

4 Capacity of Storage Sites for CCS in the Netherlands

This section will look into the capacity of the storage sites that the Netherlands possesses to store CO_2 in. To do this, the techno-economic resource-reserve pyramid for CO_2 storage concept developed by the Carbon Sequestration Leadership Forum (CSLF) in CSLF (2007) will be used. A schematic representation of the pyramid can be seen in figure 4.1.

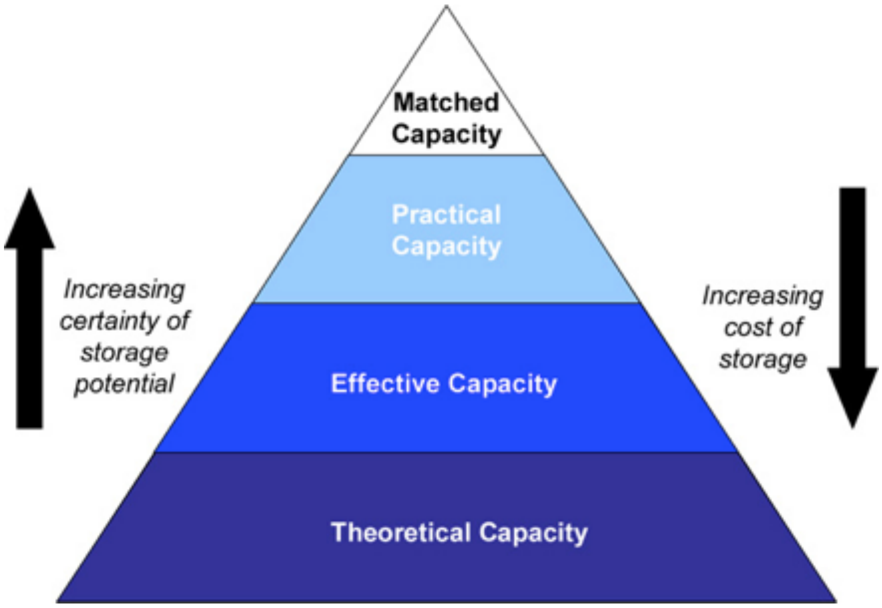


Figure 4.1: CSLF’s techno-economic resource-reserve pyramid for CO_2 storage as depicted by IEAGHG (2009a)

There are 4 layers on which the capacity of storage sites can be based; theoretical, effective, practical, and matched capacity. The theoretical capacity encompasses the whole pyramid and focuses on the full physical capacity of the storage sites. The effective capacity is sets certain geological and technical limits to the storage site(s), excluding all the sites that do not seem to be practical for CO_2 storage due to, for example, having a storage capacity that is too low or a level of injectivity that is too low. The practical capacity is an even smaller part of the pyramid that takes into account barriers existent due to legal and regulatory issues, infrastructure and general economics. Finally, the matched capacity focusses on the capacity that can be used when the storage sites are matched with large stationary CO_2 sources. The difference with the practical capacity is that there is a certain amount of capacity that cannot be filled due to lack of infrastructure and/or CO_2 sources (CSLF, 2007).

For this section it is aimed to investigate the effective capacity of storage sites for CO_2 in the Netherlands.

4.1 Off-Shore Storage Capacity

The Netherlands Oil and Gas Exploration and Production Association (NOGEPA) and the Dutch Ministry of Economic Affairs had DHV and TNO write a report on the potential capacity for CO_2 storage in depleted gas fields on the Dutch continental shelf, resulting in NOGEPA (2008). The reason the report only looks at gas fields and neglects oil reservoirs is, as is stated in the report: “*the available storage capacity* [of oil reservoirs] *is much smaller than that in gas reservoirs* […] *Moreover oil reservoirs tend to be produced with more wells than gas reservoirs which eventually increase the risk of leakage at well bores*” (NOGEPA, 2008) p. 16.

The report found a theoretical storage capacity of 1,566 megatons CO_2 in 153 gas fields throughout the Dutch continental shelf. However, if fields that have a permeability-thickness doesn't exceed 0.25 Dm (Dm stands for Darcy meter, 1 Dm = $9.87 \cdot 10^{-13}$ m^3), which is seen as the cut-off limit for flow of gases in rocks due to the internal resistance, are excluded together with fields that have too little storage capacity, defined as fields with capacities between 0 and 2.5 megatons CO_2, and gas fields that have been abandoned, the study finds an effective storage capacity of 918 megatons of CO_2 in only 55 gas fields. Figure 4.2 shows the location of the wells and the effective storage capacity of certain areas of gas fields according to NOGEPA (2008).

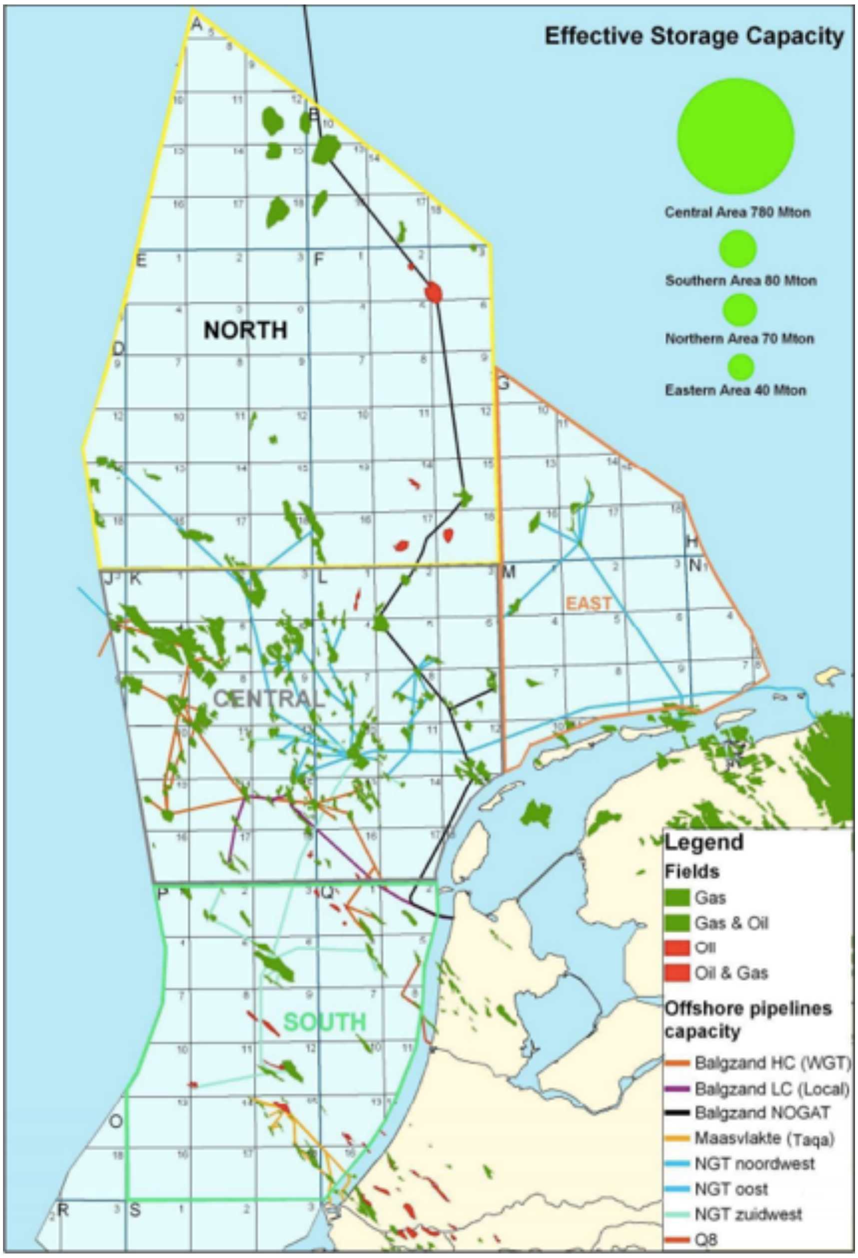


Figure 4.2: Map showing gas fields in the Dutch continental shelf that can be used for storage of CO_2 and the effective storage capacity of certain areas of the Dutch continental shelf

Energie beheer Nederland (EBN) and Gasunie published an advice report that was commissioned by the Dutch Ministry of Economic Affairs concerning a strategy for CCS called "*CO_2 transport- en opslagstrategie*" (EBN, 2010). The report makes a division between storage in the western part of the Netherlands and storage in the northern part of the Netherlands. The western category takes into account all off-shore storage on the Dutch continental shelf. According to the report, the total storage capacity of off-shore gas- and oilfields amounts to 1,160 megatons of CO_2. Figure 4.3 shows the gradual increase of the off-shore storage capacity according to EBN (2010). The report assumes that the gas- and oil-field clusters only become available when the last field of a cluster reaches its End of Field Life (EOFL). Thus EOR and EGR haven't been included. This is taken into account in figure 4.3. From the figure it becomes apparent that there will be a large availability of empty gas- and oil-fields in the near future. In 2027 already more than half of the effective storage capacity will be available.

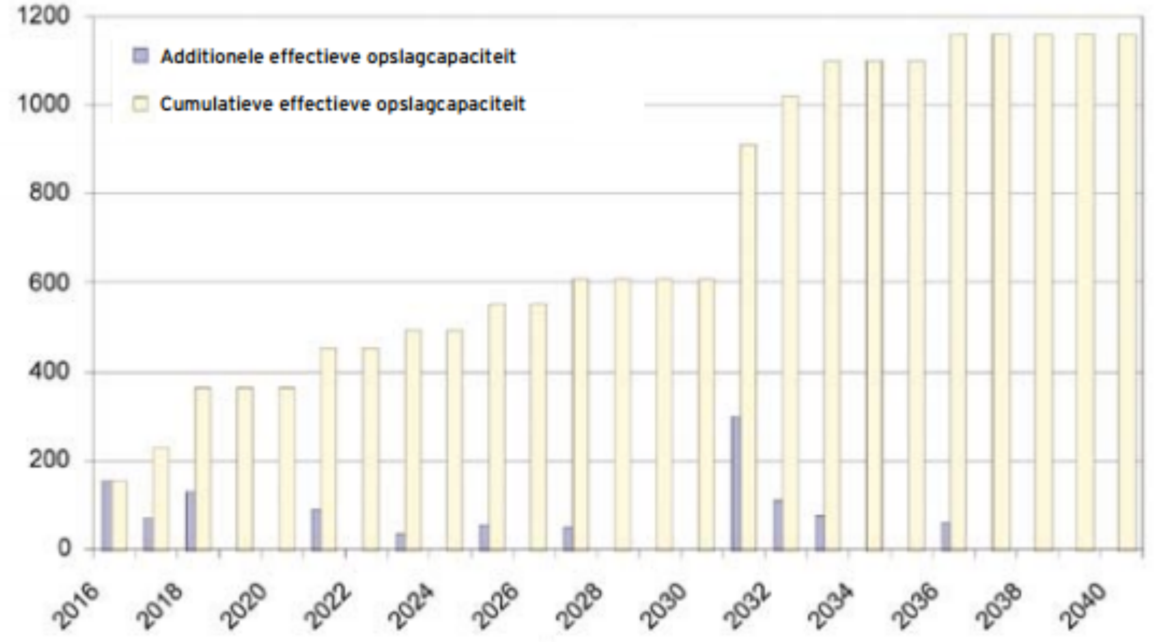


Figure 4.3 – The availability of effective storage capacity of gas- and oil-fields on the Dutch continental shelf between 2016 and 2040 (EBN, 2010)

Finally, commissioned by EnergieNed and the Dutch Ministries of the Environment and Economic Affairs, Ecofys and Spinconsult created a policy, technology and organization agenda for 2007 to 2020 for CCS (EnergieNed, 2007). In this report, a look has also been taken upon the storage capacity of CO_2 in the Netherlands. According to EnergieNed (2007), the total off-shore capacity of depleted gas fields amounts to 1,150 Megatons of CO_2. The report adds "*Only gas fields with a capacity higher than 4 Mtonne CO_2 have been taken into account because CO_2 storage would not be economically viable in smaller fields* […] *To a certain extent geological and engineering cut-off limits have been applied, but most of the related assumptions are not based on site-specific data. This means that there is still a significant degree of uncertainty*" (p. 27). Even though its reported that there is a significant degree of uncertainty, it seems that the total/theoretical capacity was cut down to show more realistic numbers concerning the total storage capacity of CO_2 in the Netherlands. Thus, it is assumed that the numbers reported by EnergieNed (2007) are the effective capacity.

EnergieNed (2007) also reports the storage capacity in depleted oil/EOR fields, aquifers, and deep coal fields. However, for the depleted oil/EOR fields and deep coal fields it wasn't specified if these storage sites were on- or off-shore. According to Ramírez *et al*. (2010), an article co-written by two scientists that also contributed to EnergieNed (2007), the majority of oil fields in which CO_2 can be stored is on the Dutch continental shelf (taking into account that not all fields are realistic to store in, thus setting requirements the storing sites should meet). No exact numbers were given by Ramírez *et al.* (2010), but it seems that it can be concluded that about 2/3 of the effective storage capacity of oil fields are off-shore and 1/3 on-shore. Thus, from the 40 megatons of effective capacity available thanks to depleted oil/EOR fields, it's assumed that 27 megatons of the capacity is off-shore and 13 megatons is on-shore. All the storage capacity of the deep coal fields is expected to be on-shore. Furthermore, aquifers have an off-shore effective storage capacity of 310 megatons of CO_2 (EnergieNed, 2007). Summarizing the findings of EnergieNed (2007), it seems that there's an off-shore effective storage capacity of 1,487 megatons of CO_2. Appendix 4.1 summarizes the different findings for the effective offshore capacity.

The estimates vary between 918 and 1,487 megatons of effective storage capacity and can probably be explained to a large extent by which fields are taken into account and which fields aren't taken into account. Because the estimate for storage in depleted gas fields of NOGEPA (2008) seems to be achieved after more detailed research than that of EBN (2010), it has been chosen to use NOGEPA (2008)'s estimate for off-shore effective storage capacity in depleted gas fields. Because EnergieNed (2007) is complete in providing possible storage sites such as depleted oil fields (independent from gas fields) and aquifers, NOGEPA's (2008) data is complimented by EnergieNed's (2007) data on depleted oil/EOR fields and aquifers.

4.2 On-Shore Storage Capacity

As earlier stated, EBN (2010) divides the storage capacity of the Netherlands in western part of the Netherlands and the northern part of the Netherlands. Besides the off-shore storage capacity in the Netherlands, there's also on-shore storage capacity. These are mainly centered in Rotterdam and in the province "Noord-Holland". In the area of Rotterdam there's an effective storage capacity of 79.0 megatons of CO_2. In the area of Noord-Holland this is 33.8 megatons of CO_2. Thus, the on-shore effective storage capacity in the western part of the Netherlands amounts 112.8 megatons of CO_2.

When thinking about the storage capacities of the northern part of the Netherlands, the gas field in Groningen seems as one of the largest potential candidate storage sites. However, as EBN (2010) expects this field only to become available at the end of this century, it has been excluded from the scope of the report. However, in the vicinity of the Eemshaven there are enough other storage sites. EBN (2010) reports a theoretical storage capacity of 850 megatons in the northern part of the Netherlands (excluding the Groningen field). Of the 850 megatons, 36 comes from fields that have a storage capacity ranging between 1 and 5 megatons. To gain a number closer to the effective storage capacity, these fields will be excluded, as a large portion of these fields are probably not interesting to store CO_2 in due to their low storage capacity. This brings the effective storage capacity of the northern part of the Netherlands to 814 megatons of CO_2. It should be noted that in NOGEPA (2008) the fields the difference between theoretical and effective capacity was 90% accountable to a too low injectivity and only 9% accountable to a too low storage capacity. It is very likely that the real effective capacity is significantly lower than 814 megatons of CO_2. However, as EBN (2010)

doesn’t report the effective capacity of the storage sites in the northern part in the Netherlands and doesn’t elaborate on the level of injectivity in these fields, it’s difficult to take a number of fields that shouldn’t be taken into account in the effective storage capacity due to too low levels of injectivity. Thus there is a relative high level of uncertainty regarding the effective storage capacity in the northern part of the Netherlands in EBN (2010).
Adding the western and northern part of the Netherlands to one another, the total amount of on-shore effective storage capacity of CO_2 in the Netherlands reported by EBN (2010) (excluding storage in the Groningen gas field) amounts to 926.8 megatons.

According to EnergieNed (2007) the storage capacity of on-shore depleted gas fields without taking Groningen into account amounts to a total of 1,600 megatons of CO_2. This alone is nearly twice as large as the capacity reported by EBN (2010). It has been reported by EnergieNed (2007) that the gas field in Groningen has a capacity of 7,350 megatons of CO_2, which results in a total capacity of 8,950 megatons of CO_2 in on-shore gas fields in the Netherlands. It is assumed that of the 40 megatons capacity in depleted oil/EOR fields, only 13 megatons is on-shore. Finally, it is reported that there is a capacity of 405 megatons of CO_2 in onshore aquifers and it is assumed that all of the 400 megatons storage capacity in deep coal fields is on-shore. This results in a total on-shore effective storage capacity of 9,768 megatons of CO_2 in the Netherlands. A summarization of these findings can be found in appendix 4.2.

There’s a huge difference between EBN (2010)’s estimate of on-shore and that of EnergieNed (2007). A large factor that explains this is the fact that EnergieNed (2007) also takes into account aquifers and deep coal fields, while EBN (2010) doesn’t. Additionally, EnergieNed (2007) takes the Groningen gas field into account, while EBN (2010) doesn’t. However, if only the depleted gas and oil fields are taken into account, the difference is still slightly more than 670 megatons. EBN (2010) states that they didn’t take into account gas and/or oil fields in Limburg and Zeeland because the storage capacity in these provinces is relatively low (p. 24). Although “a relative low storage capacity” won’t be sufficient to explain the difference between both sources, the estimates proposed by EnergieNed (2007) have been chosen to be used in this study as they are more complete in terms of addressing the whole of the Netherlands and the types of field that can be used to store CO_2 in.

The final assumptions regarding effective storage capacity in the Netherlands are shown in figure 4.4. Adding all storage capacities together gives a total storage capacity of approximately 11 gigatons of CO_2.

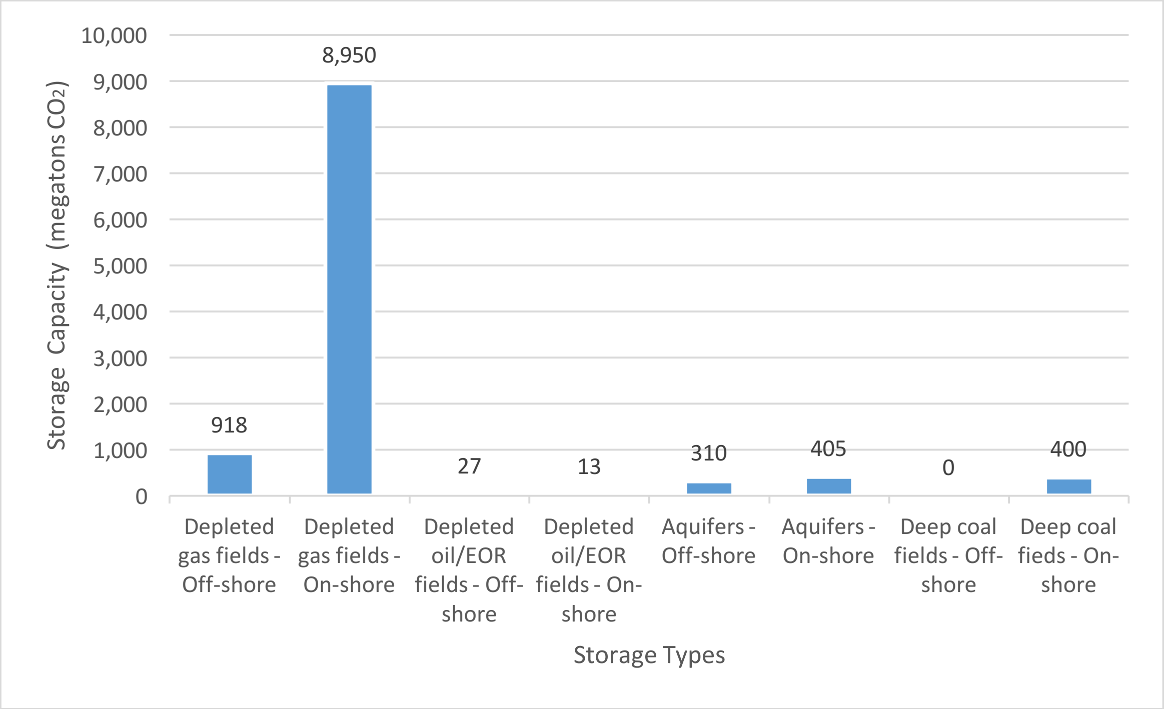


Figure 4.4 – The amount of storage capacities in different storage fields in the Netherlands

4.3 The Netherlands' Contribution Towards Global Emissions and the Global Effective Storage Capacity

CATO states that the Netherlands has a very favorable position regarding the possibilities for CO2 storage and a transport infrastructure (CATO3, 2015, p. 5). But how favorable is the Netherlands' position regarding the storage of CO_2? To put a bit of context into the storage capacity that is available in the Netherlands, it might be a good idea to compare the contribution of the Netherlands towards the global effective storage capacity and compare this with the Netherlands' contribution to the global effective storage capacity of CO_2.

IEAGHG (2009a) has some estimates on the global effective storage capacity of CO_2 in gas and oil reserves. According to the report, there's a 95% chance of having an effective storage capacity of 420 gigatons of CO_2, a 50% of having an effective storage capacity of 651 gigatons of CO_2, and a 5% chance of having an effective storage capacity of 944 gigatons of CO_2. So if the focus is only put on the gas and oil fields and the global effective storage capacity which has a 50% chance of being there is taken, the Netherlands has a 1.5% contribution towards the global effective storage capacity of CO_2. However, there's a huge potential for storage in aquifers. Sadly, the Netherlands doesn't have a large a mount of storage capacity in aquifers. The findings of the IPCC (2005) regarding global storage capacities can be found in appendix 4.3. One side note is that this amount is the theoretical storage capacity, not the effective storage capacity.

To gain a good idea about the total global effective storage capacity, the average values of the lower and upper estimate storage capacity from IPCC (2005) will be taken. To get an idea about the effective storage capacities, 75% of the theoretical storage capacity will be taken. The reason for this is that according to IEAGHG (2009a) the effective storage capacities of the global oil and gas fields were 75% of the theoretical capacity. It should be noted that it could very well be the case that for unminable coal seems and deep saline formations the

percentage decrease from going from theoretical to effective capacity is different from the decrease of oil and gas fields. However, since this is unknown and it is favorable to get a value for the effective capacity, the same percentages are taken. The values for the oil and gas fields will be taken from IEAGHG (2009a), since the average value for effective storage capacity will most likely have a much lower uncertainty than applying the method put forward above on the values of IPCC (2005).
The Dutch and global effective capacities that are assumed to be available for CO_2 storage and the Dutch contribution to the global storage capacities in percentages can be seen in table 4.1.

Table 4.1 – Assumed Dutch and Global Effective Storage Capacity for CO_2 and the Contribution of Dutch Storage Sites to the Global Effective Storage Capacity

Reservoir Type	Assumed Dutch Effective Storage Capacity (in megatons CO_2)	Assumed Global Effective Storage Capacity (in gigatons CO_2)	Dutch Contribution to Global Storage Capacity (in %)
Oil and Gas Fields	9,908	651	1.5
Unminable Coal Seams	400	80.6	0.5
Deep Saline Formations	715	4,125	0.0002
Sum of all fields	11,023	4,856.6	0.2

The low Dutch storage availability in aquifers makes the total Dutch contribution in CO_2 storage capacity relatively low. But how does it stand against the Dutch contribution towards global CO_2 emissions?

The most recent data from the World Bank is for the year 2013. In this year the global CO_2 emissions were 35,849 megatons of CO_2 (World Bank, n.d.a). In this year the Netherlands emitted 170 megatons of CO_2 (World Bank, n.d.a). This makes the Dutch contribution to the global CO_2 emissions in 2013 0.47%. According to the Global Carbon Atlas (n.d.), the global CO_2 emissions amounted to 36,262 megatons in 2015. The total CO_2 emissions of the Netherlands in 2015 was 165 megatons (Environmental Data Compendium of the Netherlands, 2017). The contribution of the Netherlands towards the global CO_2 emissions in 2015 was thus approximately 0.46%. From this data it can be assumed that the Dutch contribution has been between 0.45 and 0.50% in recent years.

The statement from CATO concerning the favorable position of the Netherlands seems to be a bit misleading. In terms of oil and gas fields, and unminable coal seams, the Netherlands might have a favorable geological position. However, due to the lack of aquifers, the contribution of the Netherlands to the global CO_2 emissions is more than two times higher than the Netherlands' contribution towards the global effective storage capacity of CO_2.

But how does this compare to other countries? Using Höller & Viebahn (2011) for the effective storage capacity of Germany, France, Denmark, Norway, the UK, and Poland, Global Carbon Atlas (n.d.) for the CO_2 emissions of these countries and the above values calculated for the Netherlands, the Emission Capacity Ratio for the year 2015 was calculated. This is the relative contribution towards global emissions per country in 2015 divided by their relative contribution towards the global CO_2 storage potential (effective capacity). This is shown in figure 4.5.

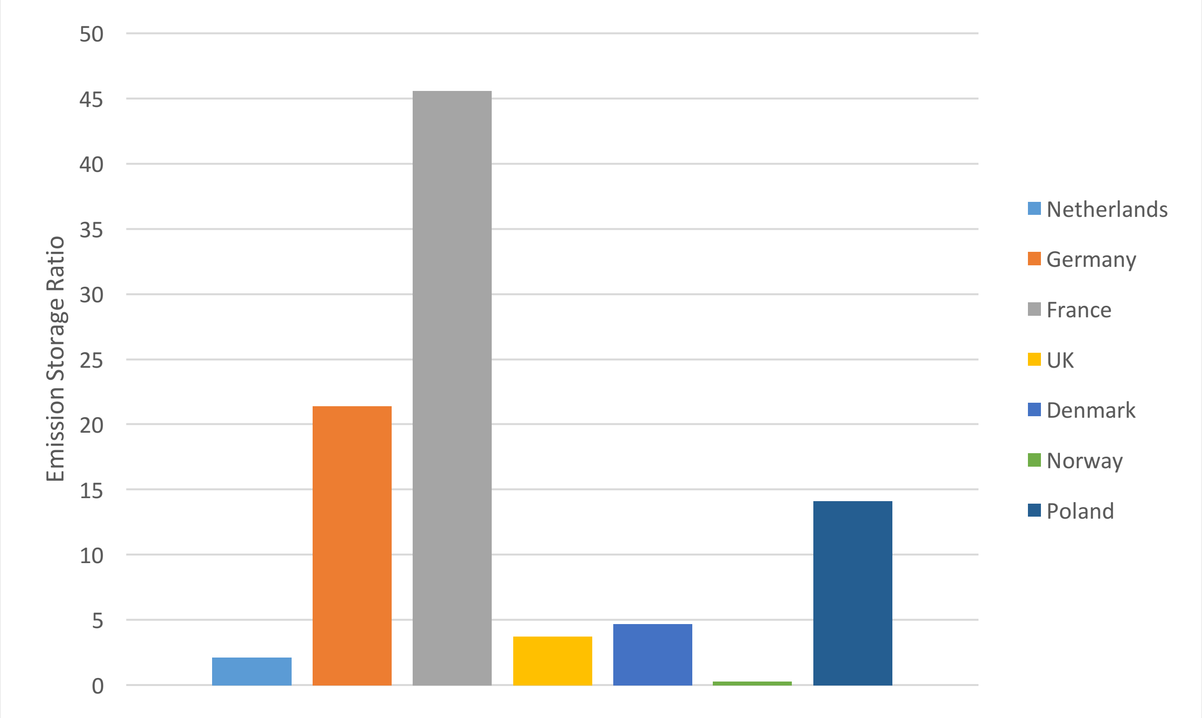


Figure 4.5 – The Emission Storage Ratio of the Netherlands, Germany, France, the United Kingdom, Denmark, Norway and Poland in 2015

Norway has the smallest Emission Storage Ratio, mainly because of their low emissions and the high potential for storing CO_2 in the Sleipner field. However, of these countries, the Netherlands is runner up. Although the UK has a larger effective CO_2 storage capacity than the Netherlands, the UK also emits way more CO_2, making their ratio increase above that of the Netherlands. Comparing the Netherlands with these countries shows that the Netherlands actually has a favorable position with regards to storage of CO_2 within Europe.

Figure 4.6 shows the theoretical CO_2 storage capacity throughout the world per region. Even though it's just the theoretical storage capacity, this figure indicates that the largest storage capacity is in North America, Russia, Australia, and the Middle East. In comparison with these regions, the position of the Netherlands is not favorable. This was to be expected considering the other regions' amount of oil and/or gas fields.

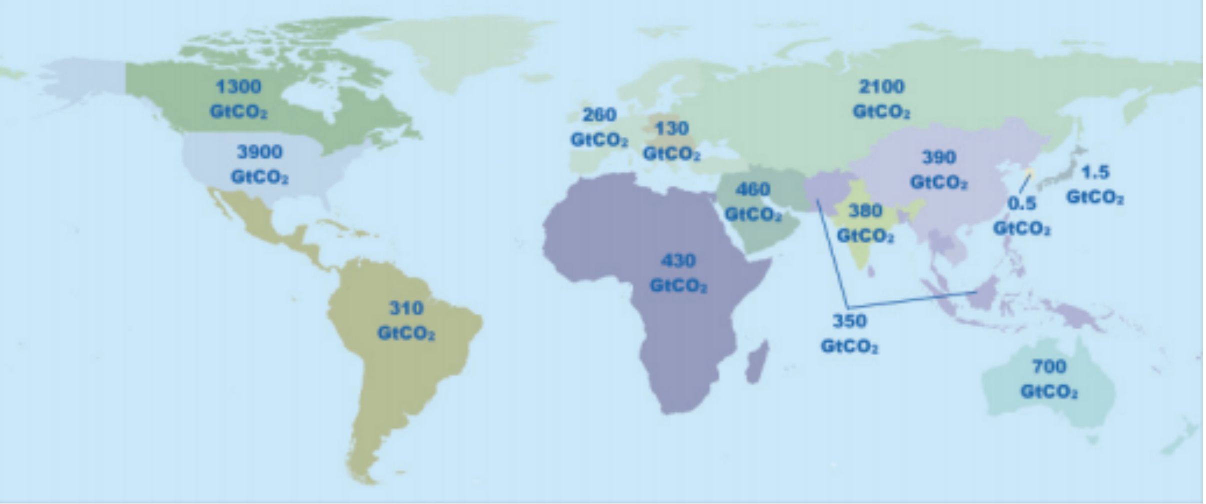


Figure 4.6 – Theoretical CO_2 storage capacity per region (EPA, 2006)

5 Projected Infrastructure for CCS in the Netherlands

An important factor that heavily influences the applicability and success of CCS is the transport of CO_2 from source to sink. A decent infrastructure needs to be implemented to assure this. For this study it is assumed that all transport will take place via pipelines. There are two reasons for this. First of all, as mentioned before, the most favorable mode of transport for CO_2 is through pipelines. Second, the scope of this research is the application of BECCS in the Netherlands. Due to this, the use of the second most used mode of transport for CO_2, ships, is not only unnecessary, but also unpractical due to the relative small scale of the Netherlands as a country or the relative short distances to off-shore storage sites.

There are several publications and articles focused on the construction of a pipeline infrastructure for the Netherlands. Ecofys (2008) was commissioned by the ministry of VROM (ministry of Housing, Spatial Planning and the Environment), now the ministry of of Infrastructure and the Environment), and investigates how a CO_2 transport network would look like in the Netherlands. This study took into account that the possibility for CO_2 being transported over national boundaries and included places in Belgium and West-Germany as possible CO_2 sources. The only storage sites that are considered are on-shore and off-shore gas fields, excluding the gas field in Groningen because it's expected that the earliest point in time that this field will be available is in 2050. The route selection for the pipelines was based on self determined shortest possible route between clusters of CO_2 sources and clusters of sinks. Ecofys (2008) mentions that of the 140 on-shore and off-shore gas fields that are taken into account in the study, most fields have become available before 2025. However, the study doesn't seem to go into in how far it is taken into account that some gas fields will become available earlier than others for the storage of CO_2. All in all, all thought the study might give a good general idea about a CO_2 infrastructure in the Netherlands, it is deemed too simplistic.

Damen, Faaij & Turkenburg (2009) go a step further than Ecofys (2008). Damen, Faaij & Turkenburg (2009) reviewed four different pathways (besides two baseline pathways) for the Netherlands which integrate different levels of implementation of CCS according to different CO_2 reduction goals for 2020 and 2050. Additionally, the different pathways also look into differences in storage sites, such as also storing CO_2 in off-shore fields in the UK and/or the Utsira formation in Norway, only storing on off-shore fields or only storing in Dutch gas fields. The study doesn't take into account Dutch oil fields as it is assumed that these represent a relatively low storage potential. One of the major advantages of this study is that the study explicitly addresses temporal and spatial aspects of the energy system and geological reservoirs. The infrastructure that the study projects consists of a CO_2 network, which is based on connecting multiple sources with multiple sinks, just as was the case with connecting the clusters in Ecofys (2008). The infrastructural requirements are computed by using a spreadsheet model that takes into account the lowest costs for transport and storage. Although addressing the temporal aspects of the geological reservoirs, the connection of sources and sinks is based on a 'first come, first serve' principle. This is a disadvantage as integrating this principle into the model diminishes the model's focus on the long term view of building an efficient infrastructure for the transport of CO_2 in the Netherlands. Furthermore, the model uses a multiplication of 3 to determine onshore pipeline costs. This is ascribed to the fact that there are infrastructural barriers that need to be crossed when installing the pipelines in densely populated urban areas in the Netherlands. Besides the fact that this number is non substantiated, the whole on-shore area of the Netherlands is not a densely populated area. Although seeming as a good article that looks into the infrastructure of CO_2 transport, due to the last points mentioned the article hasn't been chosen to be used for this study.

The study that was eventually chosen for this study to function as base for the infrastructure of CO_2 transport is van den Broek *et al*. (2010). To develop a CO_2 storage infrastructure for the Netherlands for the period 2010 to 2050 that takes into account the timing aspect, the spatial aspect, and cost-effectiveness, the study combined the MARKAL model of the Dutch electricity and cogeneration sector (MARKAL-NL-UU) with a geographical information system (GIS) (ArcGIS). The sinks that are taken into account are gas fields, oil fields, and saline aquifers. However, because the scope of the study is until 2050 the gas field in Groningen isn't included. The study focuses on a "hub-spoke network form" very similar to the connection of clusters as with Ecofys (2008) and Damen, Faaij & Turkenburg (2009). The study has several terrain factors that have different effects on the costs for the installation of the pipelines, which was checked and confirmed by a panel of pipeline engineers. Finally, van den Broek *et al.* (2010) has seven additional scenarios which are evaluated that take into account that there may be different emission reduction goals to be achieved, different restrictions concerning storage sites or different costs for the implementation of pipelines. So besides not having the disadvantages that Ecofys (2008) and Damen, Faaij & Turkenburg (2009) have, van den Broek *et al.* (2010) seems to be very detailed concerning the calculations of costs and the calculation of the most efficient infrastructure for the transport of CO_2, and takes into account multiple scenarios. For these reasons, van den Broek *et al*. (2010) was chosen to be used in this study.

The sources and storage sites that were within the scope are shown in figure 5.1. The CO_2 sources all emitted more than 0.1 megaton of CO_2 per year in 2004 and additionally are able to be retrofitted with CO_2 capture or replaced with a CO_2 capture unit. In this way it is assured that the CO_2 sources are power or industrial plants that from a realistic point of view could be part of the Dutch CCS infrastructure. The storage sites comply with a few threshold values to assure that the study uses the effective storage capacity rather than the theoretical storage capacity. CO_2 sources and sinks are clustered by categorizing them into regions. All sources and storage sites that belong to the same region have the same color.

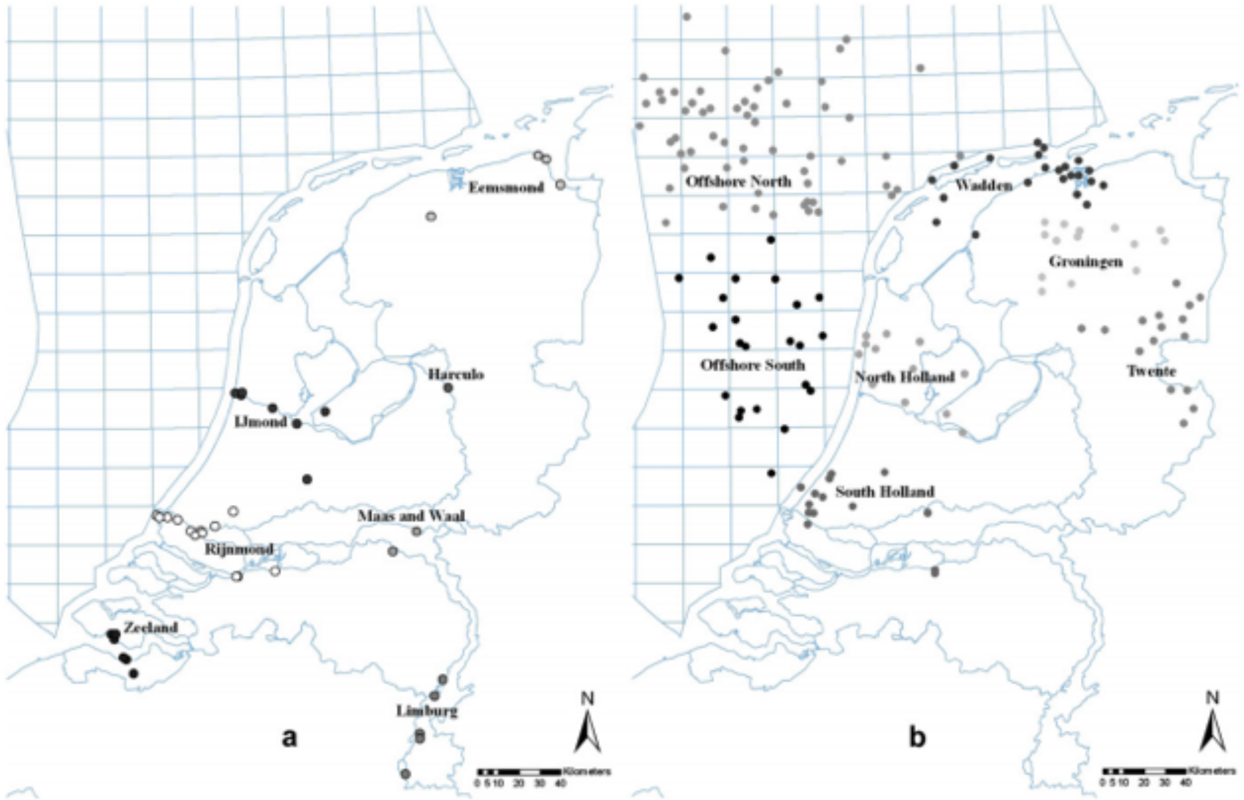


Figure 5.1 – CO_2 sources (a) and CO_2 storage sites (b) in the Netherlands from van den Broek *et al.* (2010)

In the base scenario of van den Broek *et al.* (2010), it is assumed that in 2020 there will be a reduction of 20% CO_2 emissions compared to 1990 levels and in 2050 a reduction of 50% CO_2 emissions compared to 1990 levels. It should be noted that this change in CO_2 emissions also is attributed to a share of renewable electricity of 27% in 2020 and of 41% in 2050. The projected development of a pipeline infrastructure according to this base case in 2020 and 2050 is shown in figure 5.2.

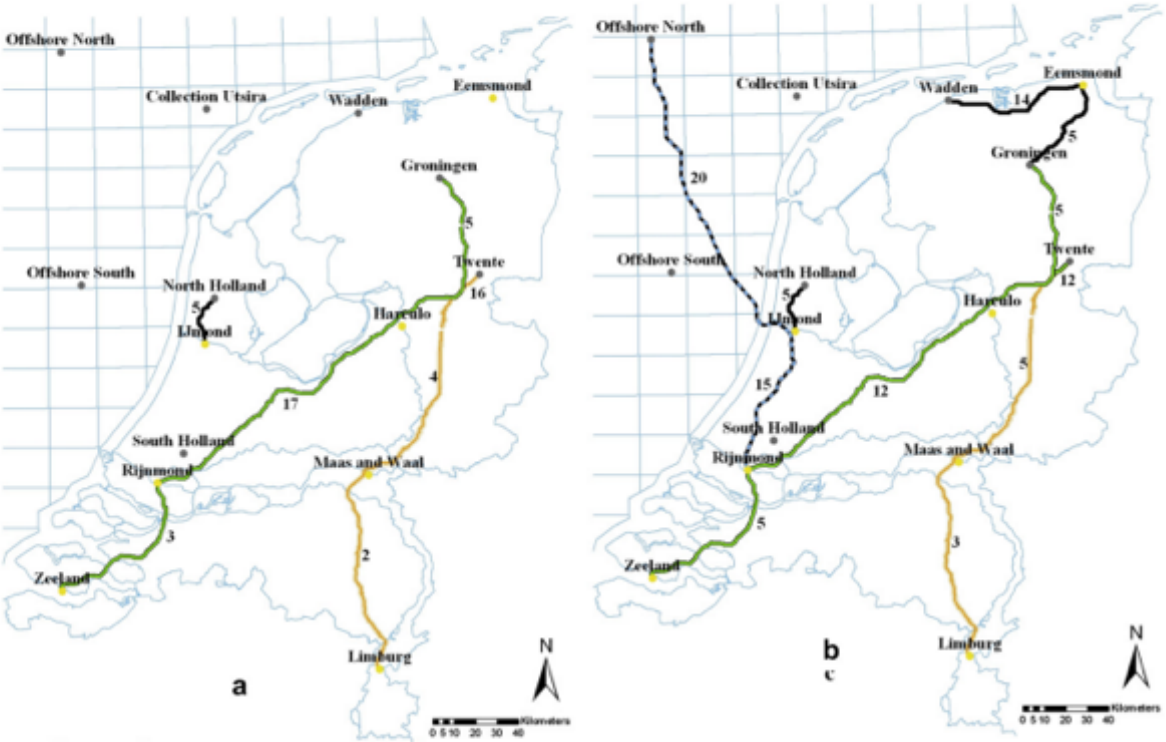


Figure 5.2 – Projected pipe line infrastructure connecting CO_2 sinks with storage sites in 2020 (a) and 2050 (b) in the base case scenario (van den Broek *et al.*, 2010)

The development of the amount of CO_2 stored annually according to the base case scenario is shown in figure 5.3.

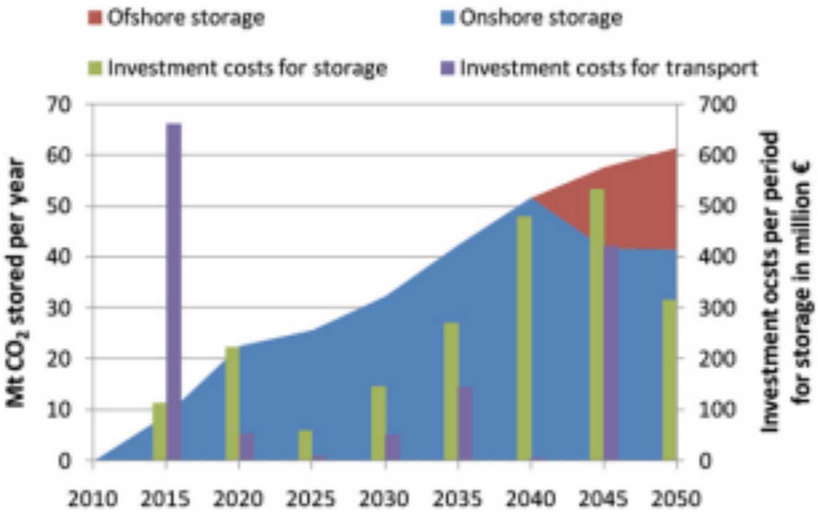


Figure 5.3 – The development of the annual amount of CO_2 stored and the development of the investment costs for transport and storage of CO_2 in the base case scenario of van den Broek *et al.* (2010)

Although the base case scenario gives a good image of the possible CO_2 emission reduction potential, this scenario follows a lower reduction than desirable. A scenario in which a reduction of 20% of CO_2 emissions in 2020 and 80% in 2050 occur compared to 1990 levels was also investigated. In this scenario the cumulative amount of CO_2 stored in 2050 increases from approximately 1,360 megatons to 2,060 megatons. This is slightly more than 1.5 times higher. A downside is that according to the model, the storage capacity in the Netherlands isn't enough to store all the CO_2 in, and a pipeline is needed to transport CO_2 to the Utsira formation in Norway. This is 40 megatons of CO_2 per year starting halfway through 2042, and 80 megatons of CO_2 per year starting halfway through 2047 (M. van den Broek, personal communication, May 16th, 2017). This makes the final storage capacity in the Netherlands in 2050 due to the infrastructure 1,540 megatons of CO_2.

It is assumed that after this point all other fields calculated in section 4, regardless whether they're empty or not, will become available for storage of CO_2. This includes the Groningen gas field.

Figure 5.4 shows the amount of CO_2 storage available for the Netherlands between 2015 and 2050 that is assumed for this study.

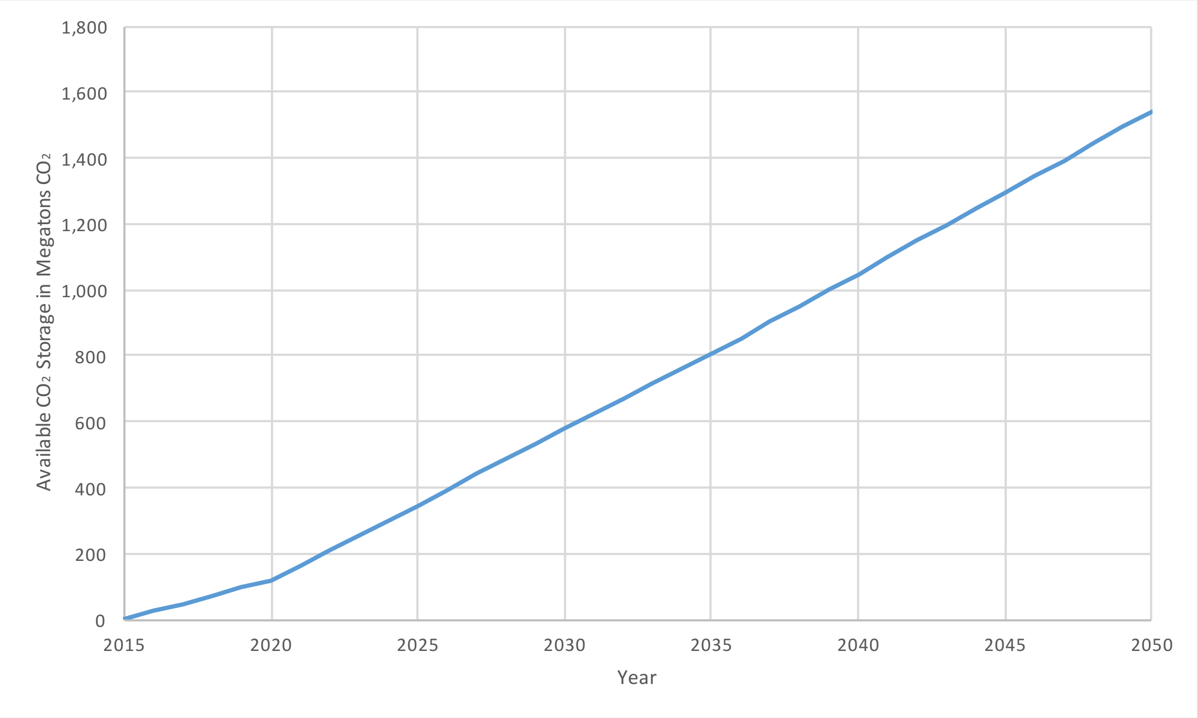


Figure 5.4 – The amount of storage space for CO_2 between 2015 and 2050 that is assumed to be available in this study (in megatons CO_2) (data from van den Broet *et al*., 2010)

6 Energy Conversion Technologies

Now that the aspects of CCS in the Netherlands have been discussed, the next step is to study the effect that biomass conversion technologies play in a BECCS system. This starts with an evaluation of the energy conversion technologies that are used to produce biomass energy. This is done in this section.

McKendry (2002) describes the different conversion technologies that can produce energy from biomass. He discusses that there are two main classes of biofuel energy processes. These are thermo-chemical conversion and bio-chemical conversion. For thermo-chemical conversion, there are mainly four processes available; combustion, gasification, pyrolysis, and liquefaction. For the bio-chemical conversion of biomass, there are mainly two processes available; fermentation and anaerobic digestion. All six processes will be discussed below.

6.1 Thermo-Chemical Conversion of Biomass

6.1.1 Combustion

Combustion is a process takes place when biomass is burned in the presence of (plentiful) oxygen. Generally speaking, there are three steps that are followed when combusting biomass; drying, devolatization or pyrolysis, and particle fragmentation ((University of Arkansas, n.d.), (Nunes, Matias & Catalão, 2014)). During the drying step, biomass takes up heat to evaporate the water present in biomass. After this step, the devolatization step takes place. During this step, volatile gases such as CO, H_2, CO_2, and CH_4 are released from the biomass. Finally, during the particle fragmentation step, the char resulting from the devolatization step is oxidized for the last bit of heat and CO that the biomass can supply. After particle fragmentation of the biomass has occurred (fully), only ash remains.

The process that is most important for the generation of energy from combusting biomass is the oxidization of the volatile gases that were released during the devolatization step. This creates heat, which can convert water into steam. If this steam passes a steam engine, electricity can be generated. Using biomass for combustion in a power plant can occur in two ways. Biomass can be used in a biomass dedicated power plant, which only uses biomass for the production of electricity, but biomass can also be mixed with, for example, coal. The latter is known as co-firing. The final possibility is to use biomass to fire a combined heat and power (CHP) generator. In this case, besides the generation of electricity, waste heat is also recovered and used for heating purposes. This increases the efficiency of biomass use significantly, as more energy is generated from the same amount of biomass.

According to Nunes, Matias & Catalão (2014), the most used technologies used for combustion are grates and fluidized beds. Biomass Technology Group (2005), which was commissioned by the United Nations Development Plan and the Global Environment Facility, goes into large detail concerning the explanation of grates and fluidized beds.

There are several types of grates such dual-chamber furnaces, travelling grates, fixed grate systems, inclined moving grates, horizontally moving grates, and underfeed rotating grates. However, the main processes that occur in all these different types of grates are the same. The biomass enters the grate furnace and the further it gets into the furnace, the further it will have processed in going through the three steps that occur during biomass combustion.

Eventually the ash will get captured and will be removed from the furnace. Due to the amount of volatile gases, full oxidation of the gases will not occur immediately. A large amount of the volatile gases only gets oxidized after entering the secondary combustion chamber, where a secondary supply of air is fed in to create perfect conditions for the full oxidization of the unburned volatile gases. Finally, the generated heat transfers its energy to water through a heat exchanger to generate electricity. Figure 6.1 shows a schematic representation of a grate furnace.

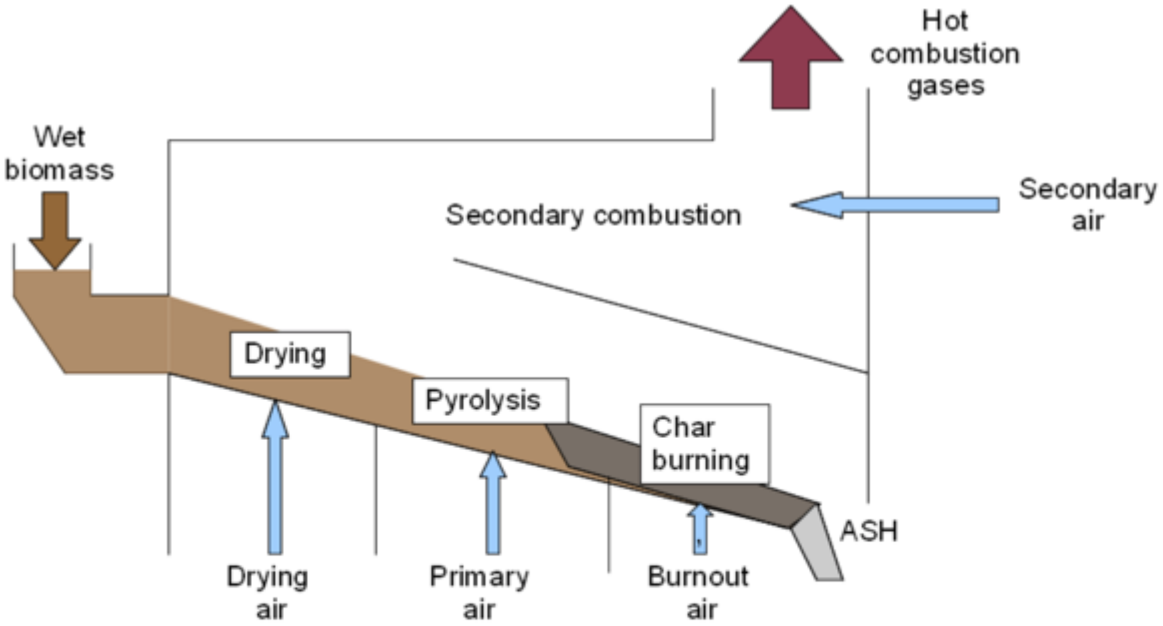


Figure 6.1 – A schematic representation of a grate furnace in which biomass combustion can take place (Strzalka, Erhart & Eicker, 2013)

There are two types of fluidized beds, bubbling fluidized beds (BFBs) and circulating fluidized beds (CFBs), but both types mostly work the same. At the bottom of the furnace a bed existing of granular material (often silica sand or dolomite) is “fluidized” by air flowing in from below through an air distribution plate. When the bed is fluidized, the bed seems to show liquid characteristics although the bed is still in its solid phase. Biomass enters the furnace by and combustion of the biomass takes place within the bed. Ash is collected and removed at the bottom of the furnace (below the air distribution plate). In the area above the bed (called the freeboard (Nunes, Matias & Catalão, 2014)) a secondary stream of air is inserted and oxidation of the volatile gases takes place. The heat then passes heat exchangers, and the generated steam can then go on to generate electricity. The difference between BFBs and CFBs is that BFBs have a low stream of air blowing upwards from the bottom part of the furnace. This results in little bed particles reaching the top part of the furnace and escaping the main section of the BFB furnace. A cyclone can be added to remove the little bit of particles that still are able to escape the main section of the BFB from the combustion gases. In the case of a CFB furnace, the velocity of the air blowing upwards from the bottom of the furnace is much higher, resulting in relatively lots of bed particles reaching the upper part of the furnace and possibly also leaving the main section of the furnace. To combat this while assuring enough bed particles in the combustion chamger of the CFB furnace, CFBs also have a cyclone that separate the bed particles from the combustion gases and redirecting these back to the combustion chamber. Figure 6.2 gives a schematic representation of a BFB and CFB.

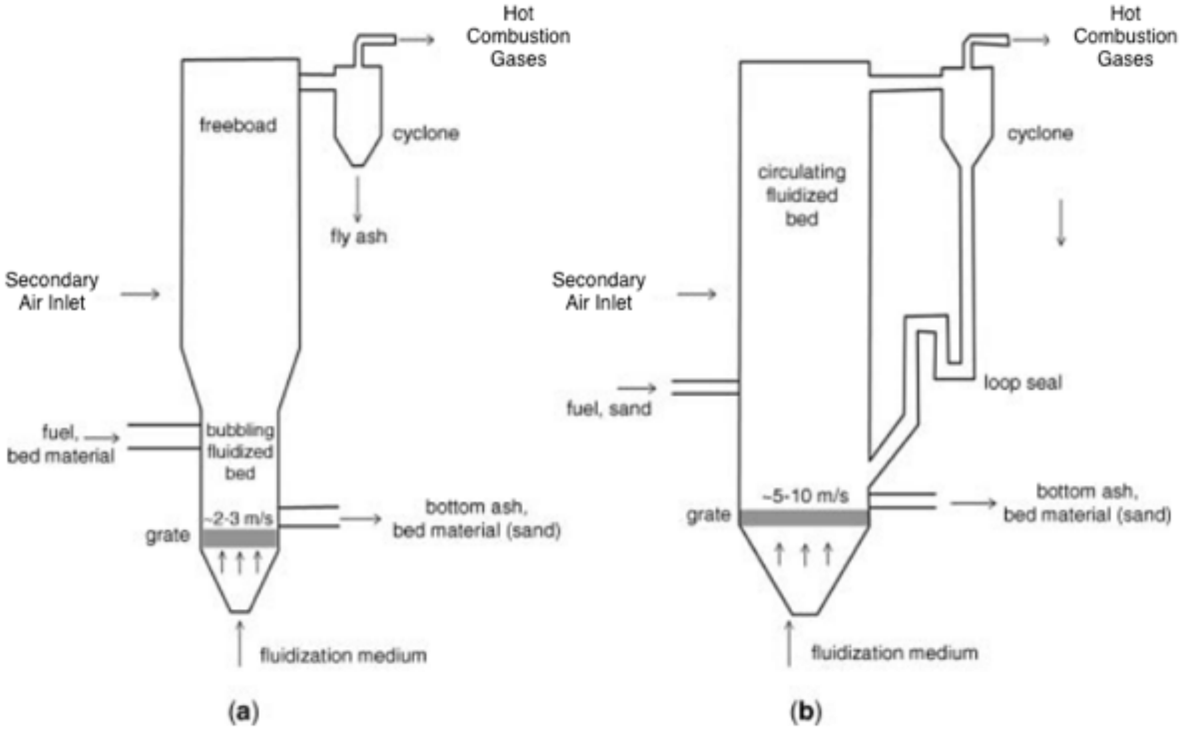


Figure 6.2 – A schematic representation of a BFB furnace (a) and a CFB furnace (b) (Edited from a figure from Lackner (2011))

6.1.2 Gasification

Gasification is a process in which biomass is converted into a gas. There are two types of gas that can be produced by means of gasification of biomass; producer gas and syngas (also known as synthesis gas). Producer gas exists of CO, H_2, CO_2, and a range of hydrocarbons including CH_4, while syngas mainly exists of a combination of CO and H_2 (Chhiti & Kemiha, 2013). Whether the resulting product is either producer gas or syngas is dependent on the process temperature (syngas is produced at higher temperatures than producer gas).

There are several applications for both producer gas and syngas. Producer gas can be used as substitute natural gas (SNG) or can be used as a fuel in a gas turbine to generate electricity (Boerrigter & Rauch, 2005). Syngas has a lot of applications. It can undergo the Fischer-Tropsch process and be converted to liquid fuels such as diesel and jet fuel (Hu, Yu & Lu, 2012), undergo the water gas shift (WGS) reaction to produce pure H_2, and can be converted to either methanol, ethanol and other alcohols (Chhiti & Kemiha, 2013). The many pathways for syngas are depicted in figure 6.3.

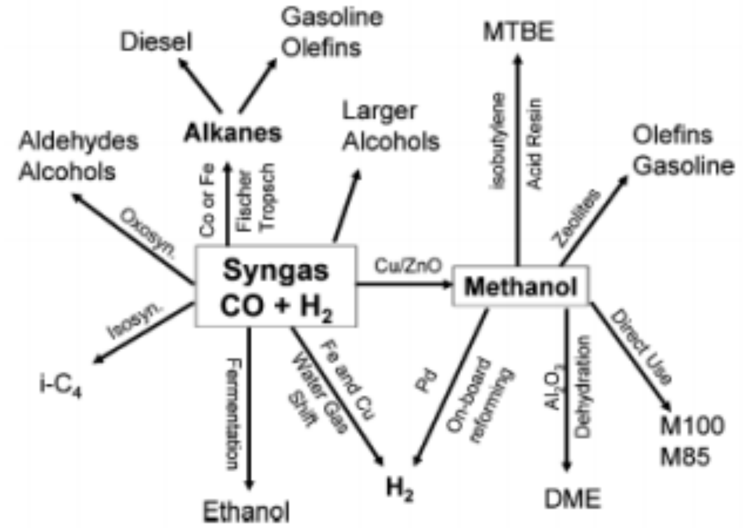


Figure 6.3 – Applications of syngas (Chhiti & Kemiha, 2013)

It's also possible to generate electricity from syngas. One of the best known gasification power plants is the integrated gasification combined cycle (IGCC). In these power plants, producer gas and syngas are first produced through gasification. The gas is cleaned and then generates electricity by combusting the gas in a gas turbine. The heat from the combustion gases are used to generate steam from water. This steam is then used in a steam turbine to increase the efficiency of electricity generation by generating even more electricity.

There are four steps that for gasification; oxidation, drying, pyrolysis (or devolatization), and reduction (Molino, Chianese & Musmarra, 2016).

Oxidation of a part of the biomass is needed to sustain the activities of the other steps. The drying step is, just like in the combustion step, for evaporation of the water in the biomass. During the pyrolysis step volatile gas such as H_2, CO, CO_2, CH_4 and H_2O are released from the biomass, together with liquid tars. The final step is the reduction step, during which the char and volatile gases react with one another to result in the final syngas mix (Molino, Chianese & Musmarra, 2016). The reactions that are most general in this step are shown below. Again, the exact final gas composition is dependent on the temperature under which these reactions take place.

$$\mathrm{C + CO_2 \leftrightarrow 2\,CO} \tag{1}$$
$$\mathrm{C + H_2O \leftrightarrow CO + H_2} \tag{2}$$
$$\mathrm{CO + H_2O \leftrightarrow CO_2 + H_2} \tag{3}$$
$$\mathrm{C + 2H_2 \leftrightarrow CH_4} \tag{4}$$

Two main reactors that are generally used in the biomass gasification process will be discussed; entrained flow reactors and fixed beds.

Fluidized bed reactors are also used for biomass gasification, but will not be gone in too as it was already discussed above in the combustion part of this section. The only difference between a fluidized bed reactor used for combustion and one used for gasification is that there isn't any air or oxygen added to let the volatile gases combust. According to Molino, Chianese & Musmarra (2016), fluidized beds are the most promising technology in biomass gasification.

In an entrained flow reactor, the fuel (which should be reduced to small sizes of around 0.1 to 1 mm) and gasifying agent enter the reactor at the top in the same direction. The fuel, gasifying agent and the reaction products drift downwards and eventually the final gas is captured. There are two types of entrained flow reactors; slagging entrained flow reactors and non-slagging entrained flow reactors. The slagging reactors have ash that leaves the reactor at the bottom in the form of a liquid slag. In a non-slagging reactor, so little ash is produced that no slag is produced. Figure 6.4 gives a schematic representation of an entrained flow reactor (slagging reactor).

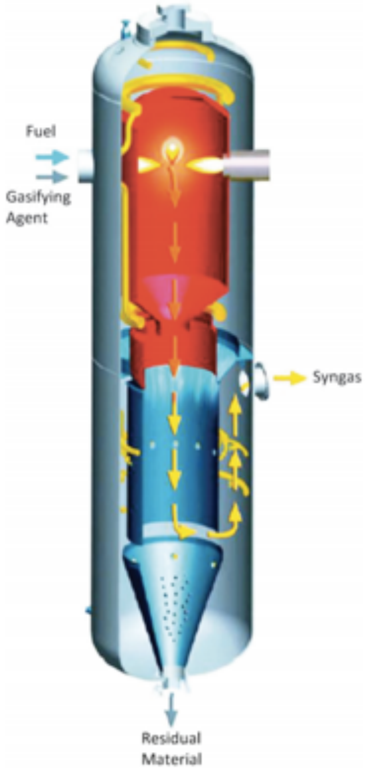


Figure 6.4 – A schematic representation of a slagging entrained flow reactor (Molino, Chianese & Musmarra, 2016)

There are two types of fixed bed reactors; updraft and downdraft fixed bed reactors. In updraft fixed bed reactors, the fuel is added from the top of the reactor and moves downward. The gasifying agent enters the reactor from the bottom and moves upwards. The syngas drift to the top of the reactor and is captured there, while the ash accumulates on the bottom of the reactor. The downdraft fixed bed reactor the fuel and gasifying agent moves downward through the reactor. In these reactors the syngas is captured at the bottom of the reactor. A schematic representation of both fixed bed reactors is shown in figure 6.5.

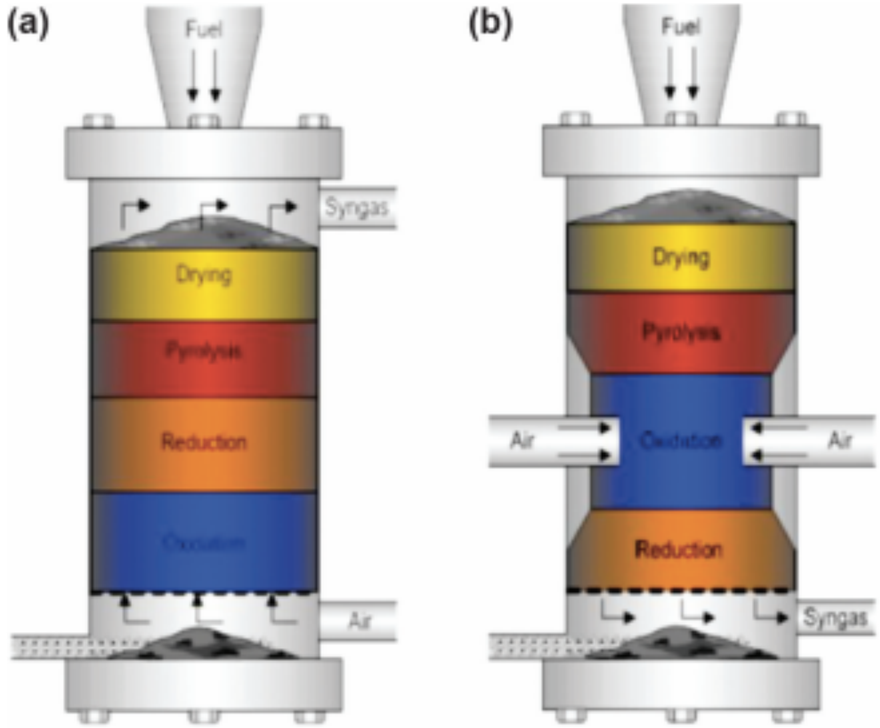


Figure 6.5 – A schematic representation of an updraft fixed bed reactor (a) and a downdraft fixed bed reactor (b) (Molino, Chianese & Musmarra, 2016)

As earlier stated, syngas can be converted into biodiesel via the Fischer-Tropsch process and into H_2 via the WGS reaction.
The Fischer-Tropsch process is a process that will convert syngas into hydrocarbons that can be used as a fuel for transport known as biodiesel. The general reaction that explains the process (in a simplified way) is

$$(2n+1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O \tag{5}$$

The carbohydrates that are in biodiesel generally range from molecules with 12 carbon atoms to molecules with 22 carbons.

The WGS reaction is a process that converts syngas into hydrogen. Hydrogen is an energy carrier that can be used for several processes such as electricity generation through hydrolysis and as a fuel for hydrogen fuel cell vehicles. The reaction that generally takes place during the WGS reaction is:

$$CO + H_2O \leftrightarrow H_2 + CO_2 \tag{6}$$

6.1.3 Pyrolysis

Pyrolysis is a process that is very similar to gasification. However, there where air or oxygen is used as a gasifying agent to assure maximum gas production during gasification, absolutely no oxygen is present in the pyrolysis process. Additionally, the main goal of the process isn't to produce producer gas or syngas. Instead, a combination of char, bio oil and producer gas/syngas are produced. The ratio is highly dependent on the type of pyrolysis that takes place. There are three types of pyrolysis; slow pyrolysis, fast pyrolysis, and flash pyrolysis

(Jahirul *et al*., 2012). Slow pyrolysis is a technique that aims to produce relatively high amounts of char. During this process, the fuel is treated for 450 to 550 seconds in a temperature between 550 and 950 Kelvin and is, thus, characterized by relatively slow heating rates (Jahirul *et al*., 2012). Fast pyrolysis is a process that doesn't put the emphasis on the production of char, and in result makes more bio oil than slow pyrolysis. During fast pyrolysis, the fuel is treated between 0.5 and 10 seconds with temperatures between 850 and 1250 Kelvin (Jahirul *et al*., 2012). This is achieved through significantly higher heating rates than is the case with slow pyrolysis. The highest loads of bio oil are generated through flash pyrolysis. Here, the fuel is treated in less than 0.5 seconds at a temperature that ranges between 1050 and 1300 Kelvin (Jahirul *et al*., 2012). The heating rates is thus incredibly high during flash pyrolysis. Figure 6.6 shows how ratios of pyrolysis products can differ due to using different types of pyrolysis. The figure originates from PNL (2009), but the data in the figure matches typical product yields that are described by Balat *et al.* (2009). Gasification is also visible on the figure as gasification can also been seen as a type of pyrolysis.

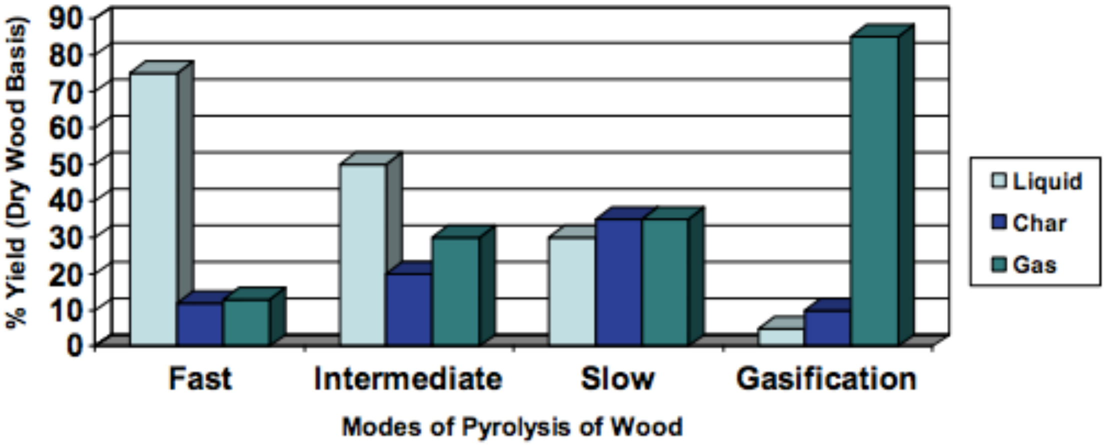


Figure 6.6 – Differing ratios of products from different types of pyrolysis when using wood as a fuel (PNL, 2009)

As earlier stated there are three products from pyrolysis; bio oil, char, and producer gas/syngas. The applications of producer gas and syngas won't be discussed here as they've already been handled in the sub-section gasification.

Bio oil is the result of the condensation of certain vapor gases that resulted from the pyrolysis process. Bio oil can be used as a substitute for conventional fuel oil, but only has heating value of approximately 40 to 50% of that of conventional fuels (Jahirul *et al*., 2012). Bio oil can also be used for the further production of other fuels, chemicals, heat or power. Figure 6.7 shows the possible further applications of bio oil in more detail.

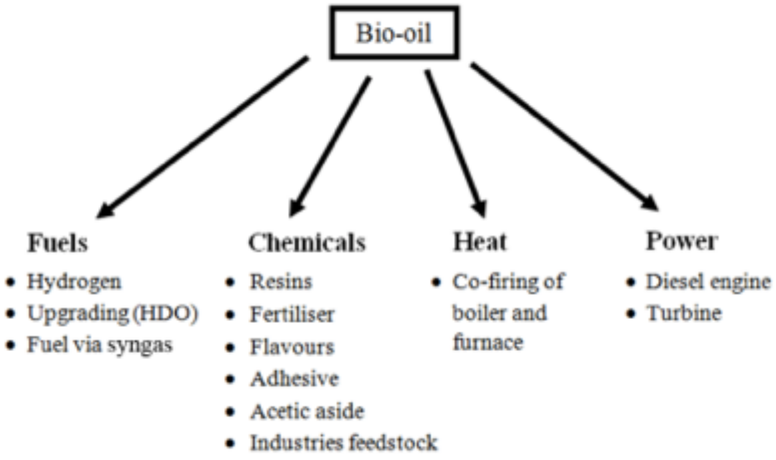


Figure 6.7 – Different applications for the use of bio oil (Jahirul *et al.*, 2012)

Char is the remnant of the biomass fuel after the volatile gases have been produced and left the fuel. The exact characteristics of the char is highly dependent on conditions such as the type of reactor used, the shape of the reactor, the fuel that has been used an d the particle size of the fuel (Jahirul *et al.*, 2012). However, in general it can be said that char can be used as a fuel in boilers, for the production of activated carbon, for the production of carbon nanotubes, and for the production of pure hydrogen gas (Goyal, Seal & Saxena, 2006).

Reactors that are commonly used for (fast) pyrolysis are BFBs, CFBs, ablative reactors and entrained flow reactors. Since BFBs, CFBs and entrained flow reactors have been discussed already, they will not be treated here.

In ablative reactors, the fuel is forced against a hot surface. Upon contact the fuel melts. When the melted fuel, which has turned into an oil, it evaporates into the gases that are generally present during the pyrolysis process. The most common ablative reactors are rotating disk reactors and vortex reactors. Spinning disk reactors are relatively simple in their process. The fuel is forced against a disk that is heated and rotates. At the point where the fuel and disk touch the fuel softens and melts, resulting in the vaporization of the important pyrolysis gases. Vortex reactors are somewhat more complex. The fuel is enclosed by a high temperature gas that is also inert and is brought into the cylindrical reactor in the same direction as the reactor’s tangent, but with a slight angle so that the fuel will eventually exit the reactor. As the biomass is pressed into the hot reactor’s wall due to the centrifugal force, the fuel melts and evaporates to create the pyrolysis gases and char. A schematic representation of both ablative reactors is shown in figure 6.8.

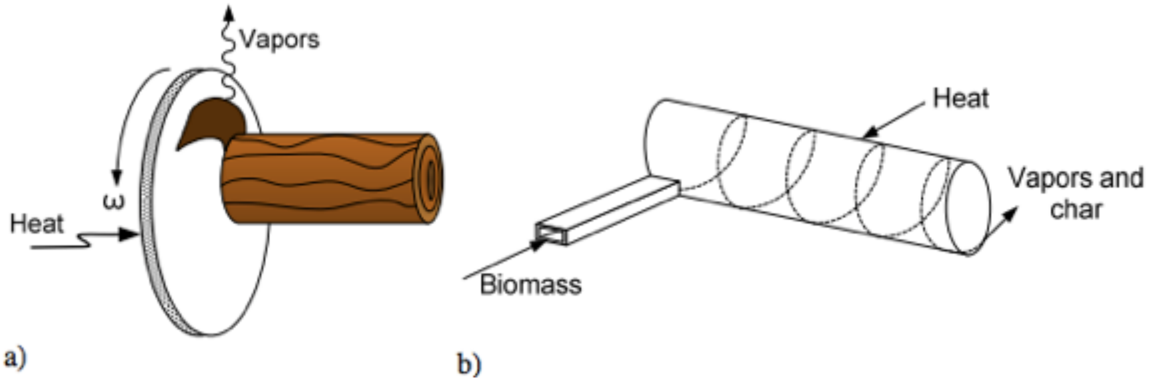


Figure 6.8 – A schematic representation of the techniques used in a rotating disk reactor (a) and a vortex reactor (b) (Ellens, 2009)

6.1.4 Liquefaction

Although basically being pyrolysis in hot liquid water, liquefaction is a complex process in which biomass is turned into bio oil ((Hakki *et al.*, 2013), Elliot *et al.*, 2015)). There is a difference between the bio oil retrieved from pyrolysis and the bio oil retrieved from liquefaction. Bio oil from liquefaction has a HHV of 28 – 36 MJ/kg (Ramirez, Brown & Rainey, 2015), while bio oil from pyrolysis only has a HHV of 14 – 22 MJ/kg (Jahirul *et al.*, 2012). However, pyrolysis has a higher maximum bio oil mass yield than liquefaction (Doassans *et al.*, 2014). Finally, bio oil from liquefaction is more viscous than bio oil from pyrolysis, but also less dense (Elliot *et al.*, 2015).

Behrendt *et al.* (2008) go somewhat into the processes that occur during liquefaction of biomass. They describe seven steps that need to be followed for the liquefaction of biomass. These steps are:

1. Preparation of the feedstock;
2. Slurrying of the feedstock within a liquid carrier;
3. Heating of the slurry to reach reaction conditions;
4. Addition of reducing gas at elevated pressure;
5. Main reaction;
6. Product separation; and
7. Solid-liquid separation and recovery of solvent.

It is difficult to describe what exactly happens during the main reaction phase of liquefaction as numerous reactions take place for cellulose, hemicellulose, and lignin and are dependent on the conditions of the liquefaction process (Brand *et al.*, 2014). It is, however, possible to give a simplified explanation of what occurs during the main reaction. According to Behrendt *et al.* (2008), the chemical steps that occur in the main reaction are:

1. Solvolysis of the biomass;
2. Depolymerization of the main components (cellulose, hemicellulose and lignin);
3. Chemical and thermal decomposition of monomers and smaller molecules leading to new molecular rearrangements through bond ruptures, dehydration, and decarboxylation; and
4. Degradation of oxygen containing functional groups in the presence of hydrogen.

Brand *et al.* (2014) summarized a few reactor designs used for biomass liquefaction, but a disadvantage of this list is that the reactors that were summarized are all batch reactors. It would be more convenient for the implementation of larger scale liquefaction power plants to transit from a batch process towards a continuous process. For this reason, liquefaction processes making use of continuous stirring tank reactors (CSTRs) gained more attention (Tran, 2016). However, these are not optimal for the high heating and cooling rates required for an improved continuous operation of a liquefaction power plant (Tran, 2016). For this reason, Tran (2016) issues the importance of the development of a plug- flow reactor (PFR) for liquefaction. The concept of the PFR is relatively easy to understand. The reactants are continuously inserted into a pipe (which is the reactor). The reactants are entrained by a liquid and move at the same speed as the liquid through the pipe, but don't react with the liquid. They reactants behave as if they were a plug being pushed through the pipe (resulting in the name PFR). The reactants only react with one another. Additionally, the conditions of the liquid that entrains the reactants/product(s) also remains constant. Judging from the discussions concerning the type of reactors that's best suitable for liquefaction, it seems that there is still growing potential for this technology to develop and improve its conversion capabilities from its current status. A schematic representation of a PFR is shown in figure 6.9.

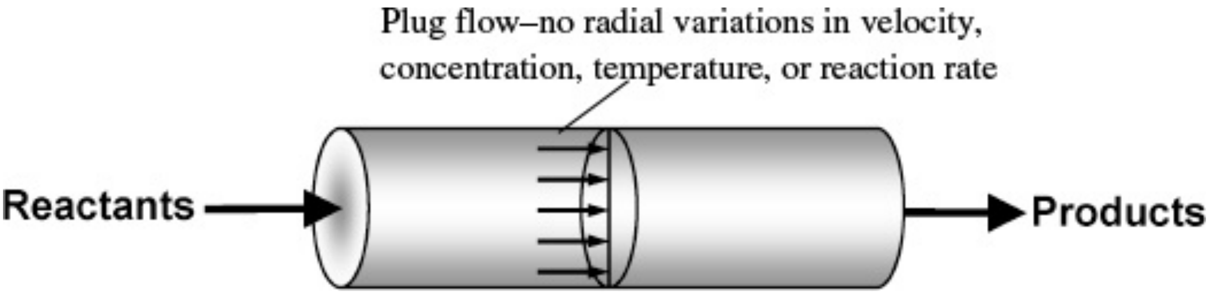


Figure 6.9 – A schematic representation of a PFR (Fogler, 2016)

6.2 Bio-Chemical Conversion of Biomass

6.2.1 Fermentation

Fermentation is a process that occurs when microorganisms are used to produce ethanol from biomass, known as bio ethanol. The materials in biomass that are converted into bio ethanol are sugars, starches and/or cellulose (Lin & Tanaka (2006). Although sugars can directly be converted into bio ethanol, starches and cellulose must first undergo hydrolysis so that these materials are converted into sugars, which are then converted into bio ethanol (Lin & Tanaka, 2006).

Bio ethanol can be used as a transportation fuel or it can be blended with some conventional transportation fuels. If bio ethanol is blended with petrol, the ethanol content can go up to 5% without needing any modifications for the combustion engine. However, if larger quantities are used for the blend or ethanol as pure transportation fuel, engine modifications are needed (Balat & Balat, 2009).

There are several steps that biomass must undergo to be converted into bio ethanol. These steps are biomass preparation, pretreatment, hydrolysis or saccharification, fermentation, and distillation ((Lin & Tanaka, 2006), (America's Energy Future Panel on Alternative Liquid Transportation Fuels, 2009)). During the preparation step, unwanted material is removed from the biomass fuel to make sure contamination doesn't take place (or as little as possible). During pretreatment, the materials in biomass that compass cellulose, such as lignin, are broken down. This makes sure that the enzymes targeting cellulose have a better accessibility to the cellulose, and increases the conversion efficiency. After this happened, the saccharification or hydrolysis step is initiated. In this step, big molecules like cellulose and hemicellulose are converted into sugars such as glucose and xylose. When the sugars have been produced, microorganisms such as yeast and certain bacteria can convert these sugars into ethanol during the fermentation step. A conversion of the glucose molecule and the xylose molecule are shown in reactions 7 and 8 respectively.

$$C_6H_{12}O_6 \xrightarrow{\text{Microorganism}} 2\ C_2H_5OH + 2\ CO_2 \tag{7}$$

$$3\ C_5H_{10}O_5 \xrightarrow{\text{Microorganism}} 5\ C_2H_5OH + 5\ CO_2 \tag{8}$$

Finally, the mixture that results from the fermentation step needs to be distilled to retrieve ethanol of high purity. In the residual of the distillation process are solids with high amounts of lignin, which can be used still as a fuel in a boiler for the production of electricity, heat, or both (America's Energy Future Panel on Alternative Liquid Transportation Fuels, 2009).

There are three main types of reactors that can be used for fermentation; batch reactors, fed-batch reactors, and continuous reactors (Zabed *et al.*, 2014). As was discussed with the case of liquefaction, (automated) continuous processes would be more convenient for larger scale fermentation plants. According to Zabed *et al*. (2014) mainly two type of reactors are used; PFRs and CSTRs.

CSTRs are relatively simple reactors. The reactants are added at the top of the reactor. In the reactor, the liquid is continuously stirred at a steady state so that the mixture in the tank is more or less the same throughout the tank (except for the place where new reactants are continuously being inserted). At the bottom of the reactor is an outlet which can transport the products away from the reactor (towards the distillation process in the case of fermentation). A schematic representation of a CSTR is shown in figure 6.10.

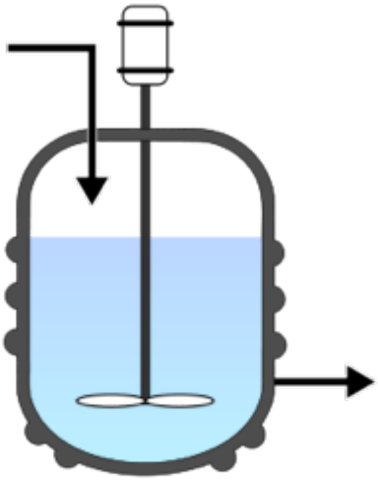


Figure 6.10 – A schematic representation of a CSTR (Wikipedia, n.d. A)

6.2.2 Anaerobic Digestion

Anaerobic digestion (AD) is a process that takes place when biomass is converted by specific microorganisms into mainly CH_4 (45 – 70%) and CO_2 (25 – 55%), but also H_2O and H_2S

(Markewitz & Bongartz, 2015). The materials in biomass that are, eventually, converted into methane are carbo-hydrates, fats, and proteins (Saedi *et al.*, 2008). Biogas is mainly used to generate electricity and/or heat by combusting it in a gas combustion engine, or biogas is added to the natural gas grid, where it can be used by filling stations as a fuel for vehicles or by residents for cooking or heating. However, for this to happen some treatment of the biogas is needed. Figure 6.11 shows the applications of biogas.

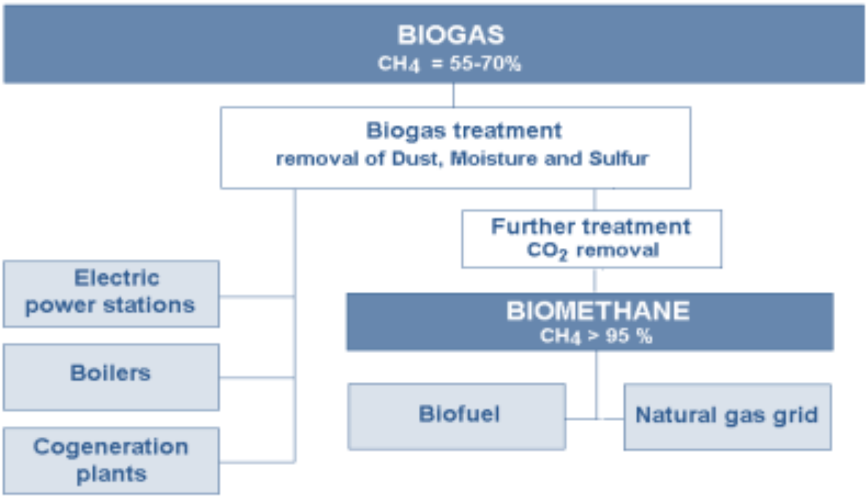


Figure 6.11 – Main applications of biogas (edited from Raboni & Urbini (2014))

There are several steps that biomass must undergo to be converted into biogas. These steps are hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Adekunle & Okolie, 2015). During the hydrolysis step, large molecules of biomass are downgraded into smaller molecules such as monosaccharides and amino acids. During the acidogenesis step, bacteria convert small sugar molecules, amino acids and fatty acids into CH_3COO, CO_2, H_2, volatile fatty acids (VFAs), and alcohols (Saedi *et al.*, 2008). Some of these products can be converted into CH_4. However, the products that still can't be converted into methane after acidogenesis are converted further during acetogenesis into products that can be converted into methane. These are mostly the VFAs and alcohols that are converted in this step. Finally, during the methanogenesis step CH_4 is made from the molecules present. The main reactions that occur in this step are:

$$\mathrm{CH_3COOH} \xrightarrow{\text{Bacteria}} \mathrm{CH_4} + \mathrm{CO_2} \tag{9}$$

$$4\ \mathrm{H_2} + \mathrm{CO_2} \xrightarrow{\text{Bacteria}} \mathrm{CH_4} + 2\ \mathrm{H_2O} \tag{10}$$

According to Ersahin *et al*. (2011), the most commonly used reactors for anaerobic digestion are completely mixed anaerobic digesters, upflow anaerobic sludge blanket reactors (UASB reactors), fluidized and expanded bed reactors, and anaerobic filters (AFs).

Completely mixed anaerobic digesters are more or less the same as CSTRs. The only difference is that at the top of the reactor, the produced biogas is captured. Fluidized and expanded bed reactors are very similar to the fluidized bed reactors discussed in the combustion section. The only difference is that in the case of anaerobic digestion, besides no oxygen being inserted for the combustion of the released gases, the microorganisms that are important key players in the acidogenesis, acetogenesis and methanogenesis steps are attached to the material that is to be fluidized. Additionally, effluent is transported away from the reactor.

The UASB reactor is a reactor that is filled with a sludge bed. In this sludge bed, granules of microorganisms important for anaerobic digestion form. The biomass is inserted from the bottom of the reactor, and moves upwards while reacting with the granules. At the top of the reactor, the biogas is captured and the effluent is transported away from the reactor. A schematic representation of an upflow anaerobic sludge blanket reactor is shown in figure 6.12.

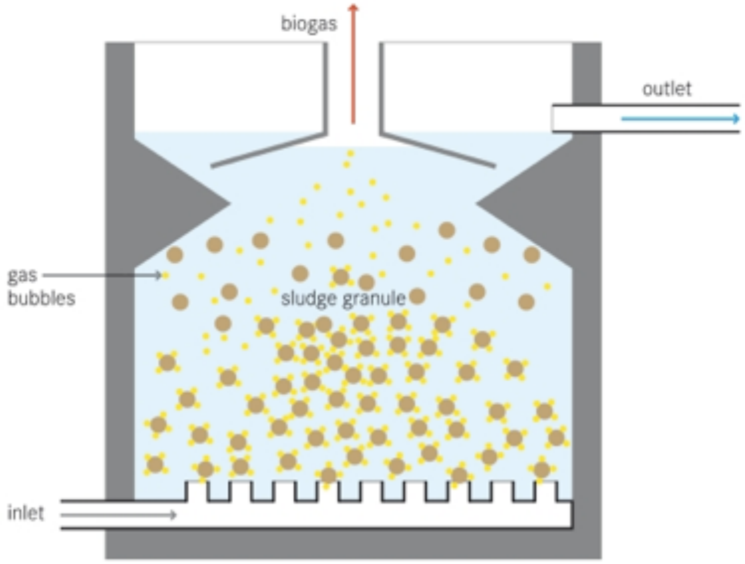


Figure 6.12 – A schematic representation of an UASB reactor (Wikipedia, n.d. B)

There are two type of AF reactors. One with a flow downwards and one with a flow upwards. Regardless of which type of AF reactor is, the reactor has a filter in it to which the microorganisms important for anaerobic digestion are attached. Due to biomass being trapped by the filter, the microorganisms can conduct anaerobic digestion to generate biogas. In both reactors biogas is recovered at the top of the reactor. Depending on the reactor, the effluent is captured at the top or bottom of the reactor (upflow AF reactor and downflow AF reactor respectively).

7 Current Status of Bioenergy in the Netherlands

To get a better idea of the possible pathways that bioenergy in the Netherlands might take, it is of use to evaluate the current status of bioenergy in the Netherlands. Since data on 2016 hasn't been made public yet, the focus of this section will be put on the period 2013 – 2015.

The amount of bioenergy, renewable energy and total use of energy in 2013 to 2015 in the Netherlands is shown in table 7.1.

Table 7.1 – The amount of energy consumed in the Netherlands produced by biomass, renewable, and the total amount of energy consumed for the years 2013, 2014, and 2015 (electricity, heat and transport) (CBS, 2016a)

Year	Final Consumption of Bioenergy (PJ)	Final Consumption of Renewable Energy (PJ)	Total Final Consumption of Energy (PJ)
2013	76.6	104.6	2,192
2014	78.7	110.5	1,993
2015	80.2	118.7	2,052

Although the total final consumption of energy shows a little fluctuation, the final consumption of renewable energy shows a steady increase by starting on 4.8% in 2013, and increasing to 5.5% in 2014, and 5.8% in 2015. Biomass has played a large role in the consumption of renewable energy, contributing to over 70% in 2013 and 2014, and approximately 67.6% in 2015. Even though the total consumption of bioenergy is increasing, the contribution to the total amount of renewable energy consumed has decreased over the past years to to higher contributions of renewable energy sources such as wind and solar power.

7.1 Biomass for Electricity and Heat

According to the CBS (2016a), the most important applications of the generation of electricity and heat through biomass are:

- Waste incineration plants (WIPs);
- co-firing of biomass;
- biomass combustion to generate electricity for companies (this also includes generating heat by use of CHP);
- biomass combustion to generate heat for companies;
- biomass combustion by households;
- landfill gas (biogas);
- biogas from sewage treatment plants;
- anaerobic digestion of manure (biogas); and
- other biogas (biogas originating from wastes such as biodegradable household waste and waste from the food industry).

Although CBS (2016a) treats the production of green gas out of landfill gas and other biogas, for some reason it isn't included in the CBS' general bioenergy summary. As green gas also contributes to the consumption of renewable energy, it will be taken into account in this study. Figure 7.1 shows the relative contribution of all different applications for the generation of electricity and heat through biomass use. Because of organization confidentiality it was not possible for the CBS to report on co-firing of biomass and biomass combustion to generate electricity for companies. For this reason, both applications have been added to each other.

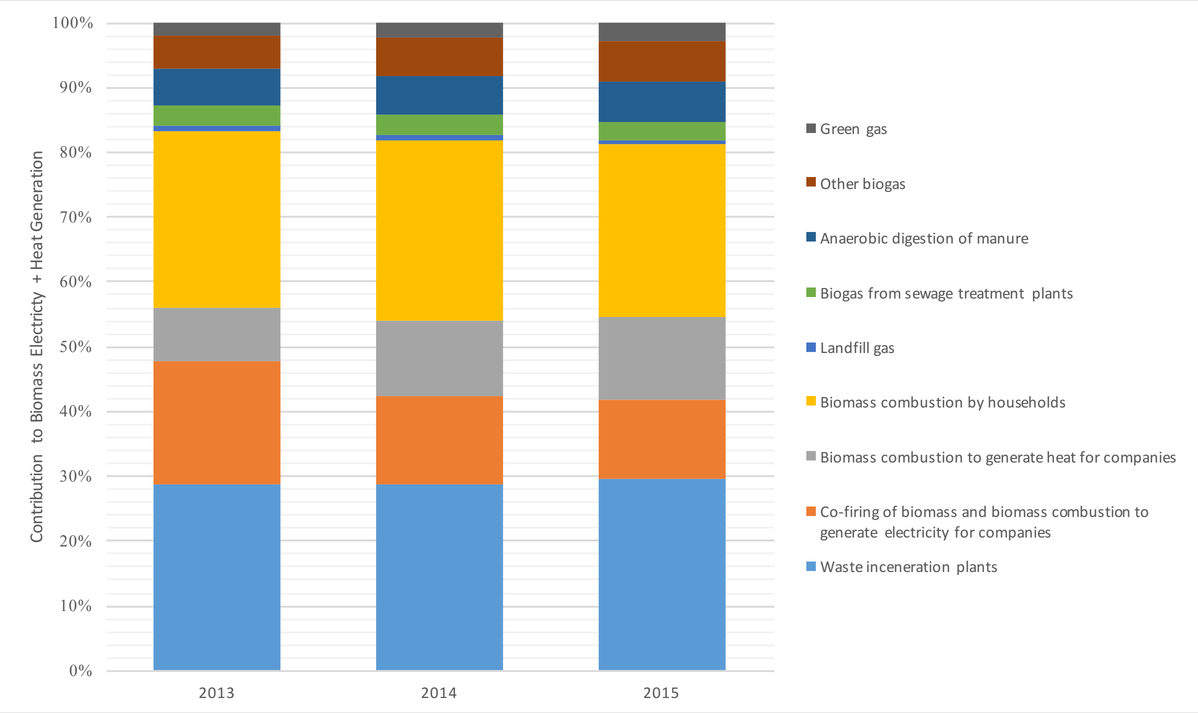


Figure 7.1 – Relative contributions of different applications of generating electricity and heat through the use of biomass in the Netherlands in 2013, 2014 and 2015 (data used from CBS (2016a))

The total amount of electricity and heat generated in 2013, 2014 and 2015 amounts to 64.7, 64.9, and 68.6 PJ respectively (CBS, 2016a). Largest contributions come from WIPs and biomass combustion by households. Bioenergy production in WPIs, biomass combustion to generate heat for companies, and the production of biogas as a whole. On the contrary, the contribution of co-firing of biomass and biomass combustion to generate electricity for companies and biomass combustion by households decreased between 2014 and 2015.
The decrease in co-firing of biomass in the Netherlands relates amongst other things to the MEP-subsidy expiring (CBS, 2016a). Together with the decrease in production price for coal, this resulted in an increase in the use of coal in the Netherlands of the last past years (CBS, 2016b). Using biomass for electricity generation by companies has, on the other hand, remained more or less the same over the last past years (CBS, 2016a).

The Netherlands Enterprise Agency (NEA) released a report on sustainable biomass and bioenergy in the Netherlands (Netherlands Enterprise Agency, 2016) in which, amongst other things, the composition of treated waste in WIPs is addressed. The composition of waste used in the Netherlands to generate bioenergy in WIPs in 2012 to 2014 is shown in figure 7.2. What becomes clear is that the largest component of waste burnt in WIPs is from organic waste and paper waste.

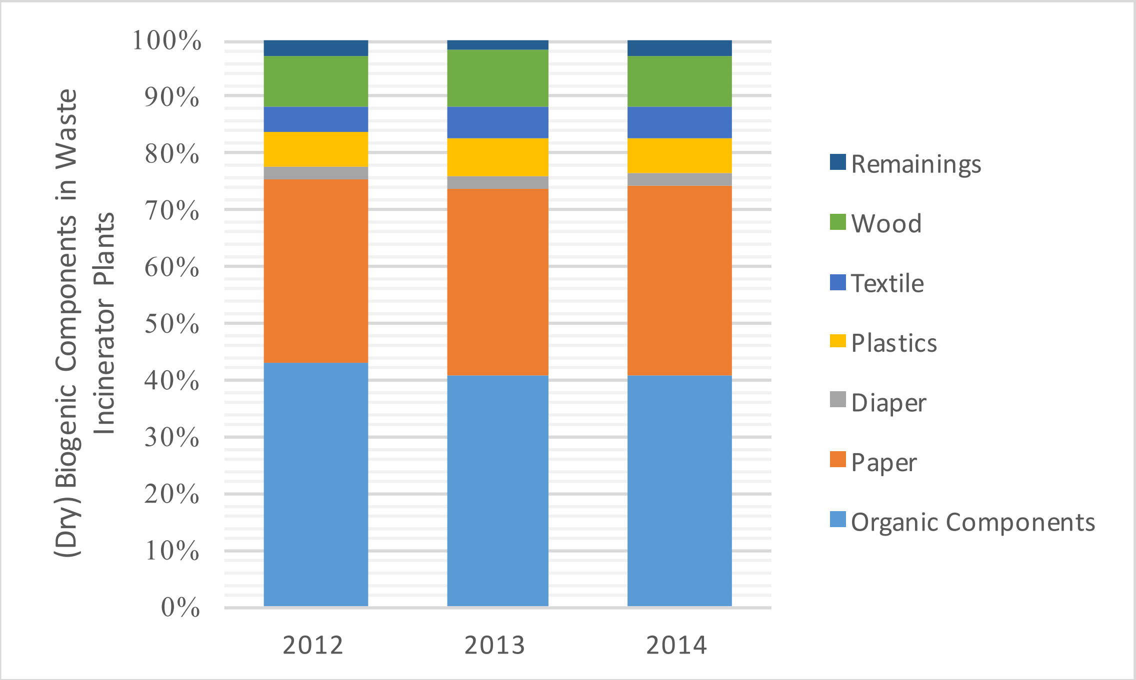


Figure 7.2 – The composition of waste used in WIPs to produce bioenergy in the Netherlands in 2012, 2013 and 2014 (data used from Netherlands Enterprise Agency (2016))

For co-firing of biomass, biomass combustion to generate electricity and heat for companies, and for biomass combustion by households, mostly woody biomass is used. The composition and total amount of woody biomass used in the Netherlands for 2013 is shown in figure 7.3. Sadly, values for 2015 weren't available and the values for 2014 were incomplete due to organization confidentiality information.

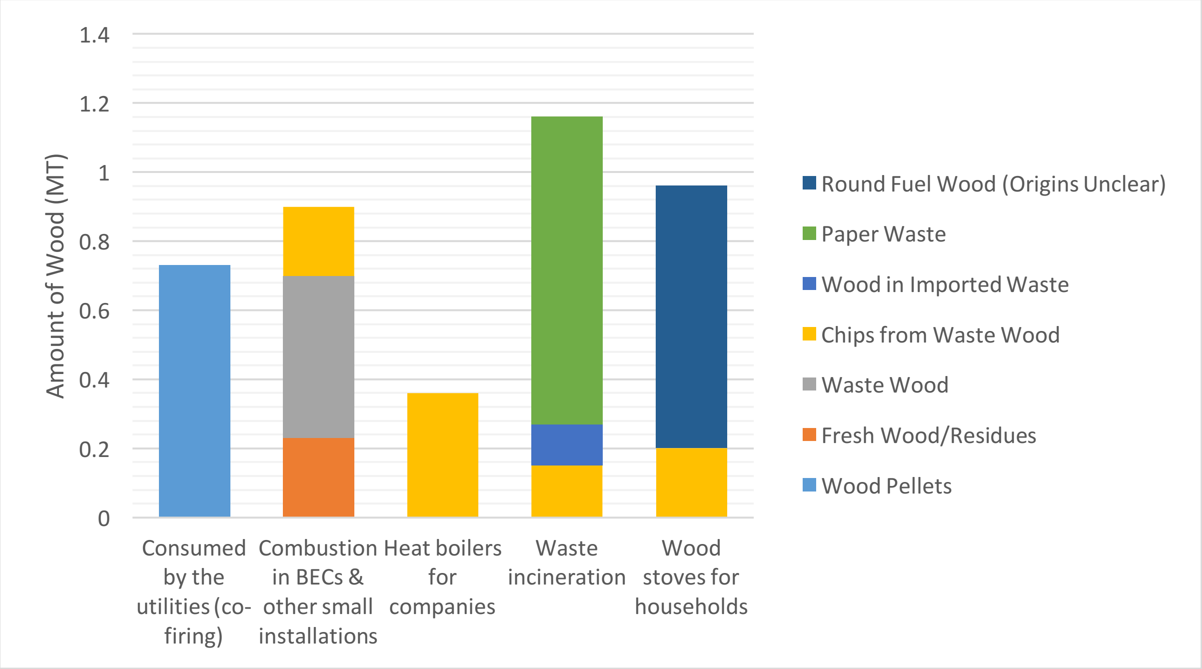


Figure 7.3 – The composition and total amounts of woody biomass used in different applications in the Netherlands in 2013 (data used from Netherlands Enterprise Agency (2016))

The green gas is biogas upgraded from landfill gas and other biogas. The majority of biogas is produced from other biogas. In 2013 this contribution was 89%, in 2014 87%, and in 2015 93% (CBS, 2016a).

7.2 Biomass for Transport Fuels

In 2013, 2014 and 2015 the total energy supplied to the transport sector by biofuels amounted to approximately 16.5, 16.2, and 18.0 PJ (Dutch Emission Authority, 2016a). The Netherlands has a blend obligation to add renewable energy to the mix of energy supplied to the transport sector. The minimal blend obligation can be found in appendix 7.1.

There are three possible biofuels that can be used in the transport: biogas, bio-gasoline, and biodiesel. Figure 7.4 shows the relative contribution to biofuel use in the Netherlands (based on the energy generated). It becomes apparent that the majority of the contribution stems from biodiesel. Bio-gasoline also has a relatively large contribution, while biogas is barely used in the Netherlands.

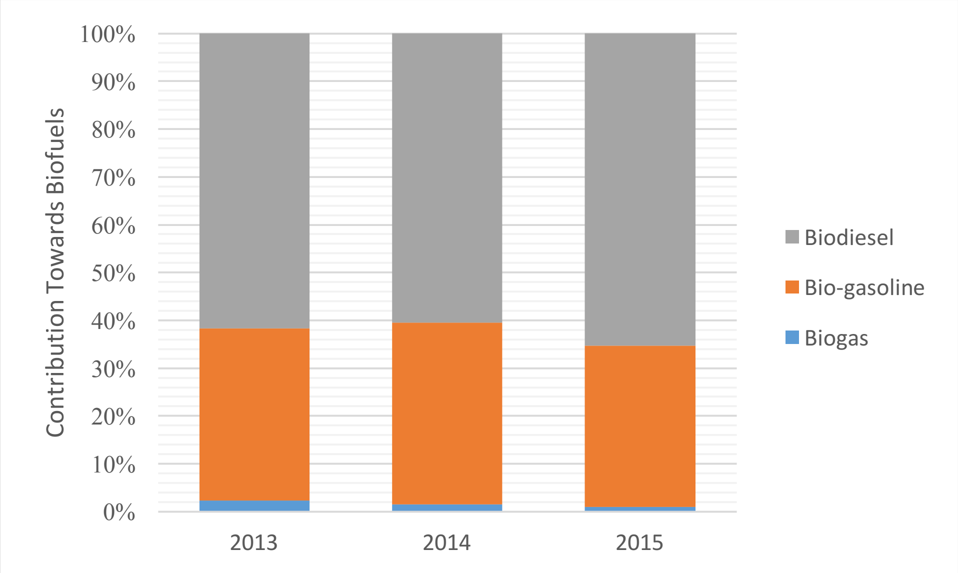


Figure 7.4 – Contributions of biodiesel, bio-gasoline, and biogas to the biofuel use in the Netherlands in 2013, 2014 and 2015 (data used from Dutch Emission Authority (2016a))

Figure 7.5 and figure 7.6 shows the types of bio-gasoline and biodiesel produced respectively. For bio-gasoline, mainly ETOH (ethanol) is produced. For biodiesel, mainly FAME (fatty acid methyl ester) is produced.

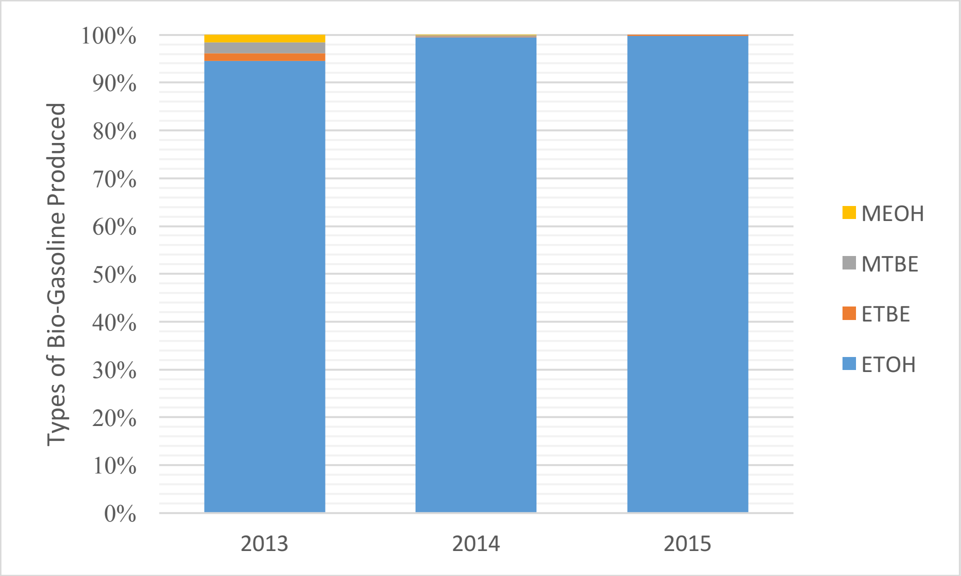


Figure 7.5 – The different types of bio-gasoline produced in the Netherlands in 2013, 2014 and 2015 (data used from Dutch Emission Authority (2016a))

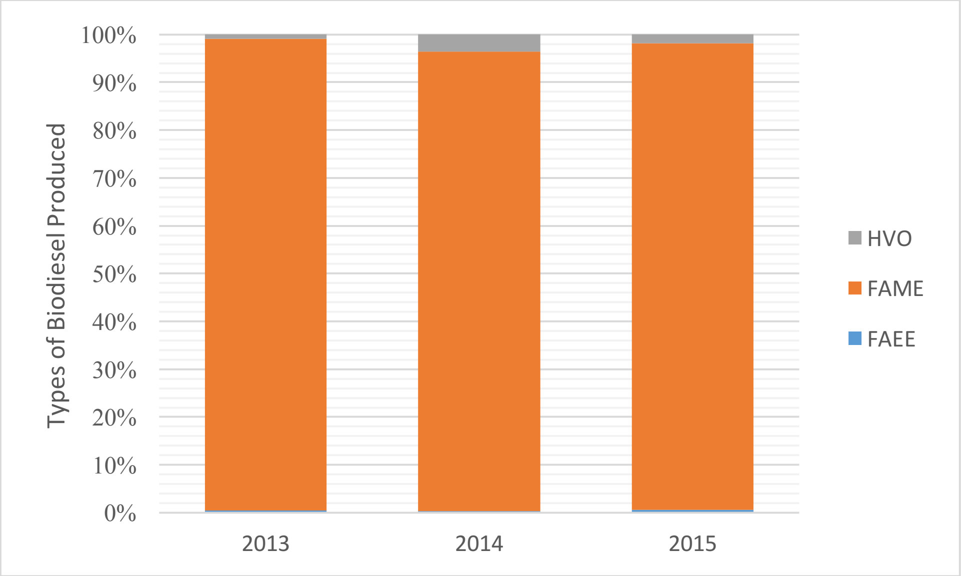


Figure 7.6 – The different types of biodiesel produced in the Netherlands in 2013, 2014 and 2015 (data used from Dutch Emission Authority (2016a))

Figure 7.7 shows the different raw materials used to produce either biogas, bio-gasoline or biodiesel. As discussed earlier, the main materials used for the production of biogas that can be used by cars (green gas) mainly originates from landfill gas/municipal waste and other biogas. There is a relatively large amount of materials used to produce bio-gasoline that have relatively large contribution. The main materials used are wheat and maize, followed up by sugar cane and sugar beet. For biodiesel the main used material is used cooking oil, followed by rapeseed and animal fat (category 1 or 2) (animal fat category 1 or 2 means that the fat is suitable for energy generation or technics).

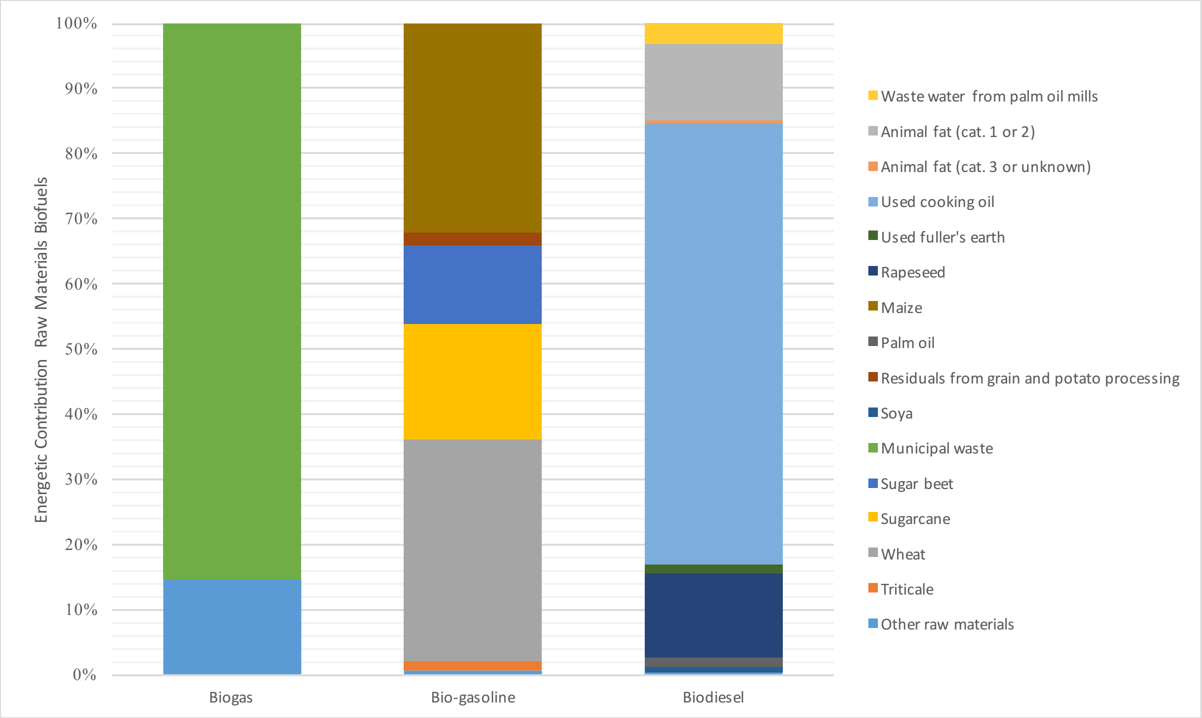
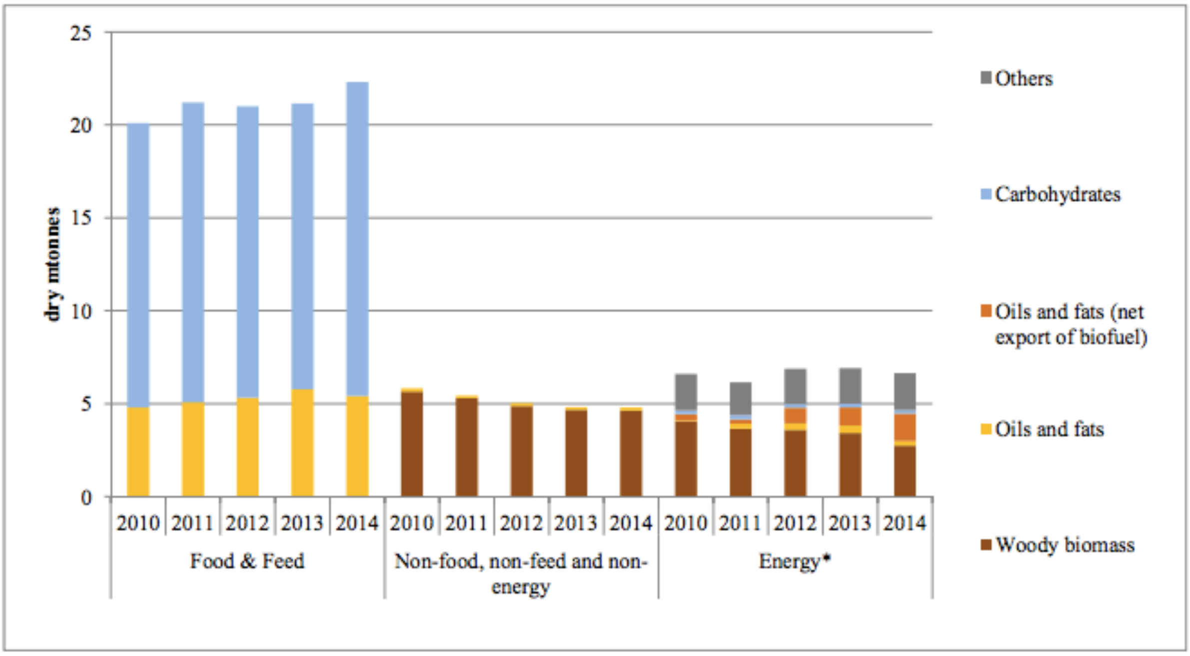


Figure 7.7 – The different raw materials used for the production of biogas, bio-gasoline or biodiesel in the Netherlands in 2015 (data used from Dutch Emission Authority (2016a))

7.3 Other Uses of Biomass in the Netherlands

Figure 7.8 shows an overview of biomass feedstock that are used in different sectors within the Netherlands between 2010 and 2014.



* Carbohydrates shown for use for energy is domestic consumption of bioethanol only, export of bioethanol is not included here due to lack of reliable data.

Figure 7.8 – An overview of biomass biomass feedstock used in different sectors in the Netherlands between 2010 and 2014 (Netherlands Enterprise Agency, 2016)

As can be expected, the majority of biomass use occurs in the food & feed industry. In 2014 about 22 tonnes was used in this industry. In the energy sector, approximately 7 tonnes was used in 2014, while in the non-food, non-feed and non-energy sectors the biomass use was about 5 tonnes. So a good +60% of biomass is used for human and animal consumption, while only around 20% is used for energy production.

8 The Development of Biomass Use in the Netherlands until 2050

This section will look into how the use of biomass will develop until 2050. The base year that has been taken is 2015, and 2030 is taken as an intermediate period taken into account.

To asses the possible change of biomass use in the Netherlands until 2050, 3 scenarios will be developed to see how different paths might affect the use of biomass and, eventually, the negative emissions realizable by the Netherlands. The scenarios revolve around a scenario where the Netherlands will only use its own biomass to produce bioenergy, a scenario where all the biomass in the world will be evenly shared, and finally a scenario in which the Netherlands will develop itself into an expert regarding the handling of biomass for bioenergy purposes and exploit this expertise by increasing the import of biomass. These scenarios will be more specifically presented below.

8.1 Scenario 1 – The Netherlands Uses Only Its Own Biomass

In this scenario the Netherlands' will only use the biomass that it produces itself. An important component in the production of electricity and heat from biomass is woody biomass. The Netherlands' Enterprise Agency (2016) has some detailed mass flows of woody biomass regarding own production, import, and export. Because the year 2014 hasn't been published in detail by the Netherlands' Enterprise Agency (2016) due to secrecy of data, only the year 2013 will be taken into account.

8.1.1 Production of Electricity and Heat from Biomass

For the production of wood products, a total of 2.9 megatons of woody biomass was used. Of this 2.9 megatons, 2.43 megatons was imported while only 0.47 megatons was self produced. This is only 16% of the total. The total output of waste from wood products that was used for the production of bioenergy amounts to 1.7 megatons of woody biomass. Seeing that only 16% of the woody biomass used for the production of wood products means that only 16% of the total waste supplied by wood products is from the Netherlands itself. That amounts to 272 kilotons of woody biomass. From the woody biomass that is used to make paper and cardboard products, 0.46 megatons of the in total 4.77 megatons that is used is from import. This is about 10%. So from the 0.62 megatons of waste from paper and cardboard products that is used by WIPs, 558 kilotons originates from the Netherlands. Finally, there's 0.76 megatons of round fuel wood that's used for wood stoves in households.

So the total amount of woody biomass that originates from the Netherlands and was used for bioenergy production in 2013 was 1.59 megatons of woody biomass. The total amount of woody biomass used for electricity and heat production amounts to 4.11 megatons. So only 39% of the woody biomass used in the Netherlands for electricity and heat production originated from the Netherlands.

In 2012, 2013, and 2014 the amount of imported waste used in WIPs was 12%, 22%, and 21% respectively (Netherlands Enterprise Agency, 2016). On the one hand, the production of energy from WIPs (taken into account that just a certain amount of that energy is from biomass in the waste) will most likely correlate to the development of the Dutch population. However, only 53% of the waste in the Netherlands was separated in 2015 (Environmental Data Compendium of the Netherlands, 2016a). The government wishes to separate 75% of the waste in 2020 (Government of the Netherlands, n.d.), and according to Milieu Centraal (n.d.) a theoretical potential of 83% waste separation can be achieved. So the increase in bioenergy produced from WIPs will be based on the 2015 value, minus 21% import, and correlate to the population growth minus the change due to increase in separation. The assumed population growth for the Netherlands was taken from the UN's World Population Prospects 2015 revision edition (UN, 2015). It's assumed that the Dutch population increases from 16.9 million people in 2015 to 17.6 million people in 2030. Between 2030 and 2050 it is assumed that this amount doesn't change. Most likely the theoretical potential of waste separation will not be reached, but a value slightly below the theoretical potential will. For this, a waste separation of 80% in 2050 is assumed. It's expected that the amount of waste separation between 2020 and 2050 will occur in a linear fashion. The 2030 value is extracted from this.

It will be assumed that co-firing of biomass will disappear completely in this scenario. A large amount of the woody biomass used in these installations (wood pellets) is imported. Additionally, the total amount of wood pellets were already facing heavy declines going from 1.43 megatons in 2010 to 0.73 in 2013 and 0.15 in 2014 (Netherlands Enterprise Agency, 2016). In combination with the expired subsidy and the cheapness of coal, there will barely be an incentive to conduct co-firing of biomass. With no numbers on the amount of pellets used in 2015, this year becomes slightly difficult to project. It will be assumed that in 2015 only 0.04 megatons of pellets were used for co-generation. Close to the decline between 2013 and 2014. Based on the relative difference between 2013 and 2015, the amount of energy produced from co-generation will be calculated.

Combustion of biomass for electricity and heat production for companies is assumed to start at 39% of the most recent known amount of energy production. The most recent known value for production of electricity for companies is calculated by subtracting the amount of energy produced by co-generation from the total amount of energy produced from co-generation and electricity production for companies from biomass.
Woody biomass is a very important component for energy generation by companies through biomass. According to the World Bank (n.d.b), the land area of forest in the Netherlands grew from 3,698 square kilometers in 2008 to 3,760 square kilometers in 2015. This is an increase of approximately 0.2% per year. It's highly uncertain to predict the future growth of the Dutch forest, but it is assumed that from 2015 will not grow any further until 2050. So it's assumed that no additional biomass will come from the land in the Netherlands. It is, however, assumed that the extra separated biomass that will become available due to increased waste separation will be used in these installations. This includes decreases in biomass from waste incinerations plants, land fill gas, green gas (indirectly through land fill gas) used in electricity production, heat production, and transport.

A large part of the biomass that was used for heat production by households already originated from the Netherlands. It's expected that this amount of supply within the Netherlands will stay the same, since, as earlier noticed, the amount of woody biomass produced in the Netherlands that isn't waste isn't assumed to increase.

The amount of landfill gas is expected to contain the same amount of imported waste as is the case with WIPs. The last known amount of landfill gas (excluding the percentage of imported waste) is expected to correlate to the Dutch population minus the change in in waste separation.

Biogas from swage treatment plants and other biogas are both also expected to correlate to the Dutch population.

The Netherlands struggles with a surplus of manure (RVO, n.d.b). According to data from the World Bank (n.d.b), the amount of arable land in the Netherlands has been changing quite some over the time. It started from 1,067 thousand hectares in 2008 to 1,006 thousand hectares in 2011, after which it started increasing again to 1,045 thousand hectares in 2014 (data for arable land in the Netherlands in 2015 and 2016 wasn't published yet) (World Bank, n.d.b). If it is assumed that the average yearly increase of arable land that happened between 2011 and 2014 (which was 1.3%) continues to occur, but reaches a limit at 1,067 thousand hectares, this will occur in 2015. This scenario assumes that this will not change from this point on. However, it is assumed that the amount of cattle will grow with the population growth to supply enough animal products to the population. Taking these two things into account means that the amount of biogas from anaerobic digestion from manure will also be assumed to increase with population growth.

Green gas originates from the both land fill gas and other biogas. Since this is the case, it's expected that the latest known amount of green gas that was produced by land fill gas will decrease by 21%, while the green gas produced by other biogas remains the same. From this starting point the amount of green gas will be expected to correlate to the development of the Dutch population minus the effect change in waste separation will have on the amount of green gas produced land fill gas.

It's expected that there isn't going to be any developments in other technologies that are able to use biomass for the production of bioenergy, since there's so little biomass available. Goals regarding sustainable energy use will need to be met through increased deployment of alternative renewable energy technologies.

This scenario results in the energy production amounts visible in table 8.1. It's assumed that the values of bioenergy produced in different applications between 2015 and 2030, and 2030 and 2050 will change in a linear manner.

Table 8.1 – Assumed volumes of bioenergy production in the Netherlands with different applications in 2015, 2030, and 2050 in scenario 1

Biomass Application	Amount of Bioenergy Produced (TJ)		
	2015	2030	2050
Waste Incineration Plants	16,040	8,290	7,110
Co-firing of biomass	380	0	0
Biomass combustion for electricity for companies	3,100	7,160	7,740
Biomass combustion for heat for companies	3,420	8,000	8,640
Biomass combustion by households	18,370	18,370	18,370

Landfill gas	290	150	130
Biogas from sewage treatment plants	1,950	2,020	2,030
Anaerobic digestion of manure	4,220	4,390	4,390
Other biogas	4,300	4,480	4,480
Green gas	80	80	80
Total	*52,150*	*52,960*	*52,970*

8.1.2 Production of biofuels from biomass

For the production of biofuels, the Dutch Emissions Authority (2016a) already reported that only 9.8% of the biofuels was produced by products coming from within the Netherlands. However, for the projection of biofuel projection from biomass not only the origin of the biofuel will be taken into account, but also the level of sustainability. This is because it is expected that in the future the nature of the biomass used for biofuels will become even more important than it is currently, and it is probable that bioenergy will not be produced from materials that also can be used in the food and/or feed industry (this assumption isn’t just for this scenario, but for all three scenarios).

As shown in appendix 7.1, the Netherlands has an obligation to blend a certain amount of renewable energy into the fossil fuels. Certain biofuels are allowed to count twice their energy content to fulfill this obligation based on their nature. The categorization between the two kinds of biofuels is termed as “single counting”, which doesn’t count twice, and “double counting”, which does count twice. According to the Dutch Emissions Authority (2016b), the reason that double counting was established was to limit the use of food crops, improve the CO_2 performance of the fuel mix, and to stimulate the development of more advanced biofuels.

Both single counting and double counting biofuels need to come from sustainable chains supplies and must be proven to be sustainable by means of sustainable certifications to be acknowledged by the Dutch Emission Authority (Dutch Emission Authority, 2016b). The difference between single counting and double counting is that double counting biofuels are biofuels produced from waste, residuals, non-food cellulosic material and lignocellulose material (Dutch Emission Authority, 2016b). Although single counting biofuels need to be produced from sustainable certified biomass, it’s possible that these biofuels were produced from cellulosic material that could have been used as food. For this reason, all single counting biofuels will not be included. Because of this, the amount of biofuels originating from the Netherlands in 2015 decreases slightly to 9.7%. Appendix 8.1 shows the sources for the production of biogas, bio gasoline and biodiesel, and how much of these sources were used for the production of the biofuels.

First of all, it is assumed in this scenario that the obligation for mixing fuels will not be important anymore due to the low availability of biomass. Increasing the share of renewable energy in transport will be orchestrated mainly by electric vehicles and hydrogen electric vehicles than either biofuel blended fuels or 100% biofuels.

It is expected that animal fat (cat. 1 or 2), used cooking oil, and municipal waste will correlate to the Dutch population. There will be more processing of animals due to needing to feed more people, and more people will also use cooking oil. Municipal waste is assumed to decrease. Thus, the growth of biogas from municipal waste is expected to correlate to population growth minus the change in separation of waste. Residuals from grain and potato processing will remain the same from 2015 until 2050 as it is assumed that the amount of arable land will not change after 2015. Other raw materials is defined by the Dutch Emission Authority (2016a) the sum of barley, empty fruit bundles of palm, molasses and purification sludge from sewage treatment plants. Although it might be expected that the amount of purification sludge will correlate to the Dutch population, the others are not expected to do so since the amount of arable land is assumed to remain the same. Thus it is assumed that other raw materials will remain its same value between 2015 and 2050.

Table 8.2 shows the total amount of biofuels that is assumed to be produced for 2015, 2030, and 2050. It’s expected that the changes between 2015 and 2030, and 2030 and 2050 happen in a linear way. It’s also assumed that the ratios of biofuels from a certain material in 2015 will remain constant between 2015 and 2050.

Table 8.2 – Total amount of biofuel that is assumed to be produced in the Netherlands in 2015, 2030, and 2050 in scenario 1

Material Used	Amount of Bioenergy Produced (TJ)		
	2015	2030	2050
Animal Fat (cat. 1 or 2)	23	24	24
Used Cooking Oil	1,472	1,533	1,533
Residuals from Grain and Potato Processing	86	86	86
Municipal Waste	150	78	67
Other Raw Materials	14	14	14
Total	*1,745*	*1,734*	*1,723*

For WIPs, (co-)firing of biomass, and biomass combustion for electricity for companies it is assumed that the bioenergy produced has been produced in CHPs with a conversion efficiency of 85%, which is the European Union’s average (Basis Bioenergy, 2015). IEA (2007) expects the conversion efficiencies of above 85 – 90%, thus it is assumed that the 2030 conversion efficiency of these plants will be 90% in 2030 and 93% in 2050. The conversion of heat plants, relevant or biomass combustion for heat for companies, will be assumed to be 84%, which is the European Union’s average (Basis Bioenergy, 2015). For these plants it’s assumed that a more or less similar path will be followed. It is assumed that in 2030 the conversion efficiency will be 87% and will increase to 90% in 2050. As biomass used by residents is for the production and direct use of heat, no losses in conversion will be assumed. For the production of biogas from landfill gas and other biogas, it is assumed that a conversion efficiency of 15% applies for the generation of electricity and 70% applies for the generation of heat (IEA, 2008). For green gas, it is assumed that the energy conversion efficiency amounts to 62.2% (Huang & Zhang, 2011). For biofuels it’s assumed that the energy conversion efficiency for biodiesel is 36.5%, for bio gasoline it’s 55.6% and for green gas used in gas cars it’s still assumed to be 66.2% (Huang & Zhang, 2011).

Adding up the amounts of bioenergy available for the Netherlands from electricity, heat and biofuels leaves us with an amount of 53,890 TJ of bioenergy used in 2015, an amount of 54,650 TJ of bioenergy in 2030 and an amount of 54,690 TJ in 2050. The amount of biomass used to produce bioenergy in 2015, 2030 and 2050 was 59,230 TJ, 58,580 TJ and 57,750 TJ respectively.

8.2 Scenario 2 – All the Biomass in the World Divided Equally per Person

In this scenario it will be assumed that all the biomass in the world will per equally divided per person in the world. The global population increases from 7,350 million people in 2015 to 8,501 million people in 2030, and 9,752 million people in 2050 (UN, 2015). Of these amounts, the Dutch population contributes to 0.23, 0.21 and 0.18% in 2015, 2030 and 2050 respectively (UN, 2015).

Regarding the projection of biomass for energy development into the future, a wide range of possibilities have been explored. Certain ranges of bioenergy production in 2050 have been proposed, being between 0 and 100 EJ pear year, 100 and 300 EJ per year, 300 and 600 EJ per year, and finally +600 EJ per year. Slade *et al.* (2011) did an assessment regarding the underlying conditions for the production of certain values for biomass production for energy use in 2050, and came up with figure 8.1.

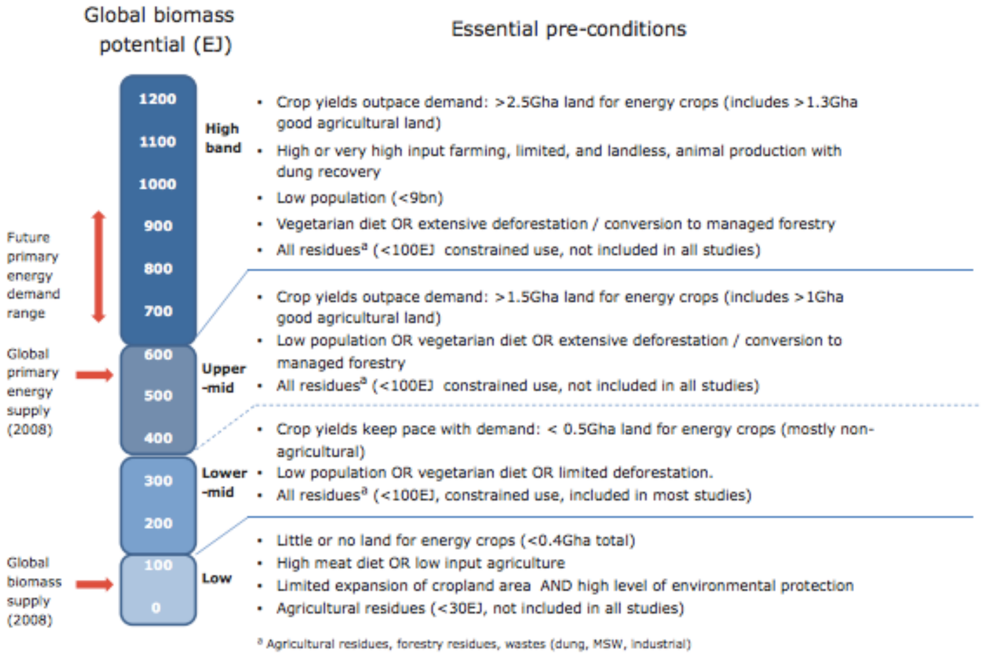


Figure 8.1 – Explanation of underlying assumptions for projections of biomass development for energy use (Slade *et al.*, 2011)

For this research it has been chosen to go for a realistic assumption. Searle & Marlins (2015) tried to update ten modeling studies that have been used widely by influential instances, such as the IPCC and the IEA, by re-examining the potentials. The re-examination tries to correct the potentials based on realistic insights in variables, such as available land area, energy crop yields, production costs, governance quality, forestry residues, and crop residues and wastes. Where the ten modeling studies first had a total range of 0 to nearly 1,300 EJ per year, after the re-examination of Searle & Marlins (2015) the range shifted towards 45 – 111 EJ per year.

Since the Searle & Marlin's approach already is very realistic in terms of achievability, it will be assumed that the maximum potential for biomass supply will be achieved in 2050: 111 EJ per year. In 2013 this amount was 57.7 EJ (World Bioenergy Association, 2016). It's assumed that the increase from 2013 until 2050 will happen in a linear fashion. Table 8.3 shows the assumed biomass supply for 2015, 2030, and 2050 for scenario 2 and the amount of bioenergy the Netherlands would be able to use based on their share of global population in these years.

Table 8.3 – The amount of bioenergy that is assumed to be available globally in 2015, 2030, and 2050 and the amount of bioenergy that is assumed to be available for the Netherlands in scenario 2

Year	2015	2030	2050
Global potential of biomass (EJ/year)	61	82	111
Biomass potential for the Netherlands (TJ/year)	139,340	172,600	199,800

Hoornweg, Bhada-Tata & Kennedy (2014) researched the global growth of municipal solid waste. They found that for scenarios SSP1, SSP2 and SSP3 it is assumed that the amount of waste generated in 2015, 2030 and 2050 will be approximately 5, 7, and 8 million tones per day. Based on these numbers, it is assumed that the amount of waste burned in WIPs in the Netherlands will increase in the same way (in a linear fashion). That is with 40% between 2015 and 2030, and 14% between 2030 and 2050.

An important factor in energy production are coal power plants. The Netherlands had 10 coals power plants in 2015, but needed to close a total of 5 of them due to governmental agreements (Greenpeace, 2015). The average lifetime of a coal power plant is 39 years (Davis, Caldeira & Matthews, 2010). However, in this scenario it is assumed that the Hemweg 8 plant will close after 2025, and the Amercentrale ketel 9 plant will close after 2027. Appendix 8.2 shows a summary of the coal power plants in the Netherlands, their electrical capacity, the year they were built in, and the year it is expected that they'll close. It is assumed that in 2033 a new, fully biomass dedicated, power plant will be built with an electric capacity of 500 MW. Additionally, another new biomass dedicated power plant will be built in 2040 with an electric capacity of 600 MW.

While the coal power plants are in operation it's expected that they will be co-firing biomass at the same relative rate until 2017 (the starting point in 2015 will be equal to the last known value from CBS (2016b), which is from the year 2013), after which the amount of co-firing will linearly increase until it reaches values in 2030 calculated by CE Delft (2016b) (visible in appendix 8.3). For the power plants closing before 2030 this means that they'll shut down before they've reached their full potential. Between 2008 and 2012 the average capacity factor for coal fired power plants in OECD Europe was 51% (EIA, 2015). This capacity factor will also be assumed in this scenario for the dedicated biomass power plants.

The biomass dedicated power plant that will start working in 2040 will work on 60% of the average capacity factor in 2040. This will then be 67.5% in 2041, 75% in 2042, 82.5% in 2043, 90% in 2044, and 97.5% in 2045 to assure that the maximum amount of biomass available for the Netherlands isn't exceeded.

For the production of electricity from biomass for companies it is assumed that the 2013 value still holds in 2015. For the production of heat from biomass for companies the 2015 value from CBS (2016b) is used. It's assumed that both values will grow in the same fashion as the availability of biomass for the Netherlands in 2030 and 2050 will grow.

It is assumed that the amount of bioenergy used for heating households will grow in the same fashion as the Dutch population will grow. Thus with 4.1% between 2015 and 2030, and no growth between 2030 and 2050.

There are several applications for the generation of biogas. It's assumed that the amount of landfill gas will correlate to the increase in global municipal solid waste. Biogas from sewage treatment plants, anaerobic digestion of manure and other biogas will correlate to the growth of the Dutch population. The amount of green gas produced is dependent on the relative growth of landfill gas and the relative growth of other biogas, as these types of biogas have been the gases that were used to produce green gas.

Table 8.4 shows the different types and amount of passenger vehicles in the Netherlands (in thousands) according to CBS (2016b) between 2010 and 2016.

Table 8.4 – The amount of different types of passenger vehicles in the Netherlands between 2010 and 2016 in thousands (CBS, 2016b)

Type of Engine	2010	2013	2014	2015	2016
Gasoline	6,070	6,277	6,290	6,332	6,402
Diesel	1,290	1,340	1,320	1,314	1,323
LPG and other	223	208	193	178	165
Electric and (plug-in) hybrids	40	91	130	156	211
Total	*7,622*	*7,916*	*7,932*	*7,979*	*8,101*

There's a strong increase for electric and (plug-in) hybrids, while LPG and other vehicles face declines. Gasoline vehicles are also increasing and diesel vehicles are staggering a bit. Of the total amount of energy used in the transport industry, 46 to 48% has been used by passenger vehicles between 2010 and 2015, while 26 to 28% was used by trucking vehicles and aviation vehicles (Environmental Data Compendium, 2016b)

Despite the increase of gasoline vehicles, it is expected that these vehicles will slowly phase out from the vehicle fleet. Because diesel engines can handle biodiesel, these passenger vehicles will remain for a longer period of time. However, it is assumed that these will face heavy declines. Not only have electric vehicles seen huge increases in the last few years, the government also has some ambitious goals regarding the share of electric vehicles in the

passenger vehicle fleet in the Netherlands in 2020 and 2025 (RVO, n.d.c). For this reason, in this scenario it is assumed that electric vehicles will eventually be most employed on the road. This is not only the case for passenger vehicles, but also for transport by trucks.
The amount of double counting biofuels in 2015 are taken as the starting point. This is divided into biofuels used by passenger vehicles and biofuels used by trucks based on their energy use in 2015 according to Environmental Data Compendium of the Netherlands(2016b). From this point it is assumed that in 2030 the blend obligation will have increased from 6.25% to 20%, diesel passenger vehicles will have decreased by 30%, gasoline passenger vehicles will have decreased by 60%, vehicles running on gas will have decreased by 100%, and the amount of trucks driving on diesel will also have declined by 30%. In 2050 it is assumed that diesel needs to be 75% biodiesel, diesel passenger vehicles will have declined by 80% compared to 2015, gasoline vehicles will have disappeared completely, and diesel trucks will have decreased by 80% compared to 2015.

Table 8.5 shows the summary of the increase in biomass used in the Netherlands in 2015, 2030, and 2050 based on the assumptions of scenario 2. Table 8.6 shows the summary of the amount of bioenergy used in the Netherlands for the same years. It is assumed that biogas from sewage treatment plants and anaerobic digestion from manure isn't part of the biomass that is to be shared equally between all earth's inhabitants. Thus, this isn't shown in table 8.5, while it is presented in table 8.6.

The energy efficiencies used in scenario 1 are also used in scenario 2.

Table 8.5 – A summary of the amounts of biomass used per application and in total in the Netherlands for the production of bioenergy in the years 2015, 2030, and 2050 for scenario 2

Application	Biomass Used for Bioenergy Production (TJ)		
	2015	2030	2050
Waste Incineration Plants	23,890	31,590	34,850
(Co-)Firing of Biomass	8,170	17,780	36,230
Biomass combustion for electricity for companies	6,280	7,350	8,230
Biomass combustion for heat for companies	10,430	12,470	13,960
Biomass combustion by households	18,370	19,130	19,130
Landfill gas & Other gas	14,060	15,140	15,410

Greens Gas	3,200	3,560	3,680
Biofuels	27,540	60,900	65,010
Total	*111,950*	*167,920*	*196,500*

Table 8.6 – A summary of the amounts of bioenergy produced per application and in total in the Netherlands for the years 2015, 2030, and 2050 for scenario 2

Application	Bioenergy produced (TJ)		
	2015	2030	2050
Waste Incineration Plants	20,310	28,430	32,410
(Co-)Firing of Biomass	6,950	16,000	33,670
Biomass combustion for electricity for companies	5,340	6,610	7,660
Biomass combustion for heat for companies	8,760	10,850	12,560
Biomass combustion by households	18,370	19,130	19,130
Landfill gas & Other gas	4,670	5,000	5,070
Biogas from sewage treatment plants	1,950	2,030	2,030
Biogas from anaerobic digestion of manure	4,220	4,390	4,390
Greens Gas	1,990	2,210	2,290
Biofuels	10,160	22,270	23,730
Total	*82,710*	*116,930*	*142,960*

8.3 Scenario 3 – The Netherlands as Expert in Biomass Handling for Bioenergy Purposes

In this scenario it will be assumed that the Netherlands will act as an expert in handling biomass for the production of bioenergy. This can be expected as more plausible if, for example, the plans of the port of Rotterdam are taken into consideration. The port of Rotterdam claims to be the largest biobased port and aims to remain the largest biobased port in the world and entrance of biomass into Europe by enlarging its area for biobased activities (Rotterdam Climate Initiative, 2014).

In this scenario it is assumed that in 2050 the amount of biomass that is available for use in the Netherlands is twice as much as in scenario 2. Thus, there will be 400,000 TJ of biomass per annum available for the Netherlands. The amounts of biomass available in 2015 and 2030 are calculated by the relative increases of biomass available globally (which is equal to the total amounts of biomass available globally in scenario 2) between 2015 and 2030, and 2030 and 2050. This means that the amount of biomass available for the Netherlands per annum in 2015 and 2030 are approximately 218,380 TJ and 296,220 TJ.

For the amount of waste transported to the Netherlands and used for energy production, it is assumed in this scenario that it will remain the same as with scenario 2.

For co-firing it is expected that the situation regarding the coal power plants that make us of biomass for co-firing remains the same as in scenario 2. For dedicated biomass power plants it is assumed that the average capacity factor will be the same as in scenario 2 and that a total of 6 biomass dedicated power plants will be installed between 2015 and 2050. The starting years and electric capacity of these power plants are shown in appendix 8.4. To assure that not more biomass will be used than is available, the biomass power plant of 600 MW that will start in 2040 will work at 70% of the average capacity factor in 2040, and 75% of the average capacity factor in 2041. Starting 2042 it will work at the same average capacity factor as all other biomass dedicated power plants.

In this scenario it is assumed that biomass integrated gasification combined cycle (BIGCC) power plants will be used in the Netherlands to produce energy. In IEAGHG (2011) [Potential for Biomass and Carbon Dioxide Capture and Storage] it is assumed that BIGCC power plants will be able to achieve electric capacities of 500 MW in 2030 and 2050. This will be also assumed in this scenario. It is assumed that 5 BIGCC power plants will be installed in the Netherlands between 2015 and 2050. The starting years and electric capacities of these BIGCCS plants are shown in appendix 8.5.
Between 2008 and 2012 the average capacity factor for natural gas fired power plants in OECD Europe was 39% (EIA, 2015). This capacity factor will also be assumed in this scenario for the dedicated biomass power plants. It is assumed that BIGCC plant 4, which starts operating in 2040, will start at 55% of the average capacity factor in 2040, and at 75% of the average capacity factor in 2041 and 2042 to assure that the amount of biomass available for use in the Netherlands isn't exceeded. In 2043 the BIGCC power plant will work at the same average capacity factor as all other BIGCC plants.

For production of energy and heat for companies, it is assumed that the amount of biomass used in 2015 will be the same as in scenario 2. Between 2015 and 2030 the increase will be twice as high as the relative increase of biomass available for the Netherlands between 2015 and 2030 in this scenario. It is assumed that between 2030 and 2050 the increase will be 1.5 times as high as the relative increase of biomass available for the Netherlands between 2030 and 2050.

It is assumed that the increase in biomass used for households will remain the same as in scenario 2 as it isn't expected that the amount of heat needed by the residents that will make use of this biomass will increase.

Compared to scenario 2 it isn't expected that there will be a change in the amount of waste in the Netherlands, or the amount of people living in the Netherlands. Thus it is expected that the amount of biogas resulting from landfill gas, other biogas, biogas produced from sewage treatment installations, and anaerobic digestion of manure will not change compared to scenario 2. As green gas is made from landfill gas and other biogas, it is also assumed that this amount will not change compared to scenario 2.

It is assumed in this scenario that transport will heavily transit towards electric and hydrogen vehicles, just as was assumed in scenario 2. Thus, the amount of biomass used for biofuels in this scenario isn't expected to change compared to scenario 2.

Not only is it assumed that the Netherlands will start building and using BIGCC plants for the production of bioenergy, it is also assumed that biomass will be used to supply the Netherlands with hydrogen through the WGS reaction of syngas after gasification. The Noorderlijke Innovation Board expects that the Northern part of the Netherlands can implement a green hydrogen based economy. It is expected that in 2030 a total of 270,000 tons hydrogen, which is equal to 38 PJ, can be produced on annual basis (Noorderlijke Innovation Board, 2017). It is expected that a 1,000 MW biomass gasification plant will be installed, which will use torrified biomass pellets to produce 90,000 tons of hydrogen (Noorderlijke Innovation Board, 2016). One third of the amount that eventually will be produced. Thus it is assumed that 1 biomass gasification power plant of 1,000 MW, producing hydrogen, will be able to produce 12.7 PJ worth of hydrogen on an annual basis. It is assumed that 4 hydrogen producing biomass gasification plants will be installed in the Netherlands between 2015 and 2050. The starting years and electric capacities of these biomass gasification plants are shown in appendix 8.6.

Table 8.7 shows the summary of the increase in biomass used in the Netherlands in 2015, 2030, and 2050 based on the assumptions of scenario 3. Table 8.8 shows the summary of the amount of bioenergy used in the Netherlands for the same years. Just as is the case in scenario 2, biogas from sewage treatment installations and anaerobic digestion of manure isn't taken into account in table 8.7, but is shown in table 8.8.

The energy efficiencies used in scenario 1 and 2 are also used in scenario 3. For BIGCC plants, the energy conversion efficiency is assumed to be 86% since it is assumed that these plants will primarily be used as CHP plant (Uddin & Barreto, 2007). This will increase to 90% in 2030, and 93% in 2050 in this scenario. The conversion efficiency of hydrogen production through the WGS reaction applied on syngas produced by wood is assumed to be 55% (Huang & Zhang, 2011).

Table 8.7 – A summary of the amounts of biomass used per application and in total in the Netherlands for the years 2015, 2030, and 2050 for scenario 3

Application	Biomass Used for Bioenergy Production (TJ)		
	2015	2030	2050
Waste Incineration Plants	23,890	31,590	34,850
(Co-)Firing of Biomass	8,170	43,690	71,680
BIGCC	0	11,620	31,080
Biomass combustion for electricity for companies	6,280	16,100	31,550
Biomass combustion for heat for companies	10,430	27,320	53,490
Biomass combustion by households	18,370	19,130	19,130
Landfill gas & Other gas	14,060	15,140	15,410
Greens Gas	3,200	3,560	3,680
Biofuels	27,540	60,900	65,010
Hydrogen	0	46,060	60,090
Total	*111,950*	*275,100*	*394,970*

Table 8.8 – A summary of the amounts of bioenergy produced per application and in total in the Netherlands for the years 2015, 2030, and 2050 for scenario 3

Application	Bioenergy Produced (TJ)		
	2015	2030	2050
Waste Incineration Plants	20,310	28,430	32,410

(Co-)Firing of Biomass	6,950	39,320	66,660
BIGCC	0	10,450	28,900
Biomass combustion for electricity for companies	5,340	14,490	29,340
Biomass combustion for heat for companies	8,760	23,770	48,140
Biomass combustion by households	18,370	19,130	19,130
Landfill gas & Other gas	4,670	5,000	5,070
Biogas from sewage treatment plants	1,950	2,030	2,030
Biogas from anaerobic digestion of manure	4,220	4,390	4,390
Greens Gas	1,990	2,210	2,290
Biofuels	10,160	22,270	23,730
Hydrogen	0	25,330	38,000
Total	82,710	196,820	300,100

9 The Effect of Applying BECCS

This section will look into the effects that BECCS will have in the three scenarios on net energy production and the amount of negative emissions that can be achieved by combining several of the earlier sections.

In the previous section, all the amounts of biomass used for bioenergy production and the amount of net energy production per application have been developed. Based on the energy produced or the biomass input, a certain amount of CO_2 is emitted. The applications that were based on their biomass input where WIPs, (Co-)Firing of Biomass, BIGCC, biomass combustion for electricity and heat and only heat for companies, and biomass combustion by households. For all the types of biogas, biofuels and hydrogen emission factors were applied to the bioenergy of the (bio)carrier. The emission factors that were applied are shown in appendix 9.1.

Based on the total amount of CO_2 emissions, the amount that can be captured is determined. This is done by using the capture efficiencies shown in table 2.1. From this amount it is calculated how much energy is needed for capture and compression of CO_2. Energy required for the capture and compression of CO_2 are used from tables 2.2 and 2.3. This is then subtracted from the net energy production of bioenergy to gain a new amount of net bioenergy produced including CCS. The amount of net bioenergy produced per year, with and without the use of CCS, is shown in figure 9.1.

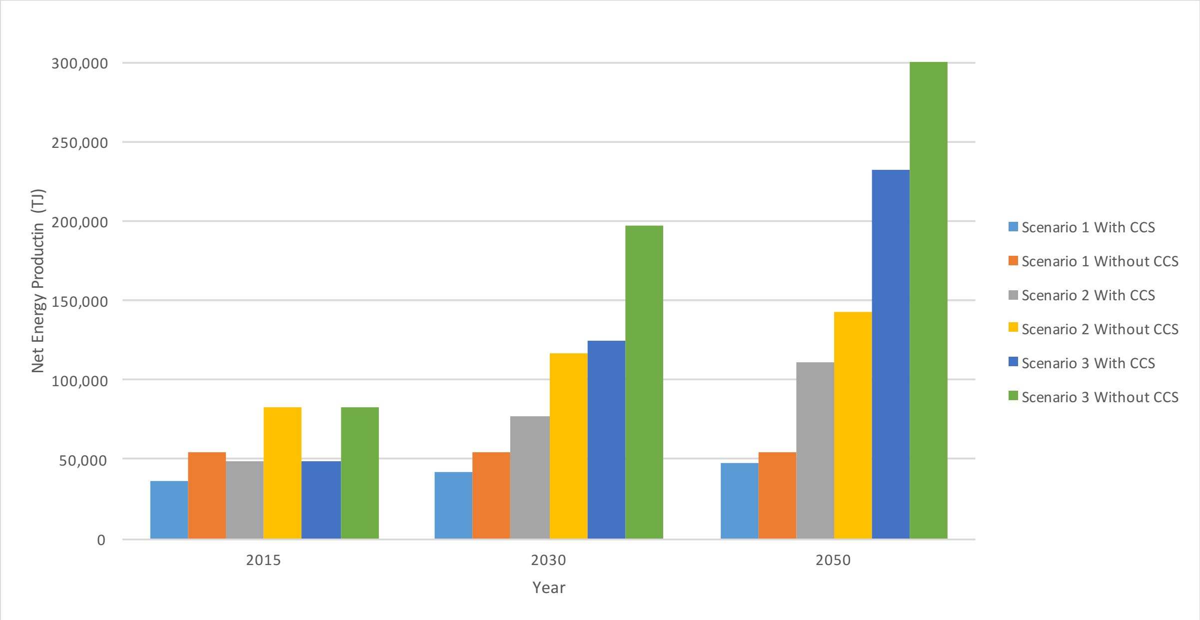


Figure 9.1 – The net bioenergy production of scenarios 1, 2 and 3 per annum, with and without the application of CCS

For scenario 1 the losses in net bioenergy production are 17, 12 and 7 PJ per annum in 2015, 2030 and 2050 respectively. For scenario 2 the losses are 34, 39 and 32 PJ per annum in 2015, 2030 and 2050 respectively. For scenario 3 the losses are 34, 72 and 69 PJ per annum in 2015, 2030 and 2050 respectively.

The amount of CO_2 that is captured, compressed and stored in CO_2 storage sites does not equal the amount of negative emissions that can be achieved in the scenarios. This is because there exist more types of emission during the production of biofuels, known as the supply chain emissions. As these emissions negate the effect of negative emissions to some extent, these emissions are subtracted from the amount of CO_2 stored. The amount of supply chain emissions per GJ of biofuel was taken from PBL (2016). Waste and biomass use by residents haven't been included in this since it is assumed that whether or not an emphasis is put on bioenergy, these emissions would've been there. Since approximately 4% of the biomass in Searle & Marlins (2011) would've been from forest residues, it has been assumed that from all solid biomass that is directly converted into bioenergy 4% is from forest residues and 96% either from fast growing biomass on marginal land or agricultural residues. The average supply chain emissions of crude vegetable oil were assumed to be the same for biodiesel. The supply chain emissions of ethanol production was assumed to be the supply chain emissions of bio gasoline. For all types of biogas it was assumed that the supply chain emissions was the same. Since hydrogen wasn't included by PBL (2016), this was taken from Kalinci, Hepbasli & Dincer (2012).

The amount of CO_2 stored per annum and the amount of negative CO_2 emissions per annum in scenario 1, 2, and 3 is shown in figure 9.2. The cumulative amount of CO_2 stored and cumulative amount of negative CO_2 emissions in scenario 1, 2, and 3 is shown in figure 9.3.

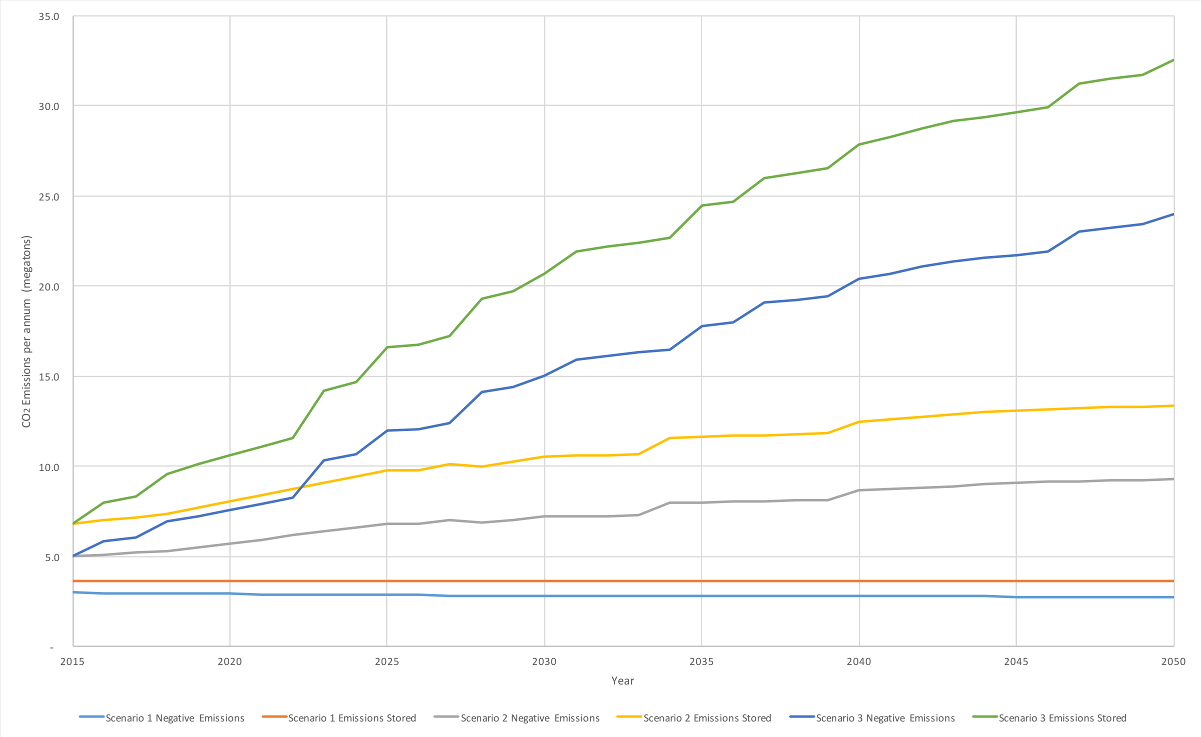


Figure 9.2 – The amount of CO_2 stored and the amount of negative emissions in scenario 1, 2, and 3 between 2015 and 2050

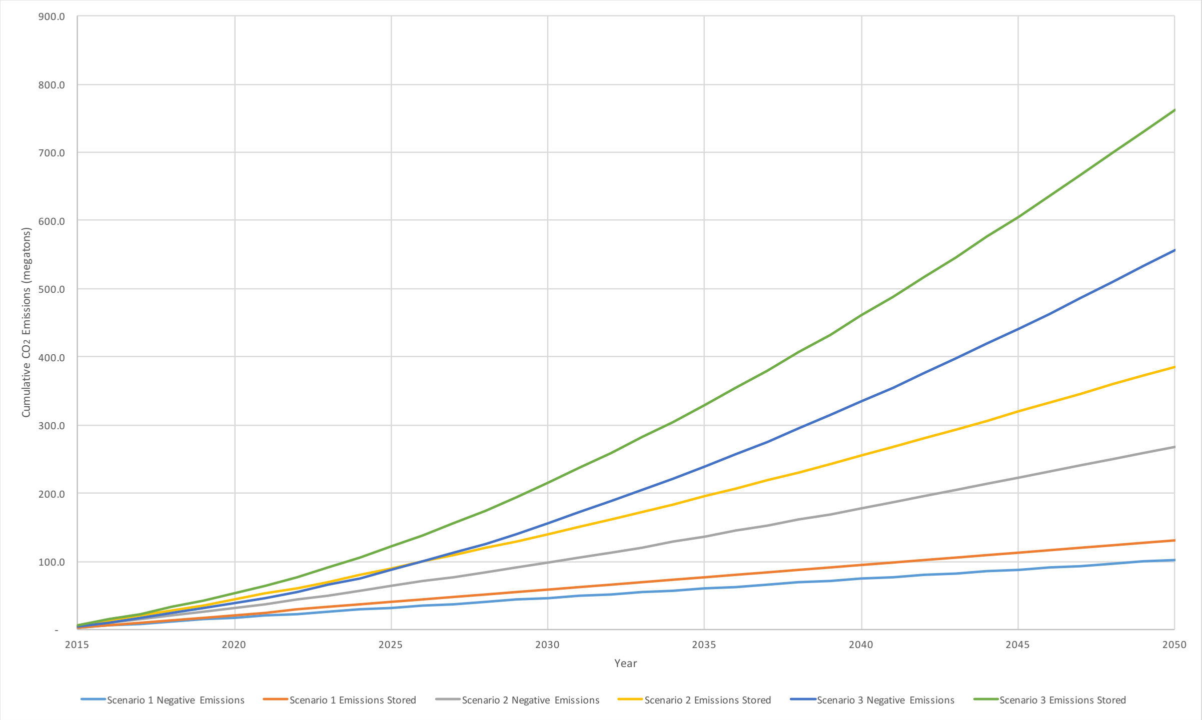


Figure 9.3 – The cumulative amount of CO_2 stored and cumulative amount of negative emissions in scenario 1, 2, and 3 between 2015 and 2050

In scenario 1 the amount of CO_2 that is stored starts at 3.6 megatons per annum in 2015 and increases slightly to 3.7 megatons per annum in 2050. The amount of negative CO_2 emissions in 2015 starts at 3.0 megatons per annum, but this decreases overtime to 2.8 megatons per annum in 2050. This decrease is the result of the decreases in bioenergy productions of several applications due to an increase in waste separation such as in waste incineration plants and biogas from landfill gas, and the disappearance of co-firing in this scenario. Eventually, this results in an amount of 132 megatons of CO_2 being stored in 2050 and a total amount of 102 megatons of negative CO_2 emissions that will be the result of applying BECCS in scenario 1.

In scenario 2 the amount of CO_2 that is stored starts at 6.8 megatons in 2015 and increases to 13.4 megatons in 2050. The amount of negative CO_2 emissions in 2015 starts at 5.0 megatons per annum, and increases to 9.3 megatons of negative CO_2 emissions per annum in 2050. Eventually, this results in an amount of 386 megatons of CO_2 being stored in 2050 and a total amount of 268 megatons of negative CO_2 emissions being the result of applying BECCS in scenario 2.

In scenario 3 the amount of CO_2 that is stored starts at 6.8 megatons per annum in 2015 and increases to 32.5 megatons of CO_2 per annum in 2050. The amount of negative CO_2 emissions in 2015 starts at 5.0 megatons per annum, and increases to 24.0 megatons of negative CO_2 emissions per annum in 2050. Eventually, this results in an amount of 762 megatons of CO_2 being stored in 2050 and a total amount of 557 megatons of negative CO_2 emissions being the result of applying BECCS in scenario 3.

As becomes clear from comparing these results with 5.3 and 5.4, transport of CO_2 and storage of CO_2 will not pose a limit on the amount of CO_2 transported and stored in all three scenarios.

10 Discussion

This research has set out to discover the possible amount of negative emissions that the Netherlands can achieve in the year 2050. This amount has been calculated to be approximately 2.8, 9.3 and 24.0 megatons of CO_2 per annum for scenarios 1, 2 and 3 respectively. In 2015, the amount of greenhouse gas emission the Netherlands was responsible for equated to 195.2 megatons of CO_2e (Environmental Data Compendium of the Netherlands, 2017). If the negative emissions of the three scenarios in 2050 were laid out against the total emissions of the Netherlands in 2015, the amount of CO_2e emissions that could be mitigated annually by BECCS would be 1.4%, 4.8% and 12.3% for scenarios 1, 2 and 3 respectively. In total BECCS is good for the mitigation of 102.3, 268.3, and 556.7 megatons of CO_2 for scenarios 1, 2, and 3 respectively. Compared to the amount of emissions in 2015, this is equal to 0.5, 1.4 and 2.9 years worth of CO_2 emissions for scenarios 1, 2 and 3 respectively.

For the Netherlands to comply with the European Union's goal of lowering greenhouse gas emissions with 80 – 95% compared to 1990, the total amount of emissions must be between 11 and 44 megatons of CO_2e emissions in 2050. This is an ambitious goal which will need the support of several different energy conversion technologies such as wind mills and solar cells. Based on the negative emissions from the three scenarios it becomes clear that BECCS can have a significant contribution towards this goal. Especially in helping mitigate emissions from sectors that are expected to be slightly more difficult in their transition towards a zero emission sector, such as the transport sector. In the Netherlands, the transport of people and goods via road, air, sea, and rail equates to 31 megatons of CO_2e in 2015 (CBS, 2017). It's expected that these emissions will decrease until 2050 due to, amongst other things, electrification of the different types of fleet. However, the chances of all vehicles turning into electric vehicles are limited. It is notably likely that fossil fuels and their accompanying CO_2 emissions will still be present in this sector in 2050. BECCS proves to be an important measure in mitigating these emissions, making the transition to a net 0 emission country easier.

The infrastructure that will be need to be built for the transport of CO_2 in a BECCS system will not pose a limiting factor on the amount of negative emissions possible for the Netherlands until 2050. The amount of storage sites available until 2050 are able to store 49% of their maximum capacity in the case of the scenario with the highest amount of CO_2 captured and stored. Also the amount of annually transported CO_2 doesn't exceed the amount that's possible to be transported to storage sites. If the amount of CO_2 captured and stored by applying BECCS after 2050 is kept steady and the total amount of storage capacity calculated in section 4 becomes available, the Netherlands will be able to keep storing CO_2 from a BECCS system for another 2,980, 800 and 320 years after 2050 for scenario 1, 2 and 3 respectively.

There are several factors that should be taken into account when reviewing the results of this study. These are reduced net energy production, additional emissions, availability of on-shore storage sites, the moment benefits from negative emissions occur and the current year. These will be discussed below.

With the application of CCS to capture and store CO_2 comes a certain price tag which has a significant influence on the whole process. This is the decrease in net availability of bioenergy for consumers. Capture and compression processes of CO_2 to prepare the carbon dioxide for storage are energy intensive. If this energy is supplied by the produced bioenergy, there is less left for consumers to use. In scenario 1 the total net bioenergy in 2015 is only 68% compared to a situation where bioenergy would be produced without application. This then eventually increases to 87% in 2050. In scenarios 2 and 3 this is 59% in 2015 and approximately 77% in 2050. A decrease in net bioenergy production requires that the energy that is now “lost” needs to be supplemented. Especially in the beginning, the full amount of the lost net energy needs to be replenished by other sources. It is very likely that these sources will initially be mainly fossil fuels, resulting in more CO_2 emissions and simultaneously less negative emissions. Because of the pressing need of low carbon emissions with energy production and the change of energy consumption per capita over time, it’s difficult to quantify these future dynamics and include this phenomenon in this study. However, it might be interesting to bring this phenomenon in to perspective in future research.

Second comes additional emissions resulting from the use of BECCS for energy production. CO_2e emissions are not only the result of combusting or converting the different types of biomass (fuels). There are emissions occurring over the whole supply chain. These are the result of growing certain types of biomass, transporting the biomass, preparation of biomass before combustion or conversion, and possibly also transport of the final product such as biofuels. These emissions the supply chain emissions. Besides supply chain emissions, there can also be a significant amount of additional emissions due to land use change (LUC). As the name suggests, these are emissions that result from changing land to prepare it for the production of biomass. For this research the supply chain emissions have been taken into account and subtracted from the negative emissions. However, effects of LUC haven’t been taken into account in the calculations. Thus, the amount of negative emissions will in reality be lower in different scenarios due to additional emissions from LUC.

The prospect of having sufficient CO_2 storage capacity is something reassuring. However, the availability of these storage sites aren’t a given. Currently, storing CO_2 onshore is avoided due to opposition of the public in the past. Provision of information regarding CCS to the public and discussion possibilities for the public to be heard should be implemented to increase public acceptance. On-shore CO_2 storage should only be allowed after approval of a majority of the public, besides all other standard measurements such as assuring safety of the storage site. Because the city of Groningen, and other nearby villages, have been plagued by earthquakes due to gas extraction, storage in the gas fields close to Groningen, which accounts for two thirds of the total effective storage capacity, will likely be more difficult to gain acceptance towards CO_2 storage. Extra measurements should be taken with regards to research towards safety and damage control in these gas fields to assure increased safety for and acceptance by the residents of Groningen.

Another factor influencing the availability of storage for CO_2 from BECCS is the implementation of CCS on power plants that generate electricity and/or heat from fossil fuels. This study didn’t take into account the implementation of this type of CCS, but it is highly unlikely that this will be the case. When this type of CCS is implemented, there will be additional CO_2 that will be needed to transported to and stored in storage sites. It is reasonable to expect that CO_2 captured from BECCS will need to compete with CO_2 from CCS of fossil fuel based power plants to be transported to and stored by CO_2 storage sites.

The fourth factor that needs to be taken into account is that negative emissions do not occur immediately. They are eventually the result of using biomass. A standard error in bioenergy production is assuming that immediate greenhouse gas benefits occur when using biomass. However, after using the biomass, there will still be an increase of CO_2 in the atmosphere. During regrowth of the biomass, the carbon will flow from the atmosphere back into the biosphere. When the same amount of biomass has been grown as was initially used for bioenergy production, then the biosphere and atmosphere will be at the same state before. This is, however, without taking consideration of emission resulting from CO_2 capture and storage, supply chain emissions, land use change (LUC) emissions and additional bioenergy production or any other forms of energy production that emit CO_2 into the atmosphere. Biomass such as forest trees have regrowth periods of several decades, making the CO_2 linger in the atmosphere for a longer period of time. Because of this, this study has used a biomass potential study that mainly incorporated the (sustainable) use of short-rotation biomass (Searle & Marlins, 2015). However, although short-rotation biomass has been used, they'll still need to regrow before the negative emissions have occurred. Thus, the negative emissions that have been assigned to a certain year are negative emissions due to use of BECCS in that year, not immediate negative emission benefits. Negative emissions will only have occurred after biomass regrowth.

Finally, it should be noted that although the base year of this study was set at 2015, we are currently nearly in 2018. This means that three years will have passed without the implementation and use of BECCS. To harvest the benefits that accompany the use of BECCS with regards to its mitigating potential until 2050, immediate implementation is of importance.

11 Conclusion

This research has aimed to see how large the potential is for negative emissions through the use of BECCS in the Netherlands until 2050. It has become clear that the application of BECCS poses major benefits for the Netherlands in aiding to reach large CO_2 emission reduction targets. It relieves pressure on the immediate grand implementation of net zero emission technologies and allows for minimal use of fossil fuels after 2050 for a significant time by being able to mitigate between 2.8 and 24.0 megatons of CO_2 per annum. In total the Netherlands will be able to mitigate 102.3 – 556.7 megatons of CO_2 until 2050, while producing 47,500 – 232,500 TJ of energy through the use of BECCS. Although certain factors such as a decrease in net energy production and LUC emissions decrease these potentials by a bit, their potential benefit cannot be denied. However, although the base year of this study is set at 2015, we are currently halfway through 2017. To be able to benefit from BECCS, it is important to start implementing this technology as soon as possible. The longer this is postponed, the lower the benefits become.

However, the application of BECCS and the benefits it can bring isn't cast in stone. This research is supported by a significant number of assumptions to make its case. The future, sadly, cannot be predicted. This results in studies that try to sketch a future image attempt to explain what might happen under certain circumstances, but do not try to predict what these circumstances are going to be. This all makes it rather uncertain what the exact effect of the application of BECCS is going to be when implemented. Nevertheless, this research provides sufficient grounds in showing the potential BECCS could have in quantifiable terms. It will be beneficial to keep researching the possibilities of negative emissions through its application and removing the cloud of uncertainty as much as possible.

In its endeavor to achieve a high level of GHG emission reduction before 2050, the Netherlands should aim to achieve as much GHG reducing benefits as possible. BECCS is one of the technologies that could aid significantly herein, and should not be ignored.

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Appendices

Appendix 1

There was no information that needed to be in this part of the appendix.

Appendix 2

Appendix 2.1 – Energy requirements of different separation technologies according to Brunetti *et al*. (2010) and Theo *et al*. (2016)

Separation Technology	Energy Requirements
Absorption	4 – 6 MJ/kg CO_2
Adsorption	2 – 3 MJ/kg CO_2
Membrane Separation	0.5 – 6 MJ/kg CO_2

Appendix 2.2 – Assumptions of the division of CO_2 capture by absorption, adsorption, and membrane separation for regular pre- and post-combustion capture

Year	Share of CO_2 Captured (%)		
	Absorption	Adsorption	Membrane Separation
2015	70	15	15
2030	40	30	30
2050	20	40	40

It is assumed that in the periods between 2015 and 2030, and 2030 and 2050 the increase will be linear.

Appendix 2.3 – Recommendations for the transport of CO2 to assure high quality transportation (de Visser *et al*., 2008)

Component	Concentration
CO_2	>95.5%
H_2O	500 ppm
H_2S	200 ppm
CO	2000 ppm
CH_4	Aquifer < 4 vol.% Enhanced Oil Recovery < 2 vol.%
N_2	<4 vol.%
Ar	<4 vol.%
H_2	<4 vol.%

Appendix 3

There was no information that needed to be in this part of the appendix.

Appendix 4

Appendix 4.1 – Off-shore effective storage accapcity according to different sources

Source	Type of Field	Effective Storage Capacity (in megatons CO_2)
NOGEPA (2008)	Depleted gas fields	918
EBN (2010)	Depleted gas and oil fields	1,160

EnergieNed (2007)	Depleted gas fields	1,150
	Depleted oil/EOR fields	27
	Aquifers	310
	Sum	*1,487*

Appendix 4.2 – On-shore effective storage capacity according to different sources

Source	Type of Field	Effective Storage Capacity (in megatons CO_2)
EBN (2010)	Depleted gas and oil fields West-Netherlands	112.8
	Depleted gas and oil fields North-Netherlands	814
	Sum	*926.8*
EnergieNed (2007)	Depleted gas fields (non-Groningen)	1,600
	Depleted gas field Groningen	7,350
	Depleted oil/EOR fields	13
	Aquifers	405
	Deep coal fields	400
	Sum	*9,768*

Appendix 4.3 – Global storage capacities for CO_2 according to IPCC (2005)

Reservoir Type	Storage Capacity (gigatons CO_2)	
	Lower Estimate	Upper Estimate
Oil and gas fields	675	900
Unminable coal seams	3 – 15	200
Deep saline formations	1,000	Uncertain, but possibly 10^4

Appendix 5

There was no information that needed to be in this part of the appendix.

Appendix 6

There was no information that needed to be in this part of the appendix.

Appendix 7

Appendix 7.1 – Blend obligation of renewable fuels into transport fuels in the Netherlands between 2011 and 2020 ((Ministry of Infrastructure and the Environment, 2013), (Dutch Emissions Authority, n.d.))

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Blend Obligation (%)	4.25	4.5	5	5.5	6.25	7	7.75	8.5	9.25	10

Appendix 8

Appendix 8.1 – The amount of double counting biofuels produced depending on production material originating from within the Netherlands in 2015 (Dutch Emission Authority, 2016a)

Material Used	Biogas (TJ)	Bio Gasoline	Biodiesel		*Total (TJ)*
		ETOH (TJ)	FAME (TJ)	HVO (TJ)	
Animal Fat (cat. 1 or 2)	0	0	23.18	0	*23.18*
Used Cooking Oil	0	0	1,438.52	33.08	*1,471.60*
Residuals from Grain and Potato Processing	0	86.10	0	0	*86.10*
Municipal Waste	150.30	0	0	0	*150.30*
Other Raw Materials	6.50	0	7.28	0	*13.78*
Total	*156.80*	*86.10*	*1,468.98*	*33.08*	*1,744.96*

Appendix 8.2 – A summary of the coal power plants in the Netherlands, their electric capacity, building year, and assumed closing year (data used from Greenpeace (2015))

Power Plant	Electric Capacity (MW)	Building Year	Closing Year
E.ON – Maasvlakte 1	500	1998	2017
E.ON – Maasvlakte 2	500	1989	2017
Essent – Amercentrale ketel 8	645	1981	2016

Delta – Borsele	406	1988	2015
GDF/Suez – Nijmegen	570	1985	2016
Nuon – Hemweg 8	630	1995	2025
Essent – Amercentrale ketel 9	600	1994	2027
GDF/Suez - Maasvlakte	800	2015	After 2050
E.ON – Maasvlakte 3	1,070	2015	After 2050
Essent - Eemshaven	1,600	2015	After 2050

Appendix 8.3 – Assumed co-firing percentages and possible energy production from biomass for the five coal power plants that aren’t shut down between 2010 and 2020 (CE Delft, 2016b)

Power Plant	Maximum Co-firing Percentage (%)	Energy Production Biomass (PJ per year)
GDF/ Suez – Maasvlakte	60	7.4
Essent – Amercentrale ketel 9	50	4.9
Nuon – Hemweg 8	40	4.0
Essent - Eemshaven	20	5.1
E.ON – Maasvlakte 3	20	3.5

Appendix 8.4 – Assumed biomass dedicated power plants in scenario 3 with starting years and electric capacity per power plant

Biomass Power Plant	Starting Year	Electric Capacity (MW)
1	2017	450
2	2018	500
3	2025	500
4	2031	550
5	2035	550
6	2040	600

Appendix 8.5 – Assumed BIGCC plants in scenario 3 with starting years and electric capacity

BIGCC Plant	Starting Year	Electric Capacity (MW)
1	2025	400
2	2030	450
3	2035	500
4	2040	500

5	2050	500

Appendix 8.6 – Assumed biomass gasification plants in scenario 3 with starting years and capacity

Biomass Gasification Plant	Starting Year	Capacity (MW)
1	2023	1,000
2	2028	1,000
3	2036	500
4	2047	500

Appendix 9

Appendix 9.1 – Emission factor per fuel type (mainly from Ministry of Health, Welfare and Sport (2016))

Fuel Type	Emission Factor (kg CO_2/GJ)
Waste	105.7
(Co-)Firing	109.6
BIGCC	90.8
Biomass used for companies (both electricity and heat)	109.6
Landfill Gas	100.7
Biogas Sewage Treatment	84.2
Biogas AD Manure	84.2
Other Biogas	84.2
Green Gas	54.9
Biogasoline/Bioethanol	72.0
Biodiesel	74.3
Hydrogen	181.48

Comparing the fuel types in this study to those in Ministry of Health, Welfare and Sport (2016)

- Waste is set equal to waste
- (Co-)Firing and Biomass used for companies are set equal to solid biomass
- BIGCC is set equal to Gas biomass
- Landfill Gas is set equal to Landfill gas

- Biogas from sewage treatment, Biogas from AD of manure, and Other biogas are set equal to Wastewater biogas
- Green gas is set equal to Methane
- Biogasoline/Bioethanol is set equal to Biogasoline
- Biodiesel is set equal to Biodiesel
- Hydrogen was self calculated
  - Obviously, CO_2 is generated during the production of hydrogen through the WGS reaction. Assuming a density of 0.090 kg/Nm^3 hydrogen and a LHV of 10.8 MJ/Nm^3 (Ministry of Health, Welfare and Sport, 2016), the amount of CO_2 generated is approximately 1.96 kg/Nm^3 H_2, or 181.48 kg CO_2/GJ.