Screening LCA for CCU routes connected to CO_2 Smart Grid

CE Delft

Committed to the Environment

Screening LCA for CCU routes connected to CO_2 Smart Grid

This report is prepared by:
Harry Croezen
Sanne Nusselder
Erik Roos Lindgreen
Diederik Jaspers

Delft, CE Delft, 10 July 2018

Publication code: 18.3N76.086

Carbon dioxide / Sources / Capture / Technology / Utilization / LCA

Client: Ministry of Infrastructure & Water Affairs

Publications of CE Delft are available from www.cedelft.eu

Further information on this study can be obtained from the contact person Diederik Jaspers (CE Delft)

CE Delft
Committed to the Environment

Through its independent research and consultancy work CE Delft is helping build a sustainable world. In the fields of energy, transport and resources our expertise is leading-edge. With our wealth of know-how on technologies, policies and economic issues we support government agencies, NGOs and industries in pursuit of structural change. For 40 years now, the skills and enthusiasm of CE Delft's staff have been devoted to achieving this mission.

Content

Summary

The Paris agreement requires significant steps in order to achieve reduction of greenhouse gases of 90-95% CO_2 eq. compared to 1990 levels. One of the possible steps is the application of novel technologies like the reuse of CO_2 in a value chain. This is attractive if can cover the cost of the capture of CO_2, while the ETS-price level is still very low. In the two Dutch provinces of North- and South-Holland, a consortium of more than 20 public and private parties is launching an initiative (CO_2 Smart Grid) aimed at utilizing CO_2 as a raw material for a circular economy (Carbon Capture and Utilization, or shortly CCU). To this end, a network will be developed in which CO_2 from different sources can be made available to different users. The proposed backbone of this network is the existing OCAP CO_2 pipeline, which already provides CO_2 from Shell in Pernis and ethanol producer Alco in Pernis to the horticulture sector in the Westland region for growth promotion of crops.

This study focusses on the Life Cycle Assessment (LCA) of different CCU routes applicable in the CO_2 Smart Grid. The results of this study can serve as input for a to-be conducted Social Cost Benefit Analysis.

CCU routes

This study compares the environmental impact of nine different CCU routes on the basis of '1 tonne of CO_2 captured in 2030 and subsequent utilization'. The nine routes are a combination of CO_2 capture options from three different sources and utilization of the CO_2 in three different applications. Table 1 gives an overview of the CCU routes considered in this LCA. Furthermore these nine different CCU routes are compared with Carbon Capture and Storage (CCS) as a reference.

Table 1 - CCU routes

CO_2 source |Utilization	Horticulture	Mineralisation	Methanol production
Waste incineration	Route 1	Route 2	Route 3
Blast furnace process and blast furnace gas	Route 4	Route 5	Route 6
Fossil oil refining	Route 7	Route 8	Route 9

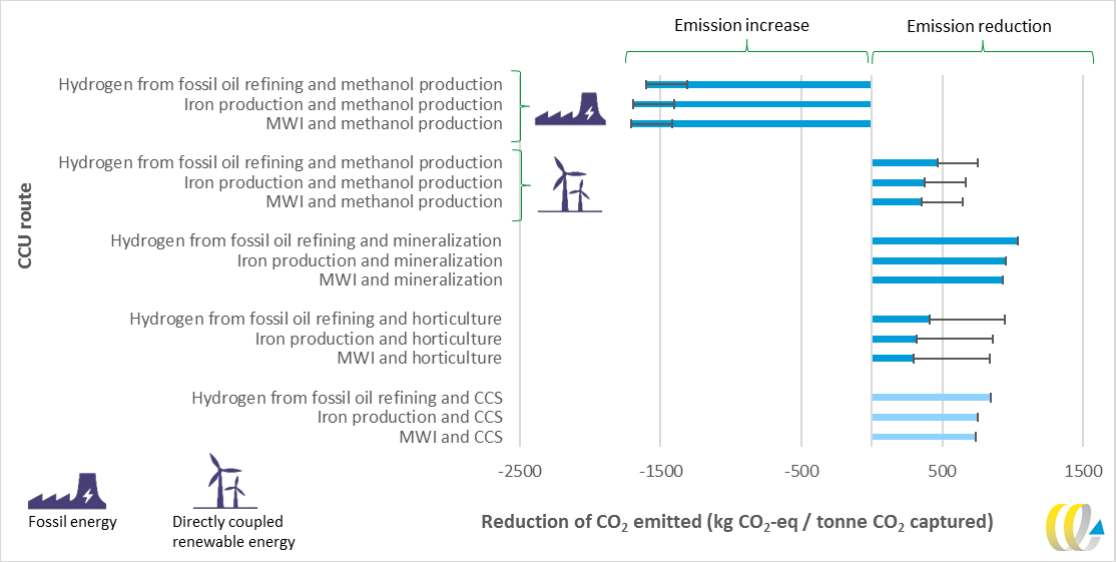
Of course there are many more CCU routes possible in the Netherlands, but this study has been limited to nine different routes which are considered relevant for the region of North-Holland (Tata Steel) and South-Holland (Rotterdam Harbour Industrial Complex).

Climate change impact of CCU routes

Reduction of climate change impact

All of the routes considered lead to a reduction of climate change impact compared to non-capture, as can be seen in Figure 1.

Figure 1 - Reduction of climate change impact per CCU route in comparison to non-capture



Note: The black bar indicates CO_2 emission reduction due to different situations. For methanol production use as fuel (lowest reduction) and use as chemical where CO_2 is stored for more than 100 years (highest reduction). For utilization in horticulture addition of captured CO_2 in the current OCAP pipeline (lowest reduction) and the addition of CO_2 during the summer (highest reduction).

The extent to which this is the case is dependent on:

- the duration of carbon storage in the produced products (e.g. permanent storage in case of mineralisation of CO_2 in mineral construction materials);
- the quantity of energy used by the capture technology;
- the quantity of energy used by the utilization technology;
- the carbon footprint of the product that is replaced (e.g. avoidance of natural gas burner to supply Dutch horticulture with CO_2 for increased plant growth).

Utilization in mineralisation

Utilization of CO_2 for mineralisation, the production of one type of mineral material (compensatie-steen), leads to net avoided CO_2 emissions of around 1 tonne of CO_2 per tonne of CO_2 captured. Despite the carbon footprint of the capture technologies, the produced Compensatiesteen avoids production of conventional sand-lime brick. When the capture technologies have a lower carbon footprint (e.g. when in the future renewable electricity mix is used), utilization in mineralisation could even lead to net negative CO_2 emissions. This means that more CO_2 emission is prevented than CO_2 captured.

Utilization in horticulture

The utilization of CO_2 in horticulture leads to net avoided CO_2 emissions of between 300 and 950 kg CO_2 per tonne of CO_2 captured. The lowest net avoided CO_2 emission is as currently reported for captured CO_2 added to the OCAP-pipeline while the highest reduction occurs when CO_2 is added to a greenhouse during summer. The net avoided CO_2 emission is caused by the avoided use of natural gas for the production of CO_2 in horticulture. This conclusion is valid until the horticulture sector made a transition to a renewable heat source (e.g. geothermal heat).

The possible sources for CO_2 supply in horticulture (the reference) in towards 2040-2050 is unknown because the future benchmark for heat supply in greenhouses has yet to be determined. A possibility is the use of biomass in CHP for both heat and CO_2 production, but also geothermal heat supply without associated CO_2 emissions is an option. The geothermal scenario would fully depend on an external source of CO_2, which can be delivered by the CO_2 Smart Grid. Whether or not the application of captured CO_2 aids the shift towards renewable energy and what would be the appropriate reference CO_2 source to consider in the future is a topic that needs further discussion.
Therefore the exact carbon footprint reduction after a switch to a fully renewable heat source in the horticulture sector is uncertain and depends on the outcome of different scenario's.

Utilization in methanol production

Utilization in methanol production will lead to net avoided CO_2 emissions when 100% renewable energy is used for methanol and hydrogen production. If fossil-based electricity is used in the process, more CO_2 is emitted than captured. The net avoided CO_2 emissions will increase when the CO_2 is used in durable products. 'Durable' in this context implies that CO_2 is sequestered for more than 100 years. In that case, this utilization method could reach net avoided CO_2 emissions of around 700 kg CO_2 per tonne of CO_2 captured. This is comparable to CCS (see Figure 1). A lot of renewable electricity is required to produce hydrogen for methanol production on a large scale. We assume additional renewable electricity supply (e.g. directly linked windfarms), ample availability of this renewable electricity for producing hydrogen, and that the use of this electricity does not compete with utilization in applications leading to lower net CO_2 emissions.

It must be noted that methanol production is not the only possible application of CO_2 in the chemical industry. The reason that methanol was selected is, apart from the availability of data from the demonstration plant in Iceland, that it is a so called platform chemical with a wide range of products which are currently based on fossil oil and gas. Other possible CO_2 utilization routes in the chemical industry include the production of polyols for the production of polyurethanes. Conclusions drawn on methanol production should thus not been seen as exemplary for CO_2 utilization in the chemical industry.

Other environmental benefits

For several reasons, no conclusions could be drawn on other environmental impacts:
- additional benefits caused by the additional cleaning of CO_2 containing (flue) gas during the capture process are unknown;
- emissions from degradation of absorbents are unknown.

Interpretation of the conclusions

The orders of magnitude of CCS and CCU applicability in 2030 are expected to be incomparable. E.g. the potential storage by means of CCS is expected to be much higher than the potential for use of CO_2 in mineralization in the Netherlands. Results must therefore only be seen on a per tonne basis and cannot be extrapolated. The spatial application of the technologies also differ, e.g. CCS can be applied the whole year round while the peak of CO_2 utilization in horticulture is during the growing season and less so in winter.

Because the study carried out is a screening LCA, the drawn conclusions should be seen as indicative figures; they offer an order of magnitude estimation and cannot be seen as representative for individual (industrial) plants present in the Netherlands. Furthermore the results are not appropriate for national carbon accounting. This means that when calculating the emissions of the Netherlands as a whole the presented reduction in CO_2 emissions cannot be taken into consideration. The same holds for using the outcomes for corporate carbon accounting practices.

To make the results applicable to individual CCU routes e.g. CO_2 capture at the AEB MWI in Amsterdam and application of the CO_2 in horticulture in Aalsmeer, a full scale LCA study will need to be conducted based on the actual variables chosen for the specific installations.

1 Introduction

In the two Dutch provinces of North- and South-Holland, a consortium of more than twenty public and private parties is launching an initiative - CO_2 Smart Grid - aimed at utilizing CO_2 as a raw material for a circular economy (Carbon Capture and Utilization, or shortly CCU). To this end, a network will be developed in which CO_2 from different sources can be made available to different users. The proposed backbone of this network is the existing OCAP CO_2 pipeline, which already provides CO_2 from Shell in Pernis and ethanol producer Alco in Pernis to the horticulture in the Westland region for growth promotion of crops.

Ecofys has conducted a pre-feasibility study in which they identified in which applications CO_2 could be utilized in North- and South-Holland in the short term (5-10 years) (Ecofys, 2017) Table 2 shows the results of the pre-feasibility study. In this pre-feasibility study, Ecofys did not analyse the source of the used CO_2.

Table 2 - Overview of identified prospective utilization application of CO_2 as raw material

CCU technology	TRL	Current (2017) (kt CO_2)	Near term (5 years) (kt CO_2)	Long term (10 years) ($ktCO_2$)
Horticulture	9	400-500	850-1,000	1,200
Carbonate mineralization	4-8	0	100-200	100-300
Polymer processing	8	-	12-23	30-45
Concrete curing	7-8	-	-	30
Synthetic methanol (including methane)	8	-	-	220
Methanol yield boosting	9	630	900	1,250
Rounded total		**~400**	**~1,000**	**~1,700**

Source: Table from (Ecofys, 2017). 'Methanol yield boosting' is specifically related to methanol production at BIOMCN in Delfzijl.

According to studies of Ecofys and CE Delft the various capture and application routes are not profitable under current market conditions. The various capture and application routes could have a social advantage, in particular because they could lead to a CO_2 emission reduction, and application might therefore provide a benefit from a societal perspective. This potential benefit can be made explicit by means of a Social Cost Benefit Analysis (SCBA). The basis of such a SCBA is a Life Cycle Analysis (LCA) in which environmental impacts are quantified. The LCA is commissioned by the Ministry of Infrastructure & Water Affairs, the MKBA will be commissioned by BLOC, both on behalf of the CO_2 Smart Grid consortium.

This study focusses on the LCA of different CCU routes applicable in the CO_2 Smart Grid. The results of this study can serve as input for the later SCBA. The study is conducted under supervision of the client, process supervisor BLOC and the core working group of the consortium.

2 Methodology

The Life Cycle Assessment (LCA) methodology is used to determine the environmental impact of a product or service throughout the entire life cycle. It can be used to compare the environmental impact of different products or services. Because the different CCU routes do not provide the same product, although CO_2 is captured in all CCU routes, a substitution approach is used. See Section 2.3.

The reporting methodology for LCA is set by the ISO14040 and ISO14044 guidelines for Life Cycle Assessment. The main lines of these methodological guidelines are followed with the important note that this study is a screening LCA, and not a full scale Life Cycle Assessment. A screening LCA aims to give an indication of the comparative environmental impact and recognizes the uncertainties because of the short span in which this study is carried out.

A number of important methodological choices are described in this chapter.

2.1 Goal and scope definition

2.1.1 Goal of the study

The main goal of the study is to identify the environmental hotspots in the different CCU routes, and make a comparison of the different routes.

The main goal is reached by:
- examining the net avoided CO_2 emission for the CCU routes;
- examining the implication of the different storage times during which the CO_2 is utilized in the intended applications;
- examining possible other environmental impacts of the CCU routes.

2.1.2 Scope of the study

In order to make a comparison, a unit of comparison needs to be defined. This unit of comparison is called the **functional unit**. The functional unit is defined as:

1 tonne of CO_2 captured in 2030 and subsequent utilization.

Different utilization-routes produce different products/services. CCU is a multifunctional system generating both the service of capturing of CO_2 as well as utilizing the CO_2 in a product/service. Since the aim of this study is to provide insight into the environmental benefit of the entire CCU process, and not into a single product, the functional unit has been set in such a way that it follows one tonne of captured CO_2 through the entire process.

There are many CCU routes possible in the Netherlands of which nine different CCU routes are compared in this study. These nine routes are based on CO_2 capture options from three different sources and utilization of the CO_2 in three different applications. A selection of routes has been made based on expected availability of CO_2 in 2030, technology readiness level and the compatibility with current industry. Table 3 gives an overview of the nine different CCU routes that are considered in this LCA. Furthermore these nine different CCU routes are compared with Carbon Capture and Storage (CCS) as a reference.

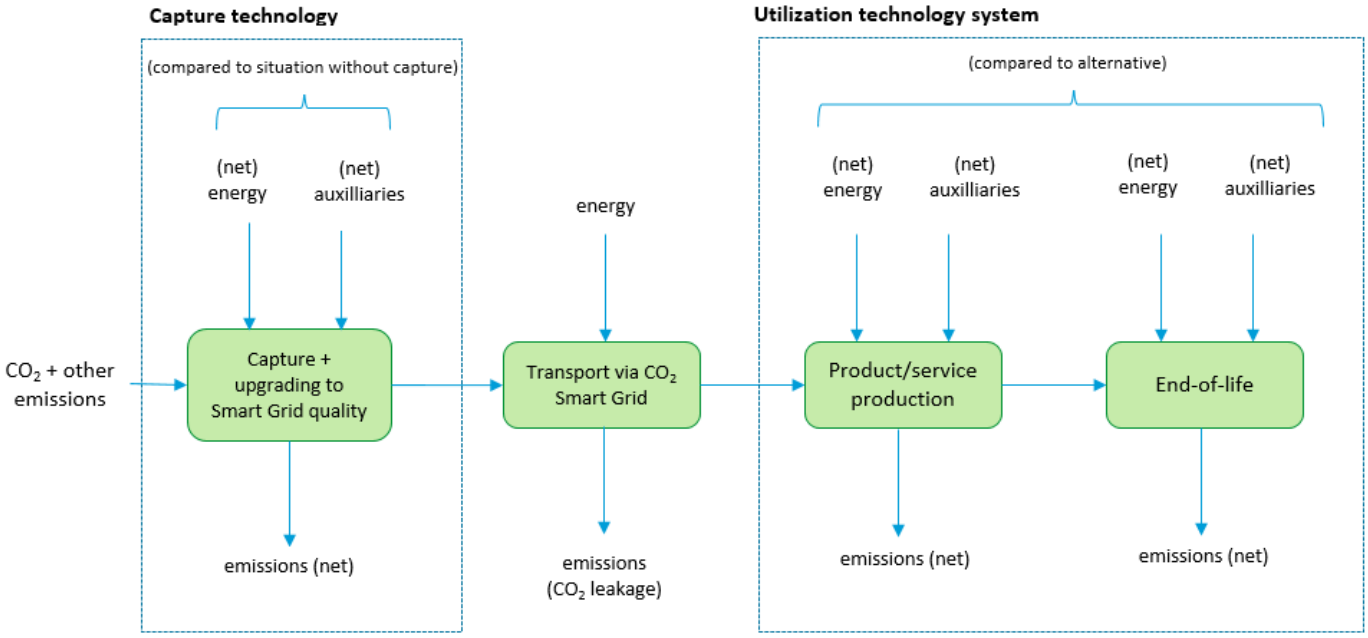
Table 3 - CCU routes

CO_2 source |Utilization	Horticulture	Mineralisation	Methanol production
Waste incineration	Route 1	Route 2	Route 3
Blast furnace process and blast furnace gas	Route 4	Route 5	Route 6
Fossil oil refining	Route 7	Route 8	Route 9

This study compares the fulfilment of the functional unit of these nine CCU routes within the **system boundaries** as shown in Figure 2. All green filled boxes represent life cycle phases that are taken into consideration in this study.

For every life cycle phase, material and energy use are taken into consideration as well as all environmental emissions relevant to the environmental impact categories considered in this study (see Section 2.2). Figure 2 shows the general system boundaries. The exact capture technology and utilization system differ per CCU route. The product or service produced because of the utilization of CO_2 also differs per utilization method. For the system description per CCU route see Chapter 3. The CO_2 source is outside of the system boundaries this means that e.g. the production of iron is considered to occur whether or not CCU is applied. The systems of iron production and CCU are therefore seen as two different production systems.

Figure 2 - System boundaries of CCU



Note: All life cycle phases with a green filling are taken into consideration in this study, including energy and auxiliary use as well as emissions.

2.2 Environmental impact categories

This study uses the ReCiPe2016 methodology to examine the environmental impact of the different CCU routes[1]. The ReCiPe2016 Midpoint Hierarchist Approach (v.1) has been chosen as it is included in the SimaPro Software (v.8.4). A wide range of different environmental impacts are included in the ReCiPe-methodology and can be studied with LCA. Within the limited time frame of the study only global warming potential (CO_2 eq. emissions) are quantified. Qualitative statements will be made on other relevant environmental impacts such as fine particulate matter formation and acidification.

2.3 Dealing with a multifunctional system

As described earlier the different utilization-routes produce different products/services. CCU is a multifunctional system generating both the service of capturing of CO_2 as well as utilizing the CO_2 in one or multiple products.

The choice of functional unit leaves us with the issue of how to show the benefit of the produced product/service per utilization method. According to ISO14044, there are different approaches if a system under study has multiple functions. The preferred approach according to ISO14044 is to prevent needing to allocate environmental burdens between the different products/services delivered by a CCU route. Allocation of environmental burdens based on economic or physical relationships introduces uncertainties into an LCA study. In the case of the produced product/service we therefore opt for preventing allocation.

Different approaches can be taken to prevent allocation, the most common ones being system expansion and substitution. The different CO_2 utilization routes produce different products/services. Using system expansion would require that all possible products are accounted for in all different options, creating very large systems that make the comparison of the actual CO_2 utilization options complex. We therefore apply substitution by assuming prevention of the currently applied production method for the product or service. The products/services prevented are described per utilization method in Chapter 3.

2.4 Fossil and biogenic CO_2

LCA convention such as e.g. the EN 16760 norm states that to assess climate change impact, all biogenic and fossil CO_2 emissions and removals should be considered. In this study not all life cycle stages are included for the CO_2 sources. For example the biogenic CO_2 uptake (removal) in biogenic products that are eventually treated as waste in an MWI are not taken into consideration in this study.

This means that no comparison can be made of the difference in impact over the entire life cycle of the biobased material and e.g. the fossil-based material in case of the coal-fired power plant. That is also not the purpose of this study. Therefore no environmental distinction is made in this study on the environmental impact of the emission of biogenic and fossil-based CO_2. In the case future studies are carried out in which the production phase of the CO_2 source is taken into consideration, the emission of the two types of CO_2 is distinguished in the figures and tables in this study.

[1] For the full methodological report see (Huijbregts, et al., n.d.).

2.5 CO_2 storage period

CO_2 is stored for different time periods in the different products considered in this study.
The ILCD-guidelines (JRC European Commission, 2010) state that:
"temporary carbon storage and the equivalent delayed emissions and delayed reuse/recycling/ recovery within the first 100 years from the time of the study shall not be considered quantitatively".

We therefore only consider only two different CO_2 storage periods:
- 100 years or less, not leading to CO_2 emission reduction;
- more than 100 years, leading to CO_2 emission reduction.

In reality also a temporary storage of CO_2 (e.g. for 40 years) can have an environmental impact. Considering those differences is outside of the scope of this study, and not (yet) common in carbon accounting.

2.6 Electricity use: changes in energy demand and energy production

Changes in the energy demand and energy production are compensated for by extra production of fossil energy (Agentschap NL, CBS, ECN, PBL, 2012). This method ('de referentiepark-methode') is used in the monitoring and evaluation of energy- and climate policies in the Netherlands. In this study we use this marginal approach to the energy system in line with Dutch convention.

Per year ECN determines a CO_2 emission factor for the exact energy production facilities being used to compensate for the increased energy demand or decreased energy production. ECN has also determined a projection for this CO_2 emission factor for the years 2020, 2023 and 2030.
The CO_2 emission factor is 0.67 kg CO_2/kWh in each of these years (ECN, 2017). Since this study looks at CCU options in the year 2030, we use this emission factor.

3 CCU routes & system boundaries

The CO_2 sources and the technologies used for carbon capture from the three different CO_2 sources are further described in Section 3.1, purification and compression is described in Section 3.2 and the utilization technologies are described in Section 3.3. Combining the three sources with the three utilization technologies leads to nine CCU routes that are examined in this study.

3.1 CO_2 sources and carbon capture

Three different industrial processes are considered as source for CO_2 capture:
- waste incineration;
- blast furnace gas from the blast furnace process (iron production);
- fossil oil refining.

These different CO_2 sources were selected based on the expectation that these sources will still be available in 2030 and beyond and because these sources emit significant amounts of CO_2 annually and can hence supply a relevant amount of CO_2 to a CCU grid. Furthermore, these sources are through individual plants already connected to the OCAP infrastructure, which forms the basis of the CO_2 Smart Grid, or can in the near future be connected without large (technological) obstacles.
Each of these sources and the technology used to capture the CO_2 are discussed per source below. For each source the carbon capture is assumed to be an addition to the current practice (tailpipe capture of CO_2) and no more amendments are assumed to be made to the current business of an industrial plant except the accommodation CO_2 capture.

3.1.1 Municipal waste incineration plants (MWI)

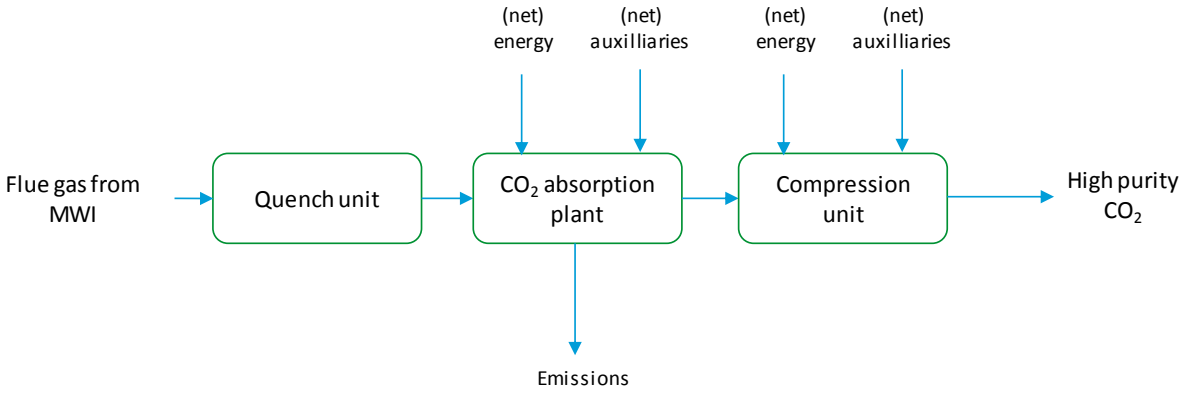
The Dutch circular economy policies aim to reduce the quantity of waste being used for energy recovery and instead to increase recycling of waste streams. We expect, however, that considering the speed at which the circular economy is taking shape in the Netherlands, waste incineration still has a role in 2030. Waste incineration plants are therefore considered to be a relevant source for CO_2 capture. Other reasons for their relevance as CO_2 source include:
- Flue gas of MWI is a point CO_2 source.
- There is an incentive for reducing waste production from the circular economy policies and the public opinion of MWI-plants is that they are not as favourable as recycling of material. The application of carbon capture at an MWI will therefore not lead to continued waste incineration when this would not be the case without CO_2 capture (no lock-in is created).
- A part of the CO_2 emissions from MWI are biogenic, since the MWI incinerates biogenic material such as garden and kitchen waste.

CO_2 emissions at MWIs are assumed to be captured by an innovative absorption technology in a CO_2 absorption plant. This technology has been developed by Procede Gas Treating, and is selected for its high Technology Readiness Level. The technology is currently applied in Delta (British Columbia) and at Twence in the Netherlands.

This technology uses Bilisol as an absorbent. This is a biodegradable solvent developed by Procede with a low degradation rate and very low volatility. A schematic representation of the processes is given in Figure 3. The hot flue gases are cooled to approximately 50°C and cleaned in a quench. CO_2 is next captured by scrubbing the flue gas with a Bilisol solution, after which Bilisol is regenerated in a separate reactor vessel heated with low-pressure steam from the MWI. Recovered high purity CO_2 (≥ 99.95 vol%) is next dehydrated and compressed to the necessary pressure for the CO_2 Smart Grid.

The use of low-pressure steam from the MWI leads to a reduction of the production of electricity. The reduction in electricity production is approximately 0.25 MWe per MW heat extracted[2].
As described in Section 2.6 the reduction in electricity production is compensated by extra production of fossil electricity.

Figure 3 - Schematic representation of carbon capture at MWIs



The capture of CO_2 emissions at MWIs is a special case, as the input, and therefore CO_2 emissions, are partly of biogenic origin. The biogenic content of the waste incinerated at MWIs is approximately 64%.[3]. As described in Section 2.4, we present the biogenic CO_2 emissions but do not make a distinction between the environmental impact of biogenic and fossil-based CO_2 emissions.

For the LCI of this capture technology see Annex A.

3.1.2 Blast furnace gas from the blast furnace process

Even in a circular economy there will be demand for primary, ore based high-grade flat steel as used in e.g. car manufacturing, due to losses and downgrading in quality of materials. Such high-grade steel can only be produced by way of the blast furnace production route for iron, as utilized at e.g. Tata IJmuiden. Tata IJmuiden is globally one of the most technologically advanced producers of such high-grade steel and is also one of the few producers operating competitively (Tata Steel, 2016) in a market plagued by overcapacity. It would hence be likely that Tata IJmuiden is still operational in 2030 and beyond. Based on this perspective, CO_2 capture from blast furnace gas at Tata IJmuiden is proposed as one of the options as feedstock for the CO_2 Smart Grid.

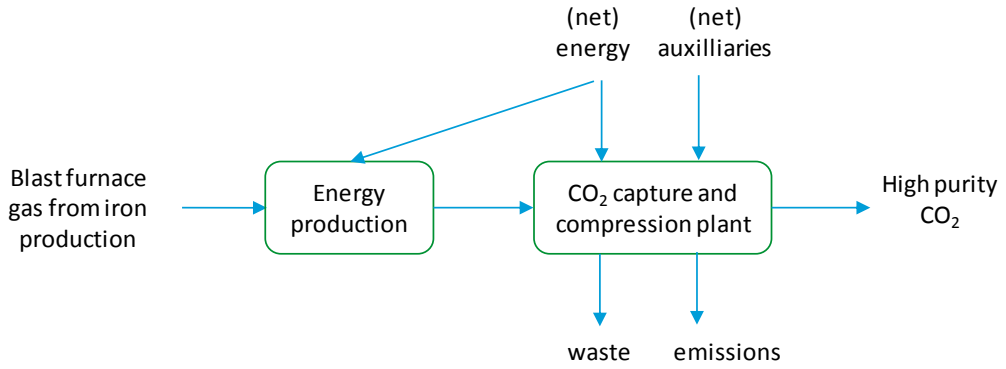
[2] Personal communication AVR, December 2017. Als reported by (ECN, DNV-GL, 2014).

[3] Based on data from (RIVM, 2017). Number applicable to 2015.

The blast furnace gas from Tata IJmuiden is currently fed into two different power plants (Velsen 25 and IJmond 1) where it is being incinerated to produce electricity. In case these two plants are not operational, a third plant (Velsen 24) will be used. Velsen 25 has the largest capacity of the three plants (375 MW). Therefore, this study looks at an amine-based capture method for the blast furnace process at the Velsen 25-plant. This technology is listed by the IEA as one of the primary technologies for CO_2 capture in iron production (IEA, 2013). For capture of CO_2 from blast furnace gas the amine considered is methyldiethanolamine (MDEA). After capture the CO_2 is compressed to the necessary pressure for the CO_2 Smart Grid.

Figure 4 shows a schematic representation of carbon capture from blast furnace gas from iron production for the iron production at Tata IJmuiden.

Figure 4 - Schematic representation of carbon capture from blast furnace gas from iron production



The CO_2 capture at the Velsen 25-plant leads to a reduction in electricity production of the plant. As described in Section 2.6, the reduction in electricity production is compensated by extra production of fossil electricity. An additional benefit of CO_2 capture in this way is that the heating value of the blast furnace gas increases (Zhang, et al., 2013). It has not been possible to quantify the impact of the increased heating value on the Velsen 25-plant, and the possible environmental benefit due to this is therefore not included. For the LCI of this capture technology see Annex A.

3.1.3 Fossil oil refining

The timeframe of realization of the large scale implementation of alternatives for conventional fuels (NH_3, biobased), especially for shipping, is still unclear. There are several risks that pose serious barriers to the development and implementation of e.g. biofuels. The most important risks are related to strong fluctuations in oil price, which has recently negatively impacted bioenergy manufacturers (World Energy Council, 2016). This is also acknowledged by the European Commission, stating that, in 2030, 'fossil fuels continue to be by far the dominant energy source' (GAIN, 2017). Therefore, we assume in this study that fossil oil refining is likely to remain in place until 2030. However, it should be noted that fossil oil refining is likely to lose some market share to other fuel types. The International Maritime Organization (IMO), for instance, will introduce regulations on CO_2 emissions from shipping by 2023 (IMO, 2016).

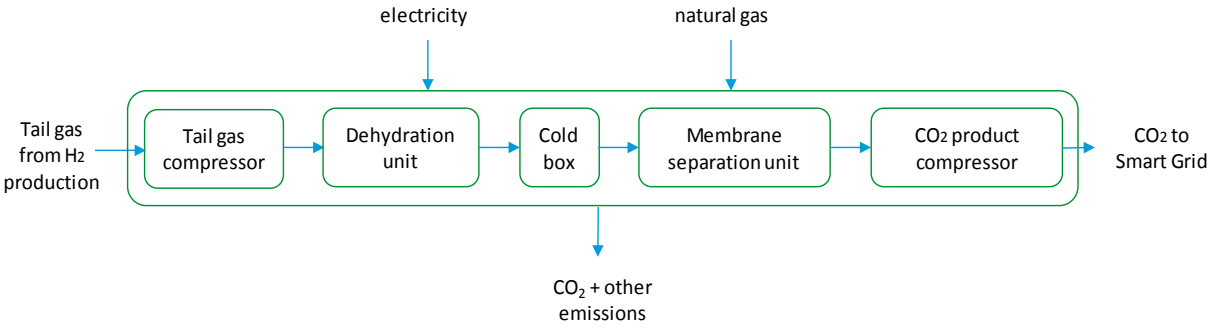
For fossil oil refineries, there are several different CO_2 emissions sources, such cracking reactors and hydrogen plants. For this sector we will consider CO_2 capture at the hydrogen plant. For capture at a hydrogen plant several different technologies are being applied commercially or demonstrated at

commercial scale[4]. In this case, cryogenic capture of the tail gas released during H_2 production will be considered. Benefits of this technology compared with alternative capture technologies include a very high purity CO_2 product.

Cryogenic capture (or 'low temperature separation') is based on separation principles involving the partial condensation of CO_2 and separating it from the gas phase in a distillation- or flash column (IEA, 2013). The selected specific technology is based on case 2B from IEA (2017), and includes the use of membranes in the setup of the CO_2 purification and compression unit. While not going into detail on its technological specifics, we briefly describe its components (see Figure 5):

- tail gas compressor: compresses tail gas to the required pressure of the cold box (see below);
- dehydration unit (dryers): dries compressed tail gas and lowers its temperature to below -55°C;
- cold box: contains coupled flash columns to separate the partially condensed CO_2 from the gas phase;
- membrane separation unit: recovers additional CO_2 from the output of the cold box;
- CO_2 product compressor: compresses the CO_2 to 110 bar(a).

Figure 5 - Carbon capture at H_2 production (cryogenic technology and membranes)



For the LCI of this capture technology see Annex A.

3.2 CO_2 upgrading: purification and compression

For utilization and for transport by means of the OCAP-pipeline system the captured CO_2 will have to meet specification requirements (see Table 4). In case specifications of the captured CO_2 do not meet requirements for utilization and/or transport, the CO_2 will have to be upgraded.

Table 4 - Specification requirements for applications and transportation

	Horticulture*	Mineralisation (Compensatiesteen)	MeOH production	CCS
CO_2 (vol%)	≥ 99.3%	60%	≥ 99.9%	≥ 99.9%
Pressure (bar(a))	≥ 21	unknown	50 - 100	130

* Specifications as currently met in the OCAP pipeline.

[4] These include VPSA, amine based capture (BASF MDEA, Shell ADIP X), cryogenic capture and a combination of cryogenic separation and cold methanol (see e.g. (Zero Emissions Platform (ZEP), 2017).

The current OCAP-pipeline pressure is standardized at 21 bar(a). For a doubling of capacity, when realising the CO_2 Smart Grid, the pressure will need to be higher. We assume a necessity of approx. 40 bar(a) in pressure. This assumption was agreed on in the project meeting of December 5th 2017. For the CO_2 Smart Grid the purity of the CO_2 will need to be 99.9 vol% to meet the requirements of all the three studied applications.

For CCS an extra compression step until 130 bar(a) is required before injection in supercritical state.

Efficient compression to the required high pressure level of the CO_2 gas takes place in several stages. Based on polytropic efficiency in an electrically driven compressor the work per ton of CO_2 is calculated per stage using the following input variables:

- mass flow in kg/s;
- input pressure;
- output pressure;
- input temperature;
- gas compressibility;
- molar weight of the gas;
- polytropic efficiency of the compressor stage;
- electric motor efficiency.

The output pressure of the previous stage is used as the input pressure of the next stage. The next stage input temperature is after intercooling when applied. When the required pressure is reached no more stages are added. This results in the work of compression per stage which are added to deliver the total work of compression in kJ/kg CO_2 compressed.

3.3 CO_2 utilization

3.3.1 Horticulture

Enhanced CO_2 levels in horticulture in greenhouses are essential for creating optimal growing conditions for commercial crops. The CO_2 used in Dutch greenhouses is currently supplied either by CO_2 produced from the combustion of natural gas in a gas burner, a CHP-unit or delivered from the OCAP-pipeline network. This latter network is a network in South-Holland currently supplying CO_2 from Alco and Shell to horticulture in South-Holland.

The horticulture sector is strongly committed to sustainability, and has the ambition to become carbon neutral by 2040. A boundary condition for realizing this goal is an abundance of externally available CO_2. The availability of external CO_2 is seen by the sector as a key enabling factor in realizing this transition. Under these developments, application of captured CO_2 in horticulture provides one of most interesting and well-developed opportunities for CCU application (Ecofys, 2017).
In the provinces North-Holland and South-Holland (i.e. roughly the area around the OCAP pipeline), horticulture is said to provide a CCU potential of 500 ktonnes at the moment, with the potential to increase to 1.2 Mtonne in 10 years. For the Netherlands, this potential is estimated at 2.1 Mtonne in 2030 due to the creation of new CCU projects (Berenschot ; EEI ; MEC, 2013).

Description of utilization technology

For this utilization system we present two figures:

1. figure that shows the utilization system of the application of CO_2 from the CO_2 Smart Grid as plant growth enhancer in horticulture;
2. figure of the reference case (the alternative): using a gas burner for the generation of (useless) heat and CO_2.

The dotted line indicates the elements of the system that are taken into account in assessing the environmental benefits of using captured CO_2 in this application.

In the reference case system, natural gas is burned to generate CO_2. The heat that is unwanted in the greenhouse is released to the air. When using CO_2 from the CO_2 Smart Grid or OCAP-pipeline, the burning of natural gas is summer is no longer needed. The quantity of natural gas incinerated that can be replaced by CO_2 from the CO_2 Smart Grid is determined based on the current incineration of natural gas in the summer, when the heat is not necessary for plant growth. Another method to determine the gas replaced by CO_2 is taken the average as has occurred in the current OCAP-pipeline. The choice for this approach is in line with previous research by CE Delft (CE Delft, 2017).

Figure 6 - System boundaries of utilization in horticulture – case A (current situation)

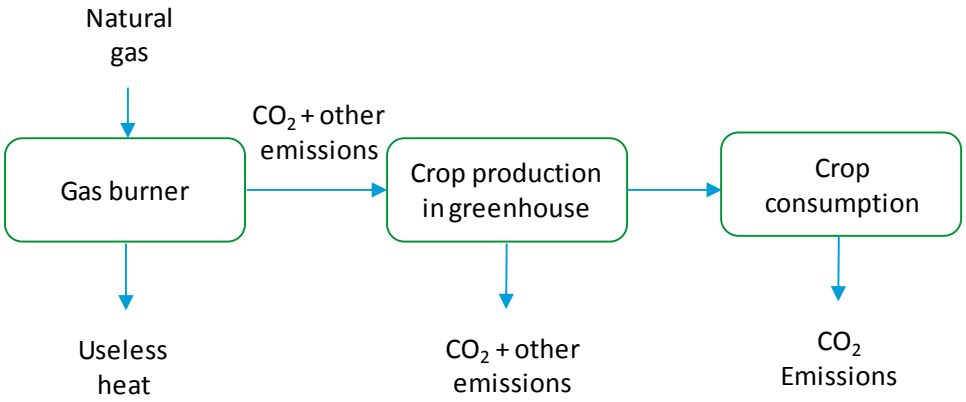
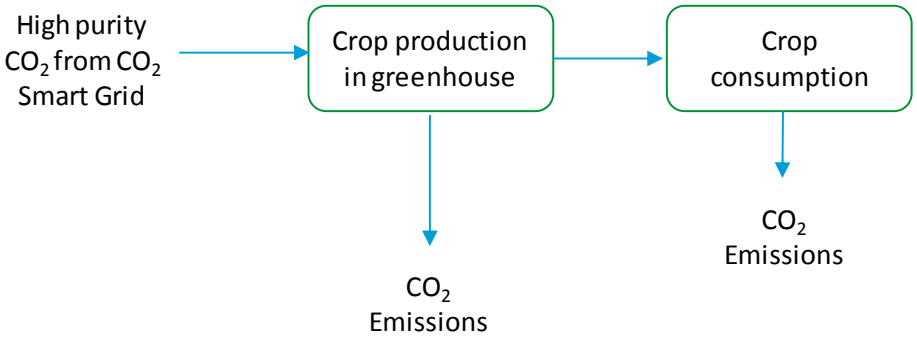


Figure 7 - System boundaries of utilization in horticulture – case B



Produced products/services

All CCU routes that include utilization in horticulture produce the following products/services:
- capture of one tonne of CO_2;
- increased plant growth.

CO_2 storage time

The CO_2 that is sequestered in plants is released back into the atmosphere relatively quickly. Therefore, the storage of CO_2 in agricultural and horticultural crops is short-cyclical. In line with conventional CO_2 accounting practices, short-cyclical CO_2 is in this study not accounted for as a reduction in CO_2 emissions.

Excluded: increased plant growth

A side effect of using a gas burner or combined heat and power (CHP) generator in summer to generate CO_2 for use in horticulture is that the production of CO_2 is limited by the production of heat. After all, crops are only able to grow properly at a certain maximum temperature. Therefore, when no heat is produced in the process of generating CO_2, i.e. by using external CO_2, the used amount of CO_2 per m^2 can be larger. This is likely to have a positive effect on the production efficiency of greenhouses (energy used per weight of crop produced) (Dieleman, et al., 2009). However, since no quantitative data is available on this issue, it has not been taken into account in this study.

Excluded: alternative CO_2 source makes energy transition possible

Currently most greenhouses in North- and South-Holland are heated by means of a combined heat and power (CHP) unit. These CHPs use natural gas to produce three products: heat, electricity (also supplied to the grid) and CO_2 used as plant growth enhancer. This means that the supply of an alternative affordable CO_2 for use as plant growth enhancer can have the effect of making a transition towards a different heating technology for greenhouses possible. This is a situation in which the abundance of external CO_2 and its application in horticulture has enabled a transition to carbon-neutral heat. Carbon-neutral heat could for example be geothermal heat, residual heat, or a combination of these and other options. Since the exact impact that using an external CO_2 source has on the energy supply is unknown, this is not included in the LCA.

3.3.2 Mineralisation

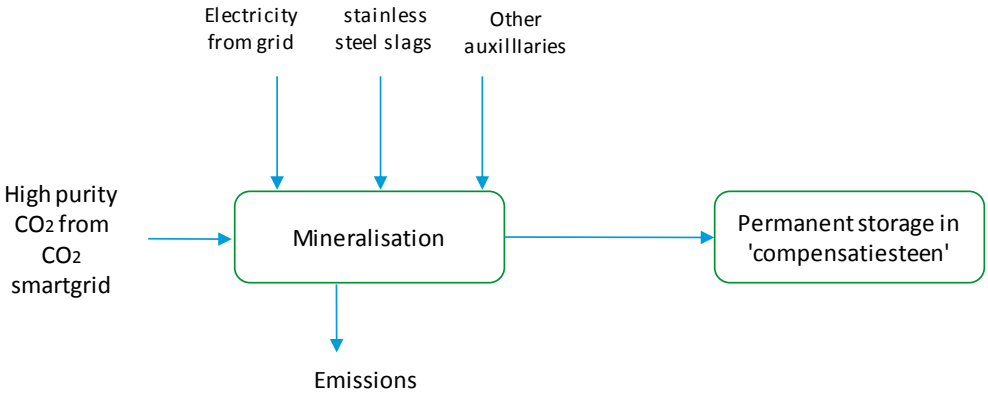
In this application route, a mineral feedstock reacts with captured CO_2 to form an inert carbonate rock. Hereby, the carbon is chemically trapped and permanently sequestered. According to Ecofys, the market potential for carbonate mineralisation is somewhere between 100 and 300 ktonnes per year within ten years (Ecofys, 2017).

There are several technologies possible for carbonate mineralisation these include reaction of several waste products with CO_2 as well as the reaction of olivine (a mineral) with CO_2. In this study, we consider the Carbstone-process, as developed by the Belgium research institute VITO, as an example for mineralisation. This process has been amended and is commercially applied (TRL 9) by the RuwBouw Groep, who sells a ‘compensation stone’ (Compensatiesteen) made through this technology. The RuwBouw Groep uses slags from stainless steel production, sand and CO_2 and converts this into a stone that can be used as a substitution for sand-lime bricks.

Description of utilization technology

The current pilot plant of the RuwBouw Groep produces 3,000 m^3 of Compensatiesteen per year. The organisation is investigating the possibilities for setting up a full-scale production plant with a capacity of sequestering 80 ktonnes of CO_2, equivalent to the production of 164,000 m^3 compensatiesteen. Compensatiesteen is produced by means of a hydraulic press, which uses little electricity. The stone is then cured in a CO_2 rich environment until it is fully saturated. Figure 8 shows the production and end-of-life of Compensatiesteen. For a full life cycle inventory see Annex A.

Figure 8 - System boundaries of utilization in carbonate mineralisation



Produced products/services

All CCU routes that include utilization of CO_2 for mineralisation in Compensatiesteen produce the following products/services:

- capture of one tonne of CO_2;
- Compensatiesteen.

CO_2 storage time

The CO_2 used in mineralisation is permanently stored, and will only come free again with continuous weathering of rock or when treated in an industrial process.

Prevention of sand-lime brick production

Compensatiesteen is a hard, stone-like material that is currently used in construction applications where originally sand-lime bricks would be used. RuwBouw Groep expects that the stone can also be used in conventional non-constructive concrete applications if the permit procedure for this application has been completed. Non-constructive applications include concrete parts which, with the exception of any transport and auxiliary reinforcement, do not contain any structural reinforcement. In this LCA we consider the prevention of sand-lime brick production.

Conventional use stainless steel slags

Stainless steel slags are currently treated and used as aggregates or sand in road construction[5]. If the stainless steel slags are used to produce Compensatiesteen, the aggregate will need to come from elsewhere. The environmental impact of aggregate production elsewhere is taken into consideration in this study.

Excluded: cleaning stainless steel slags

The stainless steel slags used by the RuwBouw Group are cleaned before being used in the Compensatiesteen. However, it is currently unclear where the cleaning process takes place, and whether this process requires a large amount of associated energy use and/or other inputs. We expect that in comparison to the conventional application of stainless steel slags as granulate or sand in road construction, no extra treatment is needed.

3.3.3 Methanol

According to Ecofys, the Dutch market potential for CO_2 based methanol amounts to 220 ktonnes/year within ten years (Ecofys, 2017). In methanol production the captured CO_2 is hydrogenated with separately produced hydrogen. This hydrogen in the studied CCU route is produced through electrolysis: the process of using electricity to split water into hydrogen and oxygen. We study the production of methanol and the electrolysis based on a fossil fuel mix (as described in Section 2.6) as well as based on directly coupled renewable energy.

Description of utilization technology

We consider the process as it is currently applied by Carbon Recycling International (CRI). CRI runs a demonstration installation with a 4,000 tonnes/year production capacity of 'Vulcanol' which has been operational since 2012[6]. CRI aims at a commercial scale of 35-40 ktonnes/year. The TRL level of this technology is estimated to be TRL 7-8. Vulcanol is fuel grade methanol which can be blended with gasoline for automobiles and used in the production of biodiesel or fuel ether. In addition, Vulcanol can be used in the production of several synthetic materials.

Figure 9 shows the utilization system of CO_2 from the CO_2 Smart Grid as feedstock for the production of methanol production based on this technology. The process yields methanol and water and some combustible by-products, which may be marketed/supplied to external customers. The heat of the exothermic CO_2 hydrogenation reaction is partially used to heat feed streams and for distillation of the raw product.

We study this CCU in the following four cases:
- complete renewable electricity use, short term sequestration of CO_2 (e.g. fuel);
- complete renewable electricity use, long term sequestration of CO_2 (e.g. chemical);
- complete fossil electricity use, short term sequestration of CO_2 (e.g. fuel);
- complete fossil electricity use, long term sequestration of CO_2 (e.g. chemical).

In the case of production with completely renewable energy use, the hydrogen is considered to be produced with renewable energy with a direct connection to the hydrogen plant, e.g. hydrogen produced by water electrolysis with electricity from *directly coupled* wind power or photovoltaic power. Hydrogen production by way of electrolysis and methanol production need not take place at

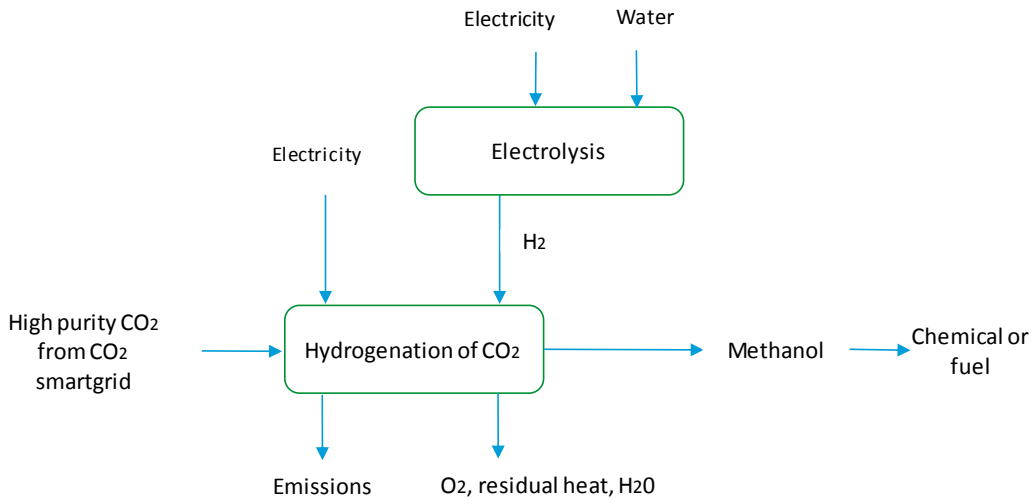
[5] See for example the products sold by Orbix: www.orbix.be/nl/materialen

[6] A second technology-provider is Japanese company Mitsui Chemicals Inc., but their technology seems less evolved.

the same location if hydrogen production can be connected with methanol production by way of a pipeline, e.g. the existing Air Liquide North-western high pressure H_2 network. Such a high pressure system may act or be utilized as a H_2 buffer by way of the 'line pack[7]' of the system.

In the case of production based in fossil electricity mix we use the carbon footprint of electricity as given in Section 2.6.

Figure 9 - System boundaries of production of methanol from CO_2 through hydrogenation



Produced products/services

All CCU routes that include utilization of CO_2 for methanol production produce the following products/services:

- capture of one tonne of CO_2;
- methanol.

The combustible by-products, residual heat and O_2 could be marketed as products but are not considered to be so in the base case modelling because not enough data has been obtained to do so.

CO_2 storage time

Given the wide range of applications for methanol it is undoable in this project to consider each of them. We will therefore indicate the time period during which the CO_2 utilized in methanol production is 'sequestered' in these applications. This will be done for two extremes in terms of duration:

- use in fuels (e.g. as oxygenate or as a component in biodiesel methyl esters or MTBE/TAME);
- use as chemical for use as a component in technical plastics.

[7] The intrinsic volume of the pipeline system.

In the case of use in fuels the carbon storage is short-cyclical, as the fuel is relatively quickly burned. In line with conventional CO_2 accounting practices, short-cyclical CO_2 is in this study not accounted for as a reduction in CO_2 emissions (see Section 2.4). In the case of use as chemical we assume CO_2 storage time of more than 100 years when used for technical plastic production that can be recycled several times.

Prevention of diesel production and use (application as fuel)

The reference technology for CO_2 based methanol production used as fuel is the production and use of conventional diesel for transportation.

Prevention of conventional methanol production (application as chemical)

The reference technology for CO_2 based methanol production is conventional methanol production in world scale units, utilizing stranded gas.

4 Reference technology: CCS

4.1 Introduction

One of the main questions to be considered and evaluated in this report is whether it is worthwhile in terms of CO_2 sequestration and/or other environmental aspects to utilize captured CO_2 for each of the considered applications instead of immediate geological storage in offshore abandoned gas fields or in offshore deep aquifers. Therefore an introduction is given into the carbon capture and storage (CCS) technology.

4.2 Background

CCS deposits captured carbon from large point sources to storage sites such that it will not enter the atmosphere, normally deposition occurs in underground geological formation such as abandoned gas fields or offshore deep aquifers. The CO_2 is captured, compressed, transport and subsequently injected.

For CCS as a reference case to this study, the injection step is that only step that differs from the CCU routes. The capture and transportation of CO_2 is also included for all CCU cases. For the injection, a compressor is used, which compresses the captured CO_2 into a supercritical fluid. The CO_2 is then injected under pressure into the geological formation, where it is trapped under an impermeable layer of rock. In this study, the electricity that is needed to inject the captured CO_2 into the geological formation is taken into account, as well as (possible) carbon leakage from the compressor.

4.3 Literature review

Several studies have assessed the carbon footprint of CCS technologies. In addition, a number of meta-studies that critically compare a variety of LCAs involved with this topic have been published.

(Cuéllar-France & Azapagic, 2015) published a well-cited comprehensive article in which numerous LCAs of CCS and CCU technologies are compared. The authors conclude that, on average, the Global Warming Potential (GWP) of CCS is significantly lower than that of CCU options. However, other environmental impacts, such as acidification potential and human toxicity potential might be higher compared to CCU. A number of CCS studies specifically address lowering the GWP of power plants. In this case, the GWP is reduced by 63-82%.

Another well-cited article describes the LCA of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2 (Koornneef, et al., 2008). While the study is slightly older, it is situated in the Netherlands, and therefore relevant to this study. The authors show that GHG-emissions per kWh produced are reduced by 71-78%, depending on the technological advancement of the power plant. The International Energy Agency published a synthesis report of LCAs of CCS technologies in 2010 (Marx, et al., 2011). The results of the LCAs of the coal power generation systems with CCS clearly indicate a substantial reduction in GWP of around 80%. Similar results are shown for application of CCS at lignite power plants.

A German study from 2007 presents an LCA and cost assessment of CCS technologies at hard coal-fired power plants and compares this to renewable energy solutions (Viebahn, et al., 2007).

The conclusion of the study is that CO_2 emissions per kWh for CCS technologies are 72-90% lower than for coal-fired power plants without CCS.

A more recent Norwegian study assesses the environmental impact of carbon capture in the context of a natural gas combined cycle electricity generation plant (Singh & Hertwichm, 2011). The authors show that, when sequestrating 90% CO_2 from the flue gas, 70% of CO_2 emissions per kWh are avoided. The Global Warming Potential is reduced by 64%. However, a number of environmental impact on midpoint level are influenced conversely: for example, both acidification (43%) and eutrophication (35%) increase. This is a similar result as (Cuéllar-France & Azapagic, 2015).

4.4 Conclusion

The consulted peer-reviewed academic references present that the reduction in carbon dioxide emissions from power plants range between 63-90%, strongly depending on the carbon capture technology and carbon source. This means that between 630 and 900 kg of CO_2 is sequestered per tonne of captured CO_2 for more than 100 years in a CO_2 storage location. The carbons sources studied in this study are different than those looked at in the literature, but the literature gives a good insight in the order of magnitude of sequestered CO_2. Some studies indicate that trade-offs might occur on other environmental effects. This points towards the importance of, in further studies, also taking into account e.g. acidification and eutrophication effects.

5 Results: Global warming

The results for this screening LCA of CCU routes are presented in two ways: per carbon capture technology/carbon source and per utilization technology. Subsequently, different forms of utilization can be more easily compared, whereas it also enables us to draw more attention to the environmental performance of the different capture methods.

Global warming, CO_2 and CO_2 eq.
Global warming is caused by greenhouse gasses. The most commonly known greenhouse gas is carbon dioxide (CO_2). This is, however, not the only greenhouse gas, other such gasses include methane and dinitrogen monoxide. All other greenhouse gasses can be expressed in CO_2 eq.; the global warming potential of a greenhouse gas compared to carbon dioxide. In this chapter we look at the impact of the CCU routes on global warming. We have not only looked at CO_2 emissions, but also other greenhouse gas emissions. *When referring to CO_2 emissions or reduction of CO_2 emissions we are therefore technically speaking about CO_2 eq. and not only CO_2.*

5.1 Results per carbon capture technology/carbon source

In this section, the results are shown separately for each the three carbon capture technologies/ carbon sources.

5.1.1 Carbon capture at a MWI

Table 5 shows the emitted CO_2 and the net avoided CO_2 emission of the different utilization-routes for CO_2 captured at an MWI in comparison with not capturing CO_2 at a municipal waste incinerator, including a breakdown. Figure 10 shows the emitted CO_2 of the different utilization-routes for CO_2 captured at an MWI.

Table 5 - Net avoided CO_2 emission per CCU/CCS route compared to non-capture

	Capture from MWI and utilization in horticulture#	**Capture from MWI and utilization for mineralisation**	**Capture from MWI and utilization for methanol production*** 100% renewable energy	**Capture from MWI and utilization for methanol production*** 100% fossil-based energy	**Capture from MWI and storage (CCS)**
CO_2 emission capture technology (kg/tonne captured)	239 kg	239 kg	239 kg	239 kg	239 kg
CO_2 emission product/service production (kg/tonne captured)	0 kg	116 kg	568 kg	2634 kg	24 kg
CO_2 emission end-of-life (within 100 years) (kg/tonne captured)	1,000 kg, of which: 361 kg fossil based 639 kg biogenic	0 kg	1,000 kg, of which: 361 kg fossil based 639 kg biogenic	1,000 kg, of which: 361 kg fossil based 639 kg biogenic	0 kg

	Capture from MWI and utilization in horticulture#	Capture from MWI and utilization for mineralisation	Capture from MWI and utilization for methanol production* 100% renewable energy	Capture from MWI and utilization for methanol production* 100% fossil-based energy	Capture from MWI and storage (CCS)
CO_2 emission reduction replacement (kg/tonne captured)	-1,076 kg	-286 kg	-1,163 kg	-1,163 kg	0 kg
Total CO_2 emitted (kg/tonne captured)	162 kg	69 kg	644 kg	2710 kg	262 kg
CO_2 emitted without CO_2 capture at MWI	- 1,000 kg	- 1,000 kg	- 1,000 kg	- 1,000 kg	- 1,000 kg
Reduction of CO_2 emission in comparison to current situation (kg/tonne captured)	- 838 kg	- 931 kg	-356 kg	1710 kg (emission increase)	- 738 kg

Results for utilization in horticulture are based on utilization in summer. For more horticulture-results see Section 5.2.1.

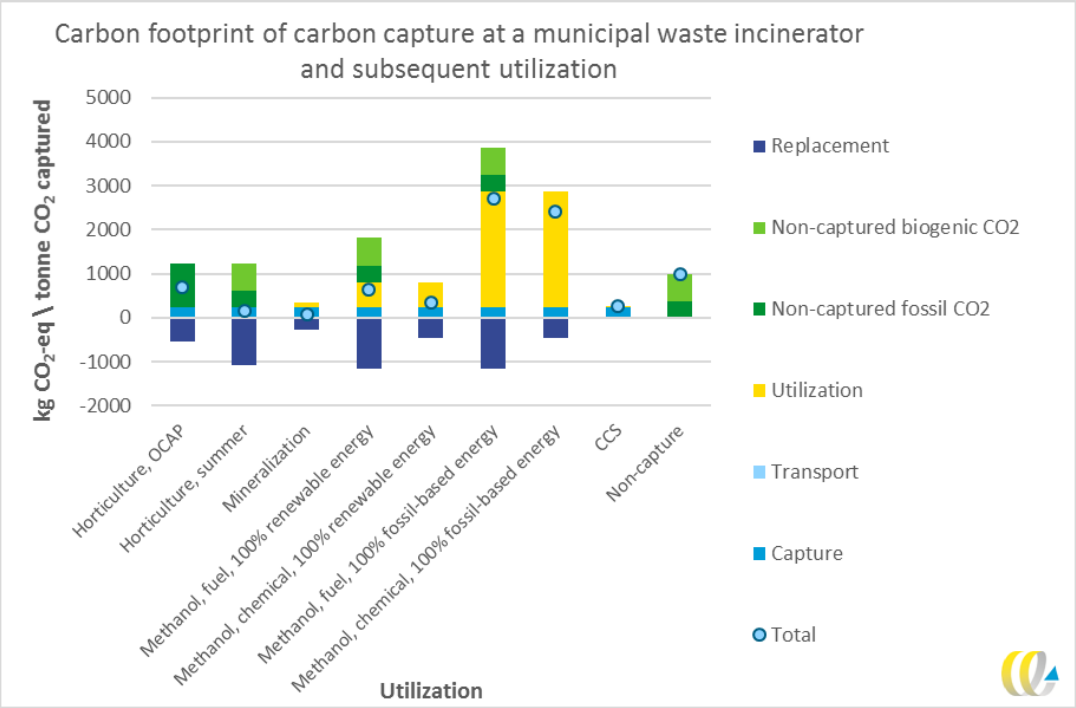
* Results for methanol production are based utilization of methanol used as fuel. For more methanol-results see Section 5.2.3.

Table 5 and Figure 10 show that the utilization-route of methanol is the least preferable option, especially when fossil fuel is used. There are several reasons for this. Firstly, all captured CO_2 is emitted very rapidly again if the methanol is applied in an application that sequesters the CO_2 shorter than 100 years, for example when the methanol is used as a fuel. In addition, the current available production technique for methanol from CO_2 is not so efficient, which is reflected in the relatively high value for the emissions associated with utilization. When methanol is used for the production of a chemical for an application where the CO_2 is sequestered for more than 100 years, the methanol utilization-route comes closer to CCS.

The carbon footprint of utilization of CO_2 in horticulture can be the same order of magnitude as that of CCS when the CO_2 is applied during summer. This is mostly linked to the large benefit associated with the avoided incineration of natural gas in the summer months. It is, in this case, the question whether this situation will still be relevant in the (near) future, and especially towards 2050, when heat production in the horticulture sector in the Netherlands will become carbon neutral. The in that case reference is no longer necessarily natural gas incineration but CO_2 could also be supplied by e.g. a wood burner. When adding CO_2 to horticulture year round, as currently applied in the OCAP-pipeline the reduction is approximately 500 kg CO_2 eq. lower, and no longer comparable to CCS. It can therefore be concluded that the CO_2 emission reduction is dependent on the specific situation.

For the mineralisation-route, the results indicate that long-term sequestration of captured carbon could be a good option. In addition, the replacement of sand-lime brick is relatively certain, and still quite a conservative (i.e. simple) avoided product. The energy use of the utilization of this route is also modest in terms of carbon footprint. There are however some uncertainties surrounding the energy use for utilization, since the modelling has been based completely on data supplied by the producer of Compensatiesteen. In the sensitivity analysis we will delve further into this uncertainty (see Chapter 7).

Figure 10 - Carbon footprint of carbon capture at a MWI and subsequent utilization per tonne captured CO_2



5.1.2 Carbon capture from blast furnace gas from iron production

Table 6 shows the emitted CO_2 and the net avoided CO_2 emissions of the different utilization-routes for CO_2 captured from blast furnace gas from iron production in comparison with not capturing the CO_2, including a breakdown. Figure 11 shows a breakdown of the emitted CO_2 of the different utilization-routes for CO_2 captured from blast furnace gas.

Table 6 - Net avoided CO_2 emission per CCU/CCS route compared to non-capture

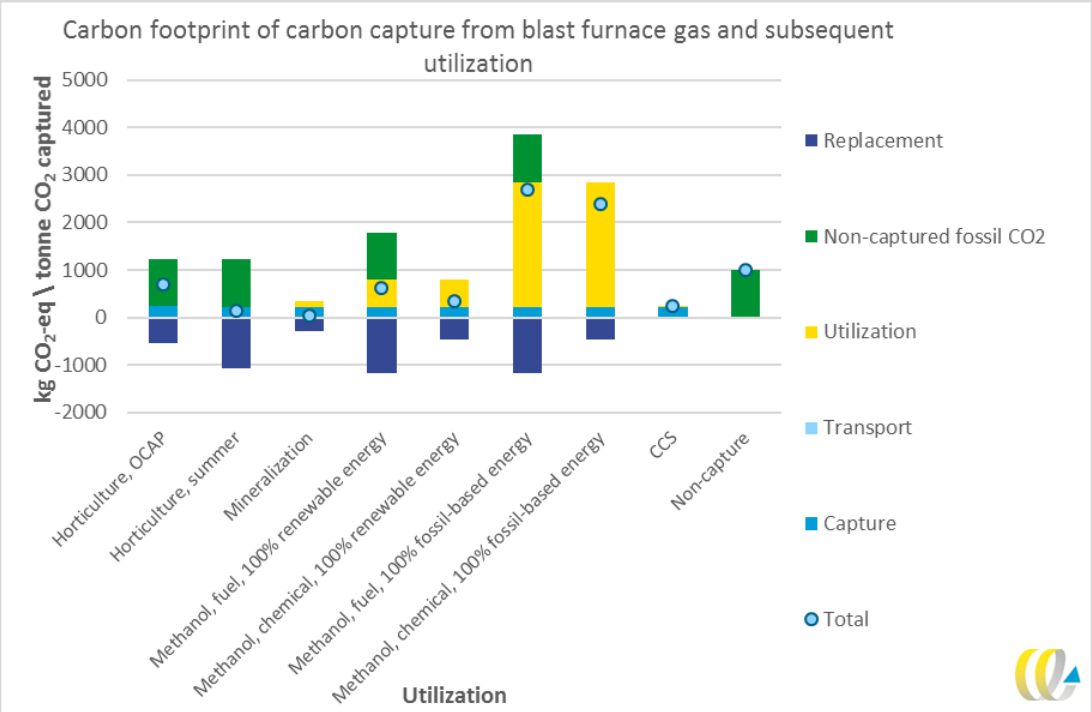
	Capture from blast furnace gas and utilization in horticulture#	**Capture from blast furnace gas and utilization for mineralisation**	**Capture from blast furnace gas and utilization for methanol production*** 100% renewable energy	**Capture from blast furnace gas and utilization for methanol production*** 100% fossil-based energy	**Capture from blast furnace gas and storage (CCS)**
CO_2 emission capture technology (kg/tonne captured)	220 kg	220 kg	220 kg	220 kg	220 kg
CO_2 emission product/service production (kg/tonne captured)	0 kg	116 kg	568 kg	2,634 kg	24 kg
CO_2 emission end-of-life (within 100 years) (kg/tonne captured)	1,000 kg	0 kg	1,000 kg	1,000 kg	0 kg
CO_2 emission reduction replacement (kg/tonne captured)	- 1,076 kg	- 286 kg	- 1,163 kg	- 1,163 kg	0 kg
Total CO_2 emitted (kg/tonne captured)	144 kg	50 kg	625 kg	2,691 kg	244 kg
CO_2 emitted without CO_2 capture from blast furnace gas	*- 1,000 kg*	*- 1,000 kg*	*- 1,000 kg*	*- 1,000 kg*	*- 1,000 kg*
Reduction of CO_2 emission in comparison to current situation (kg/tonne captured)	- 856 kg	- 950 kg	- 375 kg	1,691 kg (emission increase)	- 756 kg

Results for utilization in horticulture are based on utilization in summer. For more horticulture-results see Section 5.2.1.

* Results for methanol production are based utilization of methanol used as fuel. For more methanol-results see Section 5.2.3.

For the case of carbon capture from blast furnace gas, Figure 11 shows that the carbon footprint of the capture technique is comparable to that of capture at an MWI. The methanol-route, when produced from fossil-based energy, is again the least favourable option.

Figure 11 - Carbon footprint of carbon capture from blast furnace gas and subsequent utilization per tonne captured CO_2



5.1.3 Carbon capture at hydrogen plant (from fossil oil refining)

Table 7 shows the emitted CO_2 and the net avoided CO_2 emissions of the different utilization-routes for CO_2 captured at a hydrogen plant (from fossil oil refining) in comparison with not capturing the CO_2, including a breakdown. Figure 12 shows a breakdown of the emitted CO_2 of the different utilization-routes for CO_2 captured at a hydrogen plant.

Table 7 - Net avoided CO_2 emission per CCU/CCS route compared to non-capture

	Capture at a hydrogen plant and utilization in horticulture#	**Capture at a hydrogen plant and utilization for mineralisation**	**Capture at a hydrogen plant and utilization for methanol production*** 100% renewable energy	**Capture at a hydrogen plant and utilization for methanol production*** 100% fossil-based energy	**Capture at a hydrogen plant and storage (CCS)**
CO_2 emission capture technology (kg/tonne captured)	129 kg	129 kg	129 kg	129 kg	129 kg
CO_2 emission product/service production (kg/tonne captured)	0 kg	116 kg	568 kg	2,634 kg	24 kg
CO_2 emission end-of-life (within 100 years) (kg/tonne captured)	1,000 kg	0 kg	1,000 kg	1,000 kg	0 kg
CO_2 emission reduction replacement	- 1,076 kg	- 286 kg	- 1,163 kg	- 1,163 kg	0 kg

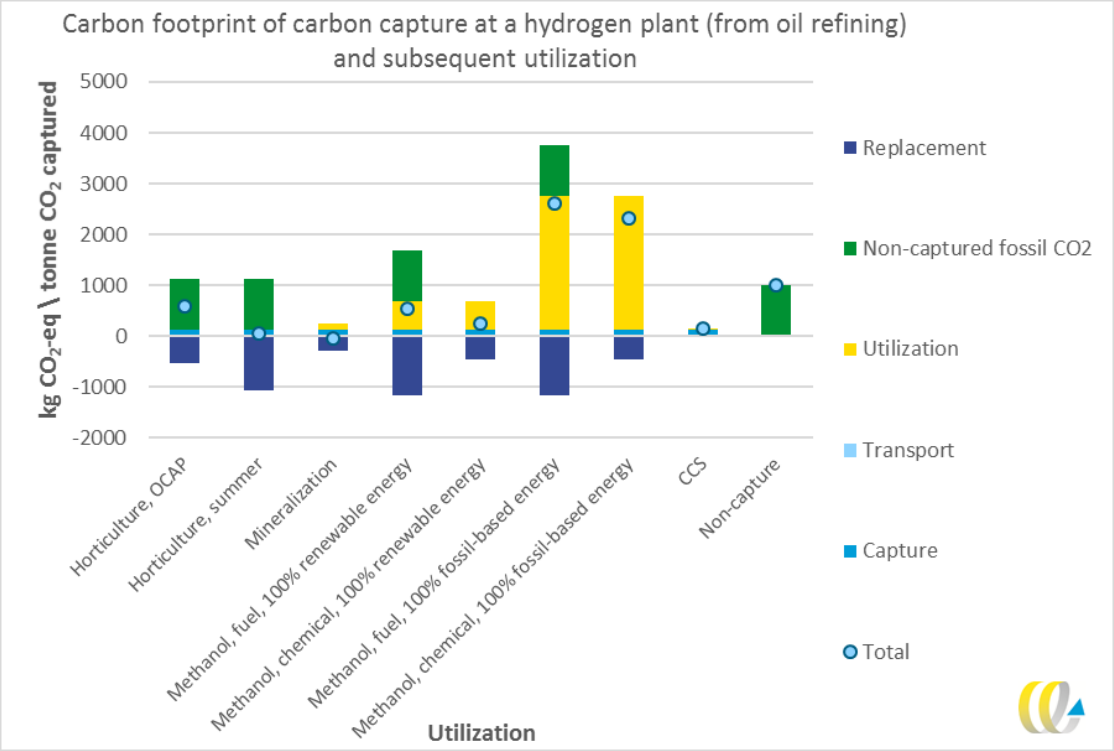
	Capture at a hydrogen plant and utilization in horticulture#	Capture at a hydrogen plant and utilization for mineralisation	Capture at a hydrogen plant and utilization for methanol production* 100% renewable energy	Capture at a hydrogen plant and utilization for methanol production* 100% fossil-based energy	Capture at a hydrogen plant and storage (CCS)
(kg/tonne captured)					
Total CO_2 emitted (kg/tonne captured)	53 kg	-41 kg	535 kg	2,600 kg	153 kg
CO_2 emitted without CO_2 capture at a hydrogen plant	- 1,000 kg	- 1,000 kg	- 1,000 kg	- 1,000 kg	- 1,000 kg
Reduction of CO_2 emission in comparison to current situation (kg/tonne captured)	947 kg	1,041 kg	465 kg	1,600 kg (emission increase)	847 kg

Results for utilization in horticulture are based on utilization in summer. For more horticulture-results see Section 5.2.1.

* Results for methanol production are based utilization of methanol used as fuel. For more methanol-results see Section 5.2.3.

Since the carbon footprint of the capture of CO_2 at fossil oil refining is comparable to that of capture from blast furnace gas as described in Section 5.1.2, the results of the different utilization technologies combined with capture do not differ much. Again mineralisation leads to a negative carbon dioxide emission (more carbon dioxide being captured than emitted), application in horticulture (in summer) is comparable to CCS while application in methanol production based on fossil-based energy is the least preferable option.

Figure 12 - Carbon footprint of carbon capture at a hydrogen plant (from fossil oil refining) and subsequent utilization per tonne captured CO_2



5.2 Results per utilization technology

In this section, we present the estimated carbon footprint per utilization technology.

5.2.1 Utilization in horticulture

Table 8 shows the emitted CO_2 and the net avoided CO_2 emission of the different CO_2 sources/capture technologies and utilization of CO_2 in horticulture in comparison with not capturing the CO_2, including a breakdown. Figure 13 shows a breakdown of the emitted CO_2.

Table 8 - Net avoided CO_2 emission per CCU route compared to non-capture

	Capture at MWI plant and utilization in horticulture	Capture at iron production and utilization in horticulture	Capture at hydrogen plant and utilization in horticulture
CO_2 emission capture technology (kg/tonne captured)	239 kg	220 kg	129 kg
CO_2 emission product/service production (kg/tonne captured)	0 kg	0 kg	0 kg
CO_2 emission end-of-life (within 100 years) (kg/tonne captured)	1,000 kg, of which: 361 kg fossil based 639 kg biogenic	1,000 kg	1,000 kg
CO_2 emission reduction replacement *	- 1,076 kg (summer)	- 1,076 kg (summer)	- 1,076 kg (summer)

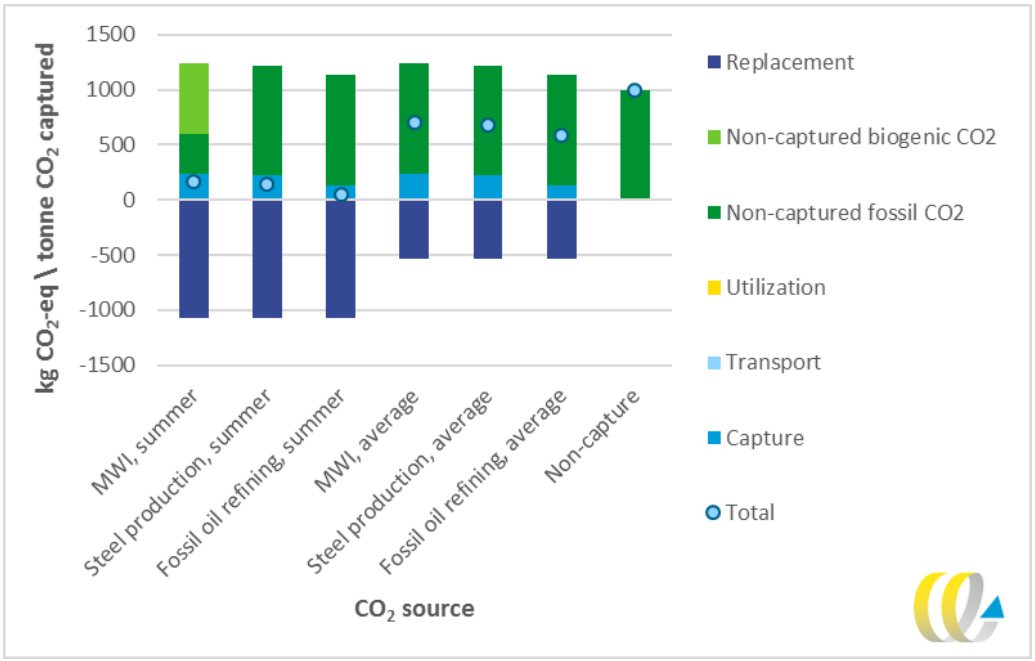
	Capture at MWI plant and utilization in horticulture	Capture at iron production and utilization in horticulture	Capture at hydrogen plant and utilization in horticulture
(kg/tonne captured)	- 538 kg (OCAP)	- 538 kg (OCAP)	- 538 kg (OCAP)
Total CO_2 emitted (kg/tonne captured) *	162 kg (summer) 700 kg (OCAP)	144 kg (summer) 682 kg (OCAP)	53 kg (summer) 591 kg (OCAP)
CO_2 emitted without CO_2 capture	- 1,000 kg	- 1,000 kg	- 1,000 kg
Reduction of CO_2 emission in comparison to current situation (kg/tonne captured) *	838 kg (summer) 300 kg (OCAP)	856 kg (summer) 318 (OCAP)	947 kg (summer) 409 (OCAP)

Note: These are indicative figures, and serve to give an order-of-magnitude-estimation.

* This table gives a range of values for both utilization of CO_2 in summer and the reduction of CO_2 emission as is achieved in the current OCAP-pipeline year round.

Table 8 and Figure 13 shows that for all three carbon capture technologies the utilization of the captured carbon in horticulture leads to net CO_2 emissions and that net more than 800 kg of CO_2 emission avoided per tonne of CO_2 captured when the CO_2 is added to horticulture in summer. This is because currently the CO_2 used in greenhouses in the Netherlands largely originate from natural gas combustion, the prevention of natural gas use (the replacement) compensates for a large part of the CO_2 emissions. In the current OCAP pipeline approximately half of the CO_2 added to the greenhouses prevents the use of natural gas use, on average 300 kg of CO_2 emission is avoided per tonne of CO_2-captured and added to a greenhouse.

Figure 13 - Carbon footprint of carbon capture and utilization in horticulture per tonne of captured CO_2



Future energy supply horticulture

When the incineration of natural gas is no longer the most logical supply for CO_2, i.e. when the heat supply will become carbon-neutral, it can be argued that the application of captured CO_2 in horticulture no longer needs to lead to the prevention of natural gas use. In that case the CO_2 could also be supplied by e.g. a wood burner. If that is the case the CO_2 emissions from utilizing captured CO_2 in horticulture will be higher than the quantity of CO_2 captured because of the energy demand for the capturing technology.

5.2.2 Utilization in mineralisation (Compensatiesteen)

Figure 9 shows the emitted CO_2 and the net avoided CO_2 emissions of the different CO_2 sources/capture technologies and utilization of CO_2 for mineralisation in comparison with not capturing the CO_2, including a breakdown. Figure 14 shows a breakdown of the emitted CO_2.

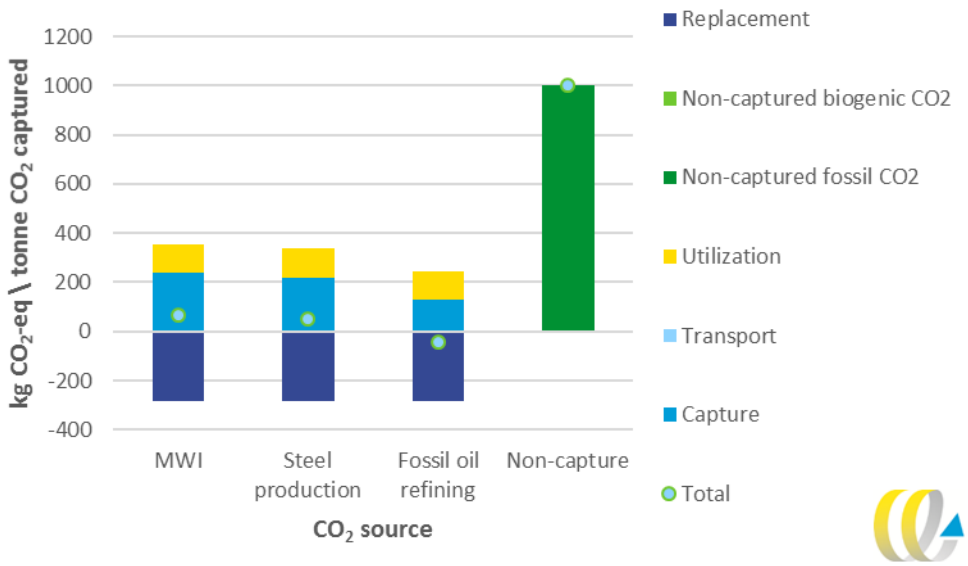
Table 9 - Net avoided CO_2 emission per CCU route compared to non-capture

	Capture at MWI plant and utilization for mineralisation	Capture at iron production and utilization for mineralisation	Capture at hydrogen plant and utilization for mineralisation
CO_2 emission capture technology (kg/tonne captured)	239 kg	220 kg	129 kg
CO_2 emission product/service production (kg/tonne captured)	116 kg	116 kg	116 kg
CO_2 emission end-of-life (within 100 years) (kg/tonne captured)	0 kg	0 kg	0 kg
CO_2 emission reduction replacement (kg/tonne captured)	- 286 kg	- 286 kg	- 286 kg
Total CO_2 emitted (kg/tonne captured)	69 kg	50 kg	-41 kg
CO_2 emitted without CO_2 capture	- 1,000 kg	- 1,000 kg	- 1,000 kg
Reduction of CO_2 emission in comparison to current situation (kg/tonne captured)	931 kg	950 kg	1,041 kg

Note: These are indicative figures, and serve to give an order of magnitude estimation.

Table 9 and Figure 14 show that the lower the carbon footprint of the capture technology is, the more likely that mineralisation of CO_2 in Compensatiesteen will lead to a net negative CO_2 emission. The figure also shows that, even in the case of a relatively high carbon footprint of the capture technology, such as capture at the MWI, there is a reduction of more than 90% of the CO_2 emissions compared to non-capture.

Figure 14 - Carbon footprint of carbon capture and utilization for mineralisation (Compensatiesteen) per tonne of captured CO_2



5.2.3 Utilization in methanol production

We study this CCU route in the following four cases:

1. Complete renewable electricity use, short term sequestration of CO_2 (e.g. fuel).
2. Complete renewable electricity use, long term sequestration of CO_2 (e.g. chemical).
3. Complete fossil electricity use, short term sequestration of CO_2 (e.g. fuel).
4. Complete fossil electricity use, long term sequestration of CO_2 (e.g. chemical).

To make the comparison as easy as possible the range of values for the four cases with the three studied capture methods/CO_2 sources is shown.

Table 10 shows the emitted CO_2 and the net avoided CO_2 emission of the different cases in comparison with not capturing the CO_2, including a breakdown. Figure 15 shows a breakdown of the emitted CO_2.

Table 10 - Net avoided CO_2 emission for capture and utilization for methanol production compared to non-capture

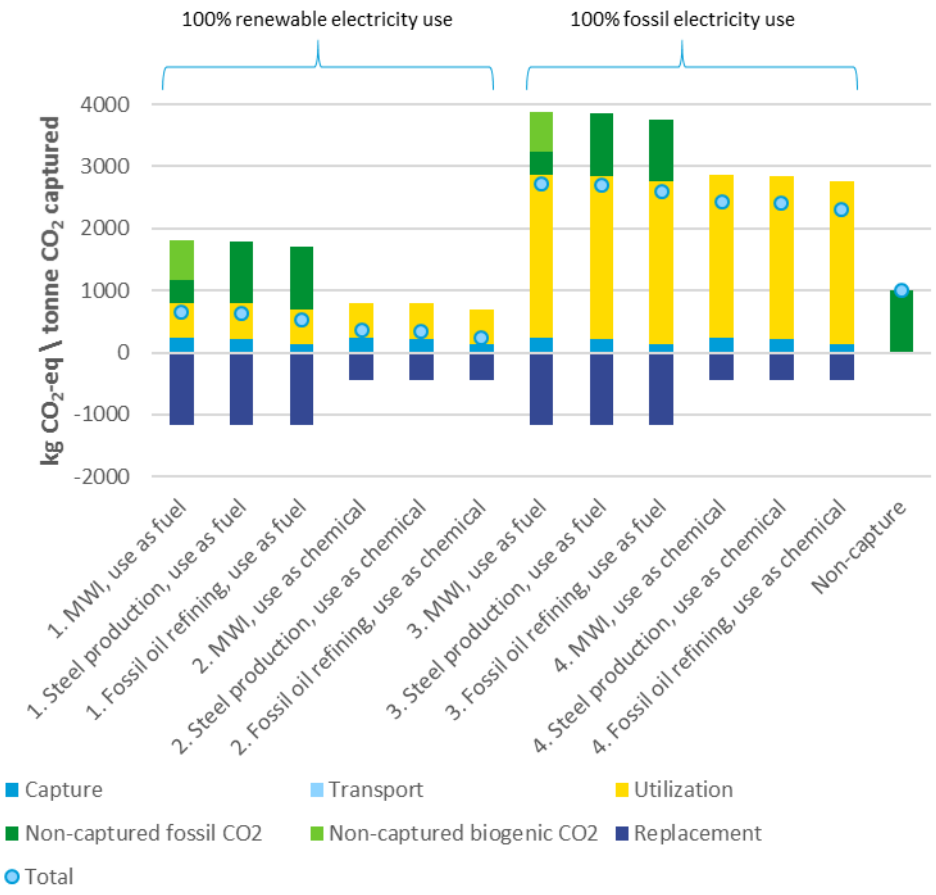
	Renewable electricity CO_2 storage <100 years	Renewable electricity CO_2 storage >100 years	Fossil electricity CO_2 storage <100 years	Fossil electricity CO_2 storage >100 years
CO_2 emission capture technology (kg/tonne captured)*	129 – 239 kg	129 – 239 kg	129 – 239 kg	129 – 239 kg
CO_2 emission product/service production (kg/tonne captured)	568 kg	568 kg	2,634 kg	2,634 kg
CO_2 emission end-of-life (within 100 years) (kg/tonne captured)	1,000 kg	0 kg	0 kg	0 kg
CO_2 emission reduction replacement (kg/tonne captured)	- 1,163 kg	- 451kg	- 1,163 kg	- 451 kg

	Renewable electricity CO_2 storage <100 years	Renewable electricity CO_2 storage >100 years	Fossil electricity CO_2 storage <100 years	Fossil electricity CO_2 storage >100 years
Total CO_2 emitted (kg/tonne captured)	535 – 644 kg	246 – 355 kg	2,600 – 2,710 kg	2,312 – 2,421 kg
CO_2 emitted without CO_2 capture	- 1,000 kg	- 1,000 kg	- 1,000 kg	- 1,000 kg
Reduction of CO_2 emission in comparison to current situation (kg/tonne captured)	- 356 – - 465 kg	- 645 – - 754 kg	1,600 – 1,710 kg	1,312 – 1,421 kg

* This table gives a range of values for all three capture technologies studied.

In case of production of methanol from CO_2 with non-renewable electricity there will be no reduction in CO_2 emissions in comparison to non-capture. In the case of 100% renewable electricity use for the hydrogen and methanol production a net reduction of CO_2 emission can be achieved ranging between 350 kg and 750 kg per tonne of CO_2 captured. The higher end of this spectrum can be reached with a capture technology with low CO_2 footprint, and utilization of the methanol in an application where the CO_2 is stored for more than 100 years.

Figure 15 - Carbon footprint of carbon capture and utilization for methanol production



Note: The methanol routes consider 100% renewable energy use, and applications where the CO_2 is stored for less than 100 years (e.g. fuels).

Discussion: renewable energy in methanol production

The utilization of 100% renewable electricity in the production of methanol using captured CO_2 might naturally lead to a discussion regarding the administration of the environmental benefits of this electricity. In the Netherlands, renewable electricity is largely made possible through the SDE+ subsidy scheme, introduced to accelerate the large-scale implementation of renewable energy technologies. The subsidy itself is made possible by the Dutch government, and mainly Dutch consumers who pay an extra fee for their electricity.

When strictly interpreting LCA rules, the environmental benefits of the renewable energy produced through the SDE+ system should therefore be rewarded to the government and consumers. Parties that make the realization of additional renewable energy possible through e.g. additional funding could make the decision to use the renewable energy for the production of 'green' methanol. However, in this case, it is important to stress that in the coming years, the net CO_2 reduction of this this application of renewable electricity will be lower than when it will be used directly to replace fossil electricity.

6 Results: Other environmental impacts

Environmental benefit additional cleaning of CO_2 containing gas

For coal-fired power plants, the deployment of carbon capture results in an additional environmental advantage: additional cleaning of the produced flue gases. This advantage results in lower emissions of e.g. SO_2 and particulate matter of coal-fired power plants: see (Royal Haskoning, 2011). For the three CO_2 sources considered in this study, any possible additional cleaning of CO_2-containing gases has not been described in detail in literature. Therefore the additional advantages of this additional cleaning are not expressed in the results of this study.

For example, the emissions associated with blast furnace gas include hydrogen sulphide, fine particulate matter and carbonyl sulphide (COS). It is likely, in line with what occurs at coal-fired plants when applying capture, that some hydrogen sulphide and fine particulate matter will be captured along with CO_2. COS is unlikely to be captured.

Capture from blast furnace gas and MWI: environmental costs of additional emissions

Furthermore additional emissions from capture associated with the application of absorbent have not been taken into consideration because of a lack of data. It is however known that the use of MEA as an absorbent has in the past led to the production of aerosols. The MDEA absorbent is less prone to degeneration than MEA is but the exact emissions because of the use of this absorbent are unknown. Additionally, engineering measures to prevent the emissions of these aerosols can mitigate this. Also, whether or not Bilisol (the absorbent used for capture from the MWI) degenerates is not known.

Environmental impacts of utilization technology system

Because of the lack of data described on the possible environmental benefits and environmental costs of the difference between capture and non-capture at the CO_2 capture location we exclusively describe the environmental impacts relevant for air quality that are related to the utilization technology. This study has considered the following environmental impact of the three utilization technology systems:

1. Fine particulate matter formation ($PM_{2.5}$ emissions).
2. Terrestrial acidification (SO_2 emissions).
3. Tropospheric ozone formation (NO_x emissions).

All utilization technology systems lead to a reduction of environmental impacts in these impact categories, even when considering fossil energy use for the capturing technologies. This means that in all cases the conventional production of product that is being replaced (natural gas combustion, sand-lime brick and methanol) has higher emissions than the emissions from the electricity used for the CCU (capture plus utilization).

Future research needed

As indicated in Chapter 4, possible trade-offs between reduction in CO_2 emissions and acidification and eutrophication exist. The acidification and eutrophication impact of the different CCU routes have not been studied. In further research it is important to take these into consideration, as well as other emissions occurring at the CO_2 capture location.

7 Sensitivity analysis

Because of the short time frame in which this screening LCA has been carried out there are uncertainties surrounding the results discussed in the previous chapter. This is partly due to the fact that the available data originates from one source, and time was too limited to verify the data.
In this chapter we describe the uncertainties that have been identified that make it possible to reach (firmer) conclusions about the studied CCU routes.

Uncertainties can arise because of several reasons. In this study, they mainly originate from a lack of available data (or time to obtain the data) and the difficulty of studying environmental impacts in the future. The most important uncertainties are briefly described below.

7.1 Uncertainties because of data availability

Uncertainties related to data availability include missing data on:
- compression energy for capture from MWI;
- carbon footprint of absorbents; carbon footprint of stainless steel slags.

Furthermore uncertainties exist in the used data, because it has not been possible to verify all data obtained from a single data source.

Capture from MWI: Compression energy

The energy needed for compression of the CO_2 captured from the MWI has been set at its most conservative because the pressure of the produced CO_2 was not mentioned in the used literature. The energy use for the compression accounts for approximately 20% of the CO_2 emissions from the capture at the MWI in the current calculations.

This uncertainty could lead to a reduction of the carbon footprint of capture at the MWI compared to the results that are presented in Chapter 5, and could make the carbon footprint of this capture technology more comparable to the carbon footprint of the other two capture technologies studied.

Capture from blast furnace gas: Carbon footprint absorbent

The carbon footprint of the MDEA-absorbent needed for the capture of CO_2 from blast furnace gas is not publically available. An approximation of the footprint has been made based on the production of methylamine. This is likely to be an underestimation of the actual carbon footprint.

This uncertainty could lead to a slight increase of the carbon footprint of the capture of CO_2 from iron production compared to the results in Chapter 5.

Capture from fossil oil refining

Because the capture technology considered for fossil oil refining does not produce CO_2 with the purity vol% required for use in the CO_2 Smart Grid an extra purification step is needed. The CATOX-technology could be used to do so. The only necessary input for this process, besides infrastructure, is pure O_2. Since very little O_2 is needed, the production of O_2 has not been taken into consideration

because the exact quantity needed is unknown. An environmental burden is however associated with this production.

This uncertainty could lead to a slight increase of the carbon footprint of the capture of CO_2 from fossil oil refining compared to the results in Chapter 5. The increase can be expected to be low because of the small quantity of O_2 needed.

Utilization for mineralisation: stainless steel slags

Stainless steel slags have been modelled as having no environmental impact because of their status as a waste product. However, stainless steel slags are actually used as aggregate in road construction, and therefore, a part of the environmental emissions for the stainless steel production should be attributed to this product. Because the economic value of stainless steel slags is unknown, economic allocation has however not been applied.

This uncertainty could lead to a slight increase of the carbon footprint of the utilization of CO_2 for mineralisation. The impact can however be expected to be limited since a tonne of steel has a much higher value than a tonne of aggregate.

All CCU routes: verification of data

Because of the short time span of the study, data for several processes within the CCU route have been obtained from a single data source. This data has not been verified extensively.
Some uncertainties exist because of this, including:

- Electricity use for the production of Compensatiesteen, which is much lower than that of the Carbstone technology, of which it has been derived from[8].
- Data on capture at the MWI has been obtained from (Monteiro, et al., 2015), a study conducted by Procede, the owner of the technology. This data has not been verified except for order of magnitude verifications.
- Data on production of methanol has been based on data on a single pilot plant from (Stefansson, 2015). This data has not been verified except for order of magnitude verifications.

7.2 Uncertainties due to future development of CO_2 Smart Grid

This study looks at the implementation of a CO_2 Smart Grid in 2030. Since it is difficult to predict the future there are a number of uncertainties concerning future development of the studied CCU routes. These include:

- other applications of Compensatiesteen;
- sustainable heat supply in Dutch horticulture;
- optimization possibilities for methanol production;
- additional cleaning of CO_2 containing gas;
- exact requirements of the CO_2 for the CO_2 Smart Grid;
- uncertainty of electricity use for CCU routes.

[8] For the Carbstone technology energy use has been determined at 200 kWe per m^3 Carbstone concrete (Vito, 2014). While the Ruwbouwgroup reports electricity use that is approximately 80% lower.

Utilization for mineralisation: other applications of Compensatiesteen

Compensatiesteen has currently been tested and approved for use in applications where it prevents the use of sand-lime brick. The stone could also be applied in in applications where it replaces concrete, but has not been approved for this application. The application of Compensatiesteen instead of concrete would lead to a bigger 'replacement' of CO_2 emissions than when using it instead of sand-lime brick.

If Compensatiesteen can replace concrete in 2030, the CCU routes including mineralisation would lead to a higher net avoided CO_2 emission than shown in the results in Chapter 5.

Utilization for horticulture: sustainable heat supply

The future heat supply for Dutch horticulture is unknown, and therefore also the possible sources for CO_2 used in greenhouses. A possibility is the use of biomass for both heat and CO_2 production, but also geothermal heat supply not yielding any CO_2 emissions is an option. Whether or not the application of captured CO_2 aids the shift towards renewable energy and what would be the appropriate reference CO_2 source to consider in the future is a topic that needs further discussion.

If a sustainable heat supply is in place in 2030 in Dutch horticulture, the CCU routes including utilization for horticulture could lead to a lower net avoided CO_2 emission than shown in the results in Chapter 5.

Utilization for methanol production: marketing of by-products

In the current study we have only looked at methanol production from captured CO_2 as it is currently applied in a pilot plant in Iceland . A possible optimization of the current practice is the marketing of by-products such as residual heat and O_2 from electrolysis. The O_2 and residual heat will need to meet the specifications required by the market.

If the by-products of methanol production can be marketed, the CCU-routes including methanol would lead to a lower carbon footprint than shown in Chapter 5.

Requirements CO_2 Smart Grid: compression and purity

The requirements of the CO_2 Smart Grid are not yet known. The exact compression of CO_2 needed for transport over distance as well as the required purity of CO_2 for the utilization technologies attached to the grid remain to be determined when the exact utilization technologies are known.

When less compression and a lower vol% of CO_2 is required, the environmental impact of upgrading the CO_2 stream to the desired level will decrease. This means that the carbon footprint of all CCU routes would decrease in comparison those shown in Chapter 5.

All CCU-routes: future renewable electricity use

In CCU routes electricity is used. We have in line with LCA and Dutch policy practices used the fossil electricity type on the margin (see Section 2.6). It is possible that the different CCU routes ensure that they use renewable electricity. E.g. using directly coupled renewable electricity for the production of Compensatiesteen.

If the electricity used would be from directly coupled renewable electricity, the carbon footprint of a CCU routes would decrease in comparison those shown in Chapter 5.

8 Conclusion

Here, we summarize the results presented in Chapter 5. In addition, we formulate conclusions based on the sensitivity assessments shown in Chapter 7.

Capture technologies and carbon sources considered have comparable carbon footprints

The three different capture technologies do not differ significantly in carbon footprint. The capture of CO_2 from iron production and capture of CO_2 the MWI are particularly comparable in terms of carbon footprint. The footprint of capture from fossil oil refining (at the hydrogen plant) is slightly lower, but the difference between the technologies in the results could be due to uncertainties surrounding the data gathered.

Utilization in mineralisation

Utilization of CO_2 for mineralisation, the production of Compensatiesteen, leads to net avoided CO_2 emissions of around 1 tonne of CO_2 per tonne of CO_2 captured. Despite the carbon footprint of the capture technologies, the produced Compensatiesteen leads to the avoided production of conventional sand-lime brick. It is possible that the footprint of the utilization technology is slightly higher than portrayed in this report because of an uncertainty surrounding the energy use in the process. This requires further study but will not lead to the technology having a net CO_2 emission compared to non-capture. mineralisation

Utilization in horticulture

In the current situation, the utilization of CO_2 in horticulture leads to net avoided CO_2 emissions between 300 and around 950 kg CO_2 per tonne of CO_2 captured. The highest end of this range is for use of CO_2 in summer and is a comparable or even better performance than well-functioning CCS. The net avoided CO_2 emission is caused by the avoided use of natural gas for the production of CO_2 in horticulture. The lower end of the range is not comparable with CCS and that what is currently reported for captured CO_2 added to the OCAP-pipeline.

The future heat supply for Dutch horticulture is unknown, and therefore also the possible sources for CO_2 used in greenhouses. A possibility is the use of biomass for both heat and CO_2 production, but also geothermal heat supply not yielding any CO_2 emissions is an option. Whether or not the application of captured CO_2 aids the shift towards renewable energy and what would be the appropriate reference CO_2 source to consider in the future is a topic that needs further discussion. Therefore the exact carbon footprint reduction after a switch to a renewable heat source in the horticulture sector has been made is uncertain.

Utilization in methanol production

Utilization in methanol production will only lead to net avoided CO_2 emissions when renewable energy is used for methanol and hydrogen production. The net avoided CO_2 emissions will increase when the CO_2 is used in durable products. ‘Durable’ in this context implies that CO_2 is sequestered for

more than 100 years. In that case, this utilization method could reach net avoided CO_2 emissions of around 700 kg CO_2 per tonne of CO_2 captured. This is comparable to the least efficient type of CCS.

It must be noted that methanol production is not the only possible application of CO_2 in the chemical industry. Other possible utilizations could include the production of polyols for the production polyurethanes.

Conclusions on other environmental impacts

For several reasons, no conclusions could yet be drawn on other environmental impacts and on emissions from the capturing technology:

- additional benefits caused by the additional cleaning of CO_2 containing gas are unknown;
- emissions from degradation of absorbents are unknown.

Because of the lack of data described on the possible environmental benefits and environmental costs of the difference between capture and non-capture at the CO_2 capture location we only describe the environmental impacts relevant for air quality that have to do with the utilization technology.

This study has considered the following environmental impact of the three utilization technology systems; Fine particulate matter formation ($PM_{2.5}$ emissions), Terrestrial acidification (SO_2 emissions) and Tropospheric ozone formation (NO_x emissions). All utilization technology systems lead to a reduction of environmental impacts in these impact categories, even when considering fossil energy use for the capturing technologies. This means that in all cases the production of product that is replaced (natural gas combustion, sand-lime brick and methanol) has higher emissions than the emissions from the electricity used for the utilization technology and in the capturing process.

Possible trade-offs between reduction in CO_2 emissions and acidification and eutrophication exist. The acidification and eutrophication impact of the different CCU routes has not been studied, and in further research it is important to take these into consideration.

Interpretation of the conclusions

The orders of magnitude of CCS and CCU applicability in 2030 are expected to be incomparable. E.g. the potential storage by means of CCS is expected to be much higher than the potential for use of CO_2 in mineralization in the Netherlands. Results must therefore only be seen on a per tonne basis and cannot be extrapolated. The spatial application of the technologies also differ, e.g. CCS can be applied the whole year round while the peak of CO_2 utilization in horticulture is during the growing season and less so in winter.

Because the study carried out is a screening LCA, the drawn conclusions should be seen as indicative figures; they offer an order of magnitude estimation and cannot be seen as representative for individual (industrial) plants present in the Netherlands. Furthermore, because a substitution methodology has been used, the results are not appropriate for consumption-based carbon accounting (see Brander & Wylie, 2011). This means that, when calculating the emissions of a country's total consumption, LCA results that are calculated through the substitution methodology cannot be included. The same holds for using the outcomes for corporate carbon accounting practices.

To make the results applicable to individual CCU routes e.g. CO_2 capture at the AEB MWI in Amsterdam and application of the CO_2 in horticulture in Aalsmeer, are full scale LCA study will need to be conducted.

9 References

Agentschap NL, CBS, ECN, PBL, 2012. *Berekening van de CO2-emissies, het primair fossiel energiegebruik en het rendement van elektriciteit in Nederland,* s.l.: s.n.

Agentschap NL, 2010. *Protocol Monitoring Hernieuwbare Energie. Update 2010.,* s.l.: s.n.

AVR, 2017. *Ketenanalyse productie duurzame energie,* Rotterdam, The Netherlands: AVR.

Berenschot ; EEI ; MEC, 2013. *De sleutelrol waarmaken : Routekaart chemie 2012-2030, energie en klimaat,* Den Haag: VNCI.

Brander, M. & Wylie, C., 2011. The use of substitution in attributional life cycle assessment. *Greenhouse Gas Measurement and Management,* 1(3-4), pp. 161-166.

CBS, 2016. *Hernieuwbare energie in Nederland 2015,* s.l.: CBS.

CE Delft, 2017. *CO2 uit afvalsector voor tuinbouw,* CE Delft: CE Delft.

Choi, H. D., 2013. *Hybrid life cycle assessment of steel production with carbon capture and storage,* Trontheim: Norwegian University of Science and Technology, Department of Energy and Process Engineering.

Cuéllar-France, R. & Azapagic, A., 2015. Carbon capture, storage and utilisation technologies : A critical analysis and comparison of their life cycle environmental impacts. *Journal of CO2 utilization,* 9(March), pp. 82-102.

Dieleman, A. et al., 2009. *Tomaten telen in een geconditioneerde kas: groei, productie en onderliggende processen,* Wageningen: Wageningen UR.

ECN, DNV-GL, 2014. *Conceptafvies basisbedragen SDE+ 2015 voor marktconsultatie,* s.l.: s.n.

ECN, 2017. *Nationale Energieverkenning 2017,* Amsterdam/Petten, The Netherlands: ECN.

Ecofys, 2017. *Prefeasibility study CO2 smart grid,* Netherlands, Utrecht: Ecofys.

GAIN, 2017. *EU-28 Biofuels Annual - EU Biofuels Annual 2017,* Washington DC: USDA, Global Agricultural Information Network (GAIN).

Geological Survey of the Netherlands, 2009. *EU GeoCapacity. Assessing European Capacity for Geological Storage of Carbon Dioxide. D30. WP5 Report. DSS and economic evaluations,* s.l.: EU GeoCapacity Consortium.

Huijbregts, M. et al., n.d. *ReCiPe 2016. A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization,* Den Haag, The Netherlands: RIVM.

IEA, 2013. *Iron and steel CCS study (techno-economics integrated steel mill),* Cheltenham, UK: IEA.

IEA, 2017. *Techno-economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS,* Cheltenham, UK: IEA Greenhouse Gas R&D Programme.

IMO, 2016. *Recent developments at IMO to address GHG emissions from ships,* s.l.: IMO .

JRC European Commission, 2010. *ILCD Handbook. International Refernce Life Cycle Data System.,* Luxembourg: Publications Office of the European Union.

Koornneef, J., van Keulen, T., Faaij, A. & Turkenburg, W., 2008. Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2. *International Journal of Greenhouse Gas Control,* 2(4), pp. 448-467.

Marx, J. et al., 2011. Environmental evaluation of CCS using Life Cycle Assessment : A synthesis report. *Energy Procedia,* Volume 4, pp. 2448-2456.

Monteiro, J.-S., Huttenhuis, P. & Versteeg, G., 2015. *Valorisation of CO2 from Waste Incineration Flues Gases Phase 2: Business Case,* Enschede, the Netherlands: Procede Gas Treating B.V..

RIVM, 2017. *Greenhouse Gas Emissions in the Netherlands 1990-2015. National Inventory Report 2017,* Bilthoven, the Netherlands: National Institute for Public Health and the Environment.

Rocha, L. et al., 2017. *Design of a new sustainable methanol plant coupled to an ethanol distillery.* Barcelona, s.n.

Royal Haskoning, 2011. *Milieueffectrapportage ROAD-project (CCS Maasvlakte) : Deelrapport Afvang,* Den Haag: Rijksoverheid.

Singh, B. S. A. H. & Hertwichm, E., 2011. Life cycle assessment of natural gas combined cycle power plant with post-combustion carbon capture, transport and storage. *International Journal of Greenhouse Control*, pp. 457-466.

Stefansson, B., 2015. *Power and CO2 emissions to methanol : Workshop at the 2015 European Methanol Policy Forum October 13,* Brussels: Carbon Recycling International (CRI).

Tata Steel, 2016. *Sustainability Report Tata Steel in the Netherlands 2015/2016,* IJmuiden: Tata Steel Nederland B.V..

Viebahn, P. et al., 2007. Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic,and ecological aspects in Germany. *International Journal of Greenhouse Gas Control,* 1(1), pp. 121-133.

Vito, 2014. *Hoe kan innovatie de bouw helpen bij het sluiten van de materialenkringlopen?,* s.l.: s.n.

WISE, 2017. *Stroomdossier: afvalverbranding.* [Online]
Available at: https://wisenederland.nl/groene-stroom/dossier-stroom-uit-afvalverbranding

World Energy Council, 2016. *World Energy Resources - Bioenergy - 2016,* s.l.: World Energy Council.

Zero Emissions Platform (ZEP), 2017. *Commercial scale feasibility of clean hydrogen ,* s.l.: ZEP.

Zhang, C., Sun, Z., Chen, S. & Wang, B., 2013. Enriching blast furnace gas by removing carbon dioxide. *Journal of Environmental Sciences,* Issue Vol. 25, Supplement 1, pp. S196 - S200.

A Life cycle inventory

For this screening LCA, various reports and studies were used for collecting relevant data.
This chapter summarizes the data and sources used, based on the previously described system boundaries.

A.1 Carbon capture from CO_2 source and preparation for injection into Smart CO_2 grid

Municipal waste incineration (MWI) plant

A study has been conducted on the application of the Procede Gas Treating technology for capture of CO_2 specifically for injection of CO_2 into the OCAP pipeline. This study gives a description of the consumables for the quench unit, the capture plant and the compression needed for injection. Because of the difference in compression assumed needed for the CO_2 Smart Grid, we have only used the data on the quench unit and the capture plant. See Table 11 for the overview of the inputs needed as obtained from (Monteiro, et al., 2015).

Table 11 - Net inputs for CO_2 capture and preparation for injection into the Smart CO_2-grid at a MWI

	Conventional MWI	MWI with capture	Net	Net per tonne captured CO_2
Electricity for capture	-	1,693 MWh/year	1,693 MWh/year	0.10 GJe/tonne CO_2
Steam for capture	-	57,596 MWh/year	57,596 MWh/year	3.48 GJ/tonne CO_2
Cooling water for capture	-	9,384,595 m^3/year	9,384,595 m^3/year	157 m^3/tonne CO_2
CO_2 capture		59,600 tonne/year	59,600 tonne/year	

Data source: (Monteiro, et al., 2015).

Reduction in electricity production

There is one aspect that is not included in the process described by (Monteiro, et al., 2015); a reduction in electricity production because of the steam/heat used by the capture technology. According to the AVR (MWI of Rotterdam) the reduction in electricity production is approximately 0.25 MWe per MW heat extracted. This means that per tonne CO_2 captured the electricity production decreased with approximately 0.87 GJe.

The reduction of electricity production can be seen as an electricity input needed for the CO_2 capture and is taken into consideration as electricity input from the Dutch electricity grid.

Compression

Monteiro, et al., (2015) do not mention the exact pressure of the produced CO_2 stream. We therefore assume that it is produced at a 1 bar(a) pressure. This means that the stream still needs to be compressed to 40 bar(a). Further compression has been based on the operational conditions of a compressor given in (Geological Survey of the Netherlands, 2009). Based on this source to get to 40 bar(a) from 1 bar(a) an approximate 295 MJe/tonne CO_2 captured is needed.

Monteiro, et al.,(2015) also do not mention the exact purity of the CO_2 gas stream produced. However, since their study refers to producing CO_2 to be injected in the OCAP line, the purity is likely to be 93% (see Section 3.2).

The off gas of MWIs needs to reach a high purity level; there is stringent emission regulation in the Netherlands. The CO_2 capture unit is placed after the conventional purification steps. This might lead to a further reduction in emissions, but this is not taken into consideration in this screening LCA because of a lack of data.

Blast furnace gas from the blast furnace process

This study looks at an amine-based capture method for the blast furnace process. This technology is listed by the IEA as one of the primary technologies for CO_2 capture in iron production (IEA, 2013). The net inputs for this technology are given by (IEA, 2013) and shown in Table 12.

Table 12 - Net inputs for CO_2 capture from blast furnace gas and preparation for injection into the Smart CO_2 grid

	Conventional iron production	Iron production with capture	Net	Net per tonne captured CO_2
Electricity for capture	-	572,622,619 kWh year	572,622,619 kWh/year	0.6 GJ/tonne CO_2
Steam for capture	-	8,082,495 GJ/year	8,082,495 GJ/year	2.35 GJ/tonne CO_2
MDEA make-up for capture	-	688 tonne/year	688 tonne/year	0.2 kg/tonne CO_2
MDEA disposal for capture	-	688 tonne/year	688 tonne/year	0.2 kg/tonne CO_2
Raw water for capture	-	10,557,185 m^3/year	10,557,185 m^3/year	3 m^3/year
CO_2 capture	-	3,439,360 tonne/year	3,439,360 tonne/year	-

Data source: (IEA, 2013).

Reduction in electricity production

There is one difference between the technology as described by the IEA and the likely application of the technology for Tata IJmuiden: the blast furnace gas from Tata IJmuiden is currently fed to two different power plants (Velsen 25 and IJmond 1) where it is being incinerated to produce electricity. In case these two plants are not operational a third plant (Velsen 24) is used. Of the three Velsen 25 has the largest capacity of 375 MW. Applying the CO_2 capture at the Velsen 25 plant leads to a reduction in electricity production of Velsen 25.

The reduction of electricity production can be seen as an electricity input needed for the CO_2 capture. Figure 16 shows the configuration of the Velsen 25 plant. The steam produced by the turbine is 540°C and 180 bar(a), the steam is fed into the High Pressure (HP) turbine after which it is fed back into the boiler where it is reheated to 540°C and 40 bar(a). The steam is then used in the Intermediate Pressure (IP) turbine where after which it reaches Low Pressure (LP) turbines. The condensing occurs at 24 degrees and 30 mbar(a).

Figure 17 shows the Velsen 25 plant with CO_2 capture assuming no changes in the boiler efficiency and no net change in parasitic power consumption. The steam for the MDEA reboiler (2.35 GJ/tonne CO_2 as given by (IEA, 2013)) is supplied from the outlet of the IP turbine. The outlet of the IP turbine is the most logical place to tap steam from since it has the least influence on electricity production (latest

possible stage) and still reaches the required 120°C required for the MDEA reboiler. The loss in electricity production therefore occurs at the LP turbine.

The overall electric efficiency of the Velsen 25 plant is 43%. The HP turbine has the highest efficiency and the LP turbine the lowest efficiency. The approximate efficiency of the LP turbine is 27%. Assuming the turbine runs on full load, the reduction of efficiency is minimal due to the steam extraction. This therefore leads to a reduction in production of 0.65 GJe per tonne of CO_2 captured.

Figure 16 - Velsen 25 plant without CO_2 capture, per 0.48 tonne CO_2

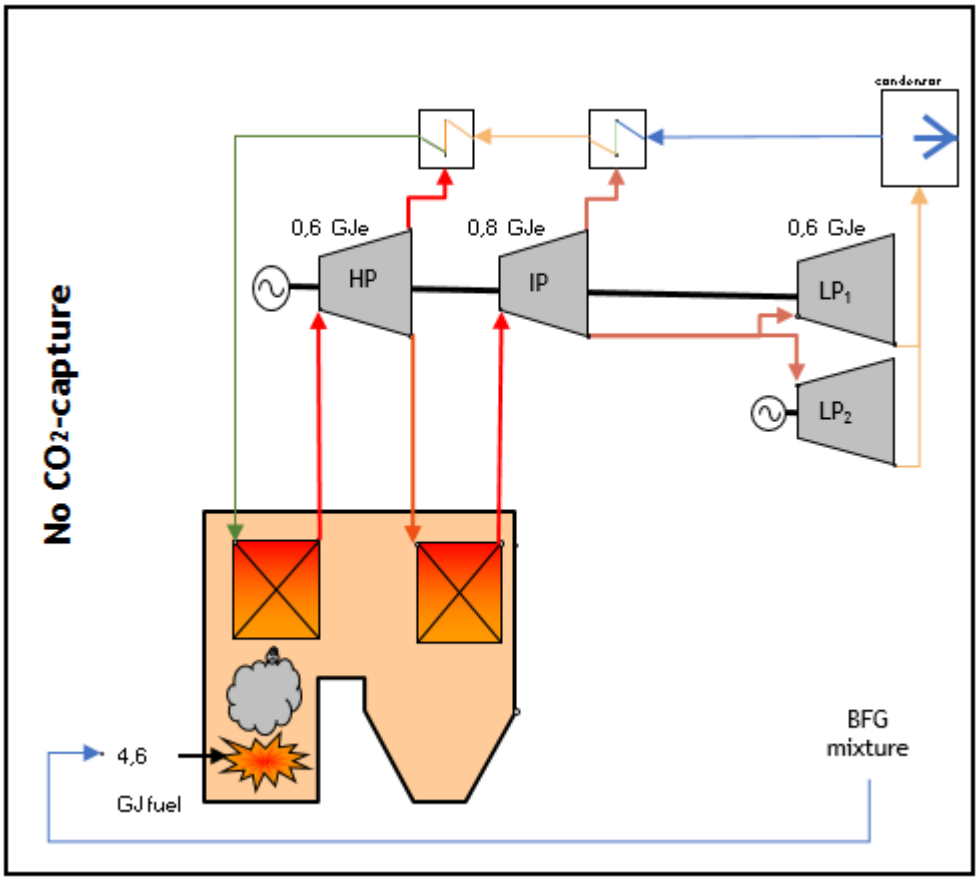
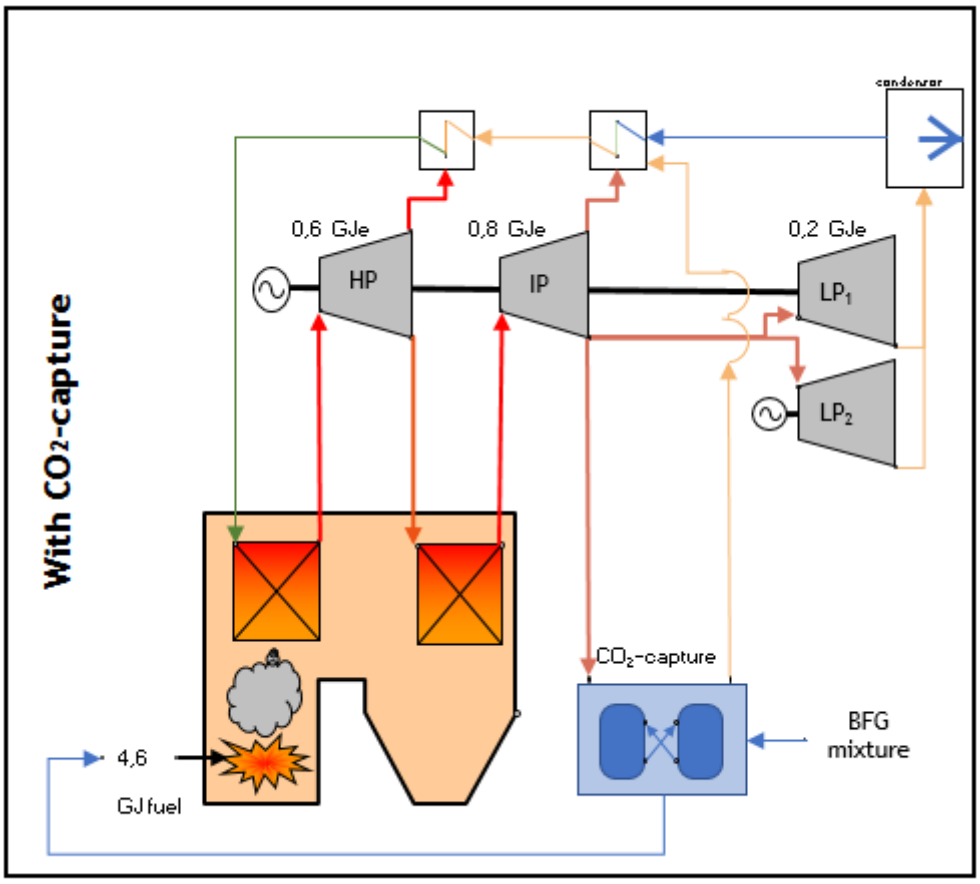


Figure 17 - Velsen 25 plant with CO_2 capture, per 0.48 tonne CO_2



Increased temperature blast furnace gas

Due to the capture technology the lower heating value of the blast furnace gas increases (Zhang, et al., 2013). This means that a higher electricity production could be achieved when supplying the blast furnace gas after CO_2 capture to the boiler. Since the exact influence of an increase in lower heating value for the Velsen 25 plant is unknown the result of the increased temperature blast furnace gas is not included in this study.

Compression

The capture technology as described by (IEA, 2013) produces CO_2 with a purity of 99.9% at a pressure of 110 bar(a). To be able to meet the specifications of 40 bar(a) for the CO_2 Smart Grid much less compression is needed. Compression energy has been estimated based on the operational conditions of a compressor given in (Geological Survey of the Netherlands, 2009). Based on this source the energy needed to get from 40 bar(a) to 110 bar(a) is approximately 100 MJe / tonne CO_2 captured. This energy use is subtracted from the total energy use for the capture at the blast furnace.

Emissions

The blast furnace gas from Tata Steel is used to produce energy from at the Velsen 23 plant. The gas is incinerated here, removing a number of harmful substances. However this plant currently still emits fine particulate matter, H_2S and COS. When adding a CO_2 capture unit after the Velsen 23 plant there is a possibility that the emissions of fine particulate matter and H_2S decrease.
Since no concrete data is available, however, on the exact impact of installing a CO_2 capture unit these possible benefits are not taken into consideration. The use of MDA as an absorbent has in the past lead to the production of aerosols. The MDEA absorbent is less prone to degeneration than MDA is but the exact emissions because of the use of this absorbent are unknown.

Fossil oil refining

The description of the CO_2 capture plant at the hydrogen facility has been obtained from (IEA, 2017). This report describes the energy balance for a conventional hydrogen facility as well as the energy balance of the plant with several different CO_2 capture technologies. We have calculated the difference between the conventional hydrogen plant and the plant using a cryogenic capture technology (including membranes) as described in Case 2B to get to an energy consumption per tonne CO_2 captured (see Table 13).

Table 13 - Net inputs for CO_2 capture and preparation for injection into the Smart CO_2 grid at a hydrogen plant

	Conventional hydrogen plant	Hydrogen plant with capture	Consumption for capture	Net per tonne CO_2 captured
Electricity to grid	9.9 MWh	0.3 MWh	9.6 MWh	0.22 MWh
Natural gas consumption (Feedstock)	1,219.7 GJ/h	1,219.7 GJ/h	0 GJ/h	0 GJ/h
Natural gas consumption (Fuel)	201.4 GJ/h	198.3 GJ/h	3.2 GJ/h	- 0.075 GJ
CO_2 captured	0 tonne/h	42.89 tonne/h	-	

Note: Conventional hydrogen plant based on the base case and hydrogen plant based on case 2B from (IEA, 2017). Figures might not add up due to rounding.

The capture technology as described by (IEA, 2017) produces CO_2 with a purity of 99.64% at a pressure of 110 bar(a). Other components in the CO_2 stream include 0.27 vol% CH_4 and 0.07 vol% CO. To be able to meet the specifications of 99.9% vol% for the CO_2 Smart Grid a further treatment step is needed. Further purification would naturally happen with the CATOX technology in which the CO_2 stream is combined with O_2 along a catalytic bed. No energy is needed for this process. High purity O_2 is needed, but only a small amount per tonne of CO_2. Therefore the production of O_2 is disregarded.

Compression energy has been estimated based on the operational conditions of a compressor given in (Geological Survey of the Netherlands, 2009). Based on this source the energy needed to get from 40 bar(a) to 110 bar(a) is approximately 100 MJe/tonne CO_2 captured. This energy use is subtracted from the total energy use for the capture at the hydrogen plant.

The emissions from a conventional hydrogen plant after fossil oil refining are limited to water vapour and CO_2. When capturing the CO_2 in a CO_2 capture plant therefore no other emissions are captured in the process.

A.2 CO_2 utilization

Horticulture

As explained previously, the reference case for the utilization of captured CO_2 in horticulture is using a gas burner for the generation of heat and CO_2. Little quantitative information on the reduction of CO_2 emissions through the delivery of captured CO_2 in horticulture is available. In a previous (confidential) study by CE Delft, the quantity of gas used exclusively for the production of CO_2 is said to be 7 m^3 gas/m^2. Using a CO_2 emission factor of 2.04 kg CO_2/m^3 for the incineration of natural gas, this amounts to 14.28 kg CO_2 emission/m^3. This is equal to 490 m^3 gas avoided per tonne CO_2 added to the greenhouse.

This quantity is specific for the addition of CO_2 during the summer period. Over the entire year the same confidential study by CE Delft shows that in the OCAP-pipeline when one tonne of CO_2 is added to a greenhouse approximately 0.5 a tonne of CO_2 from natural gas burners are avoided. We show both of these cases.

Table 14 - Inventory horticulture case

	Amount	Reference
Gas use of greenhouses (reference case)	7 m^3/m^2 of greenhouse space.	(CE Delft, 2017); confirmed by LTO glaskracht/OCAP
Avoided burning of natural gas (summer)	490 m^3/tonne CO_2 added to greenhouse	(CE Delft, 2017); confirmed by LTO glaskracht/OCAP;
Avoided burning of natural gas (OCAP)	245 m^3/tonne CO_2 added to greenhouse	(CE Delft, 2017)

Mineralisation

For the utilization of the captured CO_2 in mineralisation in Compensatiesteen, the developer RuwBouw Group was contacted. RuwBouw Group provided data on the electricity use, the amount of Compensatiesteen per tonne CO_2 in, the input of stainless steel slags, and the amount of avoided production of sand-lime brick.

Table 15 - Inventory mineralisation case

	Amount/tonne CO_2 in	Reference
Electricity	82.05 kWh	Interview with developer
Compensatiesteen	2.05 m^3 (= 4 tonne)	Interview with developer
Input of stainless steel slag (max.)	3.75 ton	Interview with developer
Avoided production of sand-lime brick (max.)	3.75 ton	Interview with developer

The avoided sand-lime brick is modelled as German sand lime brick production. Electricity used in the process is assumed to be medium-voltage.

No data has been obtained on the cleaning of the stainless steel slags before utilization in the Compensatiesteen process.

Methanol

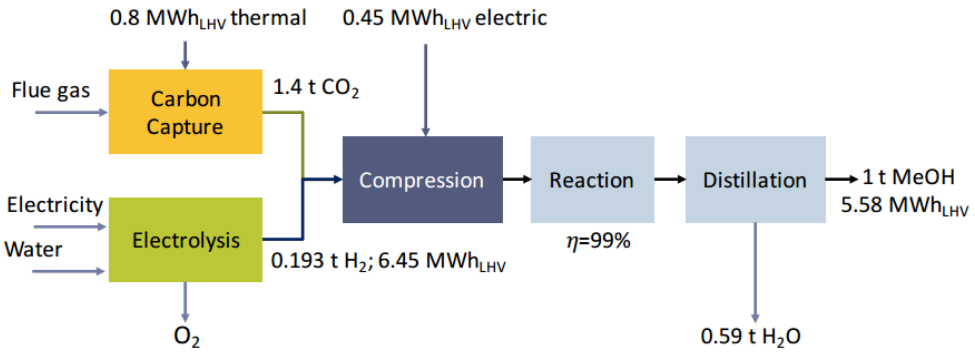
Data on the production of methanol using captured CO_2 was retrieved from a mass energy balance as presented in (Stefansson, 2015). Figure 18 shows the readily available data on the production process including the ratios of weight between raw materials and desired products. Additionally, data from (Rocha, et al., 2017) was used for the electricity use of the electrolysis step.

Table 16 - Inventory methanol case

	Amount	Reference
Electricity hydrogenation CO_2	0.32 MWh/tonne CO_2 in	(Stefansson, 2015)
Electricity electrolysis H_2	51.20 MWh/tonne H_2 produced	(Rocha, et al., 2017)
Hydrogen (in)	0.14 tonne/tonne CO_2 in	(Stefansson, 2015)
Water (out)	0.42 tonne/tonne CO_2 in	(Stefansson, 2015)
Methanol (out)	0.71 tonne/tonne CO_2 in	(Stefansson, 2015)

The hydrogen used in the process is assumed to be produced through chlor-alkali electrolysis, using a diaphragm cell. For grey electricity, medium voltage Dutch average electricity is used.
For the sensitivity case, in which green electricity is used, this is assumed to be derived from a >3MW onshore wind turbine.

Figure 18 - Mass balance and energy balance for CRI CO_2 to methanol technology



Bron: (Stefansson, 2015).

A.3 Carbon Capture and Storage (CCS)

The reference technology of CCS is mainly based on data retrieved from (Koornneef, et al., 2008). Furthermore extra compression from 40 to 130 bar(a) is determined based on (Geological Survey of the Netherlands, 2009). This case is kept very simple, and no infrastructure is taken into account.

Table 17 - Inventory CCS

	Amount/tonne CO_2 in	Reference
Electricity for compression from 40 bar(a) to 130 bar(a)	100 MJe	(Geological Survey of the Netherlands, 2009)
Electricity for injection - compression energy	7 kWh	(Koornneef, et al., 2008)
Fugitive CO_2 emissions from compressor	0.0003	(Koornneef, et al., 2008)