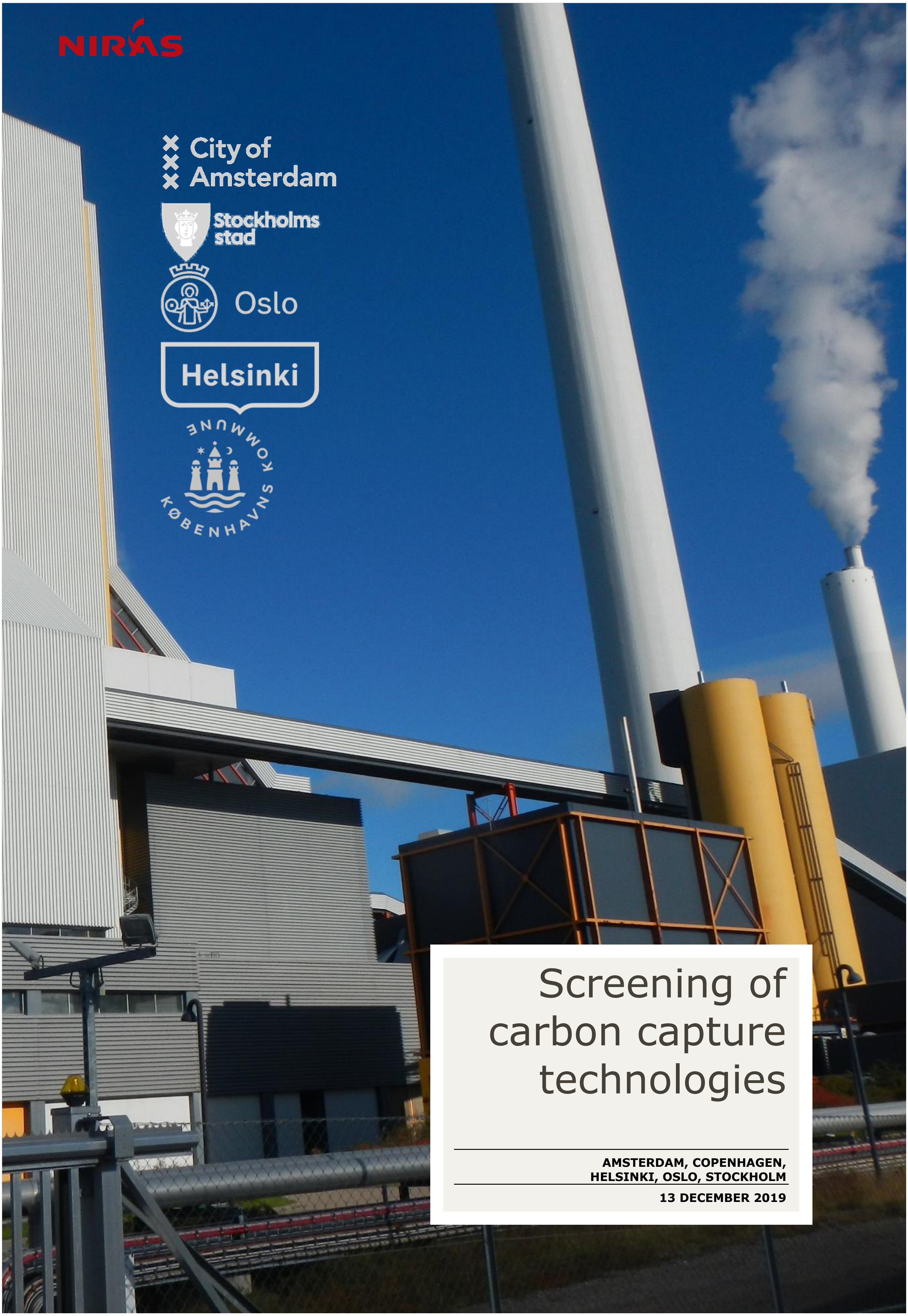

NIRAS

City of Amsterdam
Stockholms stad
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Screening of carbon capture technologies

AMSTERDAM, COPENHAGEN, HELSINKI, OSLO, STOCKHOLM

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Contents

Foreword

This Technology Screening Report is a part of a project on Carbon Capture Storage and Utilization (CCSU) from a city perspective. The project is funded by the Carbon Neutral City Alliance (CNCA) and is carried out in collaboration between five leading climate action cities, all members of the network; Amsterdam, Copenhagen, Helsinki, Oslo and Stockholm.

Carbon Neutral City Alliance is a collaboration of leading global cities working to cut greenhouse gas emissions by 80-100% by 2050 or sooner — the most aggressive GHG reduction targets undertaken anywhere by any city. The network enhances knowledge sharing and encourages member cities to test and implement radical, transformative changes to core systems.

NIRAS have contributed to the project with the development of this report and an additional two individual notes. In total 10 notes, a technical report and a fact sheet have been produced throughout 2019.

1 Introduction

1.1 Executive summary

Cities can reduce their Green House Gas emissions to a certain extent but are finding it increasingly difficult to become CO_2 neutral by emissions reductions alone. In order to achieve zero (or even negative) emissions, which is the ambition of many cities, it has become evident that Carbon Capture technologies must be implemented.

The main body of this report contains an overview of applicable technologies for the capture, transportation and Sequestration (storage) or Utilisation of CO_2 from combustion and industrial processes in cities. This is done on the format of a technology catalogue, which seeks to describe the spectrum of available solutions. Of these, carbon capture by amine absorption stands out as a mature technology that is already being deployed. In the same manner, large scale sequestration by injection in depleted hydrocarbon reservoirs is already an operational technology, albeit mostly as a method to extract residual hydrocarbons. This does not change the fact that the injected CO_2 is sequestered in the reservoirs

Although sequestration is the most certain way to ensure that carbon capture leads to real emission reductions, certain utilisation pathways may become increasingly relevant. These comprise the production of hydrocarbons, in the first instance to substitute fossil sources, and in the long term to produce necessary raw materials and compact fuels as a supplement to those derived from biomass. For this reason, also utilisation is briefly discussed.

1.2 List of abbreviations

BECCS	Bio-energy Carbon Capture and Storage
CCS	Carbon Capture and Storage
CCSU	Carbon Capture, Storage and Utilisation
CCU	Carbon Capture and Utilisation
EOR	Enhanced Oil Recovery
GHG	Green House gas
SOEC	Solid Oxide Electrolyser Cell
TRL	Technology Readiness Level

1.3 Purpose of report

This report is requested by five of the world most ambitious climate cities including Amsterdam, Helsinki, Copenhagen, Oslo and Stockholm - all five cities are a part of the Carbon Neutral Cities Alliance (CNCA). The five cities have some of the most ambitious CO_2 reduction targets, which can be difficult or impossible to achieve solely through measures such as energy efficiency, renewable energy from wind and solar, and requirements for green mobility. Even with these measures cities will still have CO_2 emitters from e.g. industry and waste incineration, and the CO2 emissions from transport is difficult and expensive to reduce. It is thus clear that technologies for removing carbon in the form of CO_2 from the emissions from the cities is a necessity to reach the set goals and to mitigate the global climate crisis.

The purpose of this report is to present information on technologies within Carbon Capture and Storage (CCS) as well as Carbon Capture and Utilisation (CCU). The intended audience of this report includes city officials, as well as policy and decision makers with interest in these technologies. The catalogue of technologies is intended as a high-level introduction to these technologies and is not detailed enough to support decisions on which path to make for a given situation or a given city, which would require more detailed studies. This technology catalogue is generic and can also be used by other cities for a first inspiration.

Finally, an overview of significant international developments in CCSU is given, and selected Utilisation pathways are proposed.

1.4 Background information

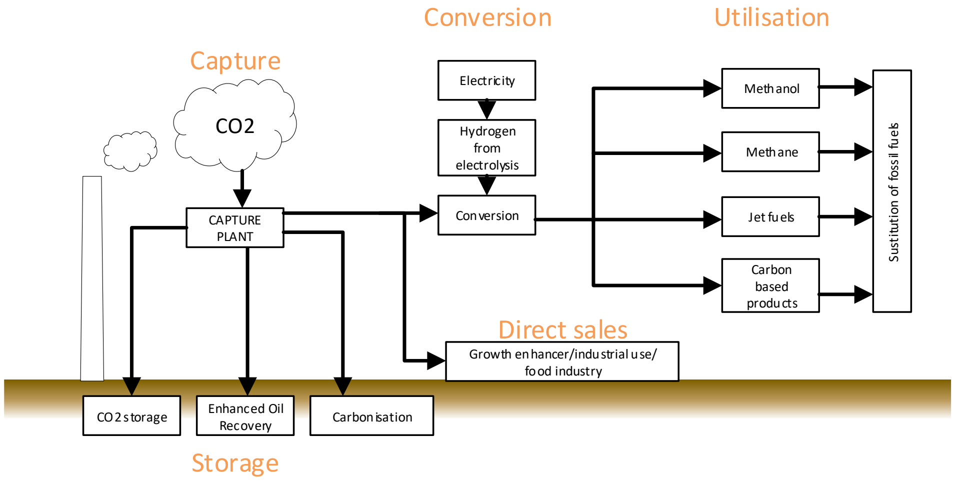
Plentiful research and background material are available within the topics of CCS and CCU. This report builds on some of the most recent knowledge found in e.g. reports from EIA [1], Global CCS Institute [2] and IPCC [3]. The report is also based on the authors work on among other projects a technology screening for a specific waste incineration plant in Denmark, which has included close contact with suppliers of CCSU technology. A list of relevant references is included in section 5.

2 Technology screening CCSU

Earlier CCS was perceived of a way to make coal fired power plants more climate friendly, and for that reason Carbon Capture was by some not acknowledged as solution to the Climate Crisis. In recent years Carbon Capture combined with waste-to-energy or biomass fuelled power plants is now by the majority acknowledged to be a necessary measure to abate climate changes. When Carbon Capture and Storage is combined with bioenergy as the fuel source (BECCS) the technology becomes "carbon negative" – removing CO_2 from the atmosphere due to bioenergy being perceived as carbon neutral. The actual removal of CO2 from the atmosphere is seen as an essential instrument to maintaining global warming at acceptable levels as noted in IPCC scenarios [3].

The Carbon Capture and storage or utilisation processes consist of three parts; (1) CO_2 is captured from a flue gas stream, (2) the conditioned CO_2 is transported, and (3) either stored permanently (CCS) or utilised to make fuels or other products. These three steps are further detailed in sections 2.4 to 2.8 below.

Figure 2.1: Main paths of Carbon Capture and Storage or Utilisation

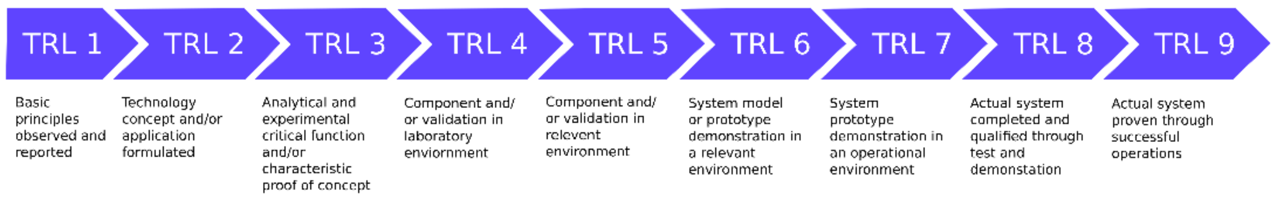


The most relevant CO_2 paths for Carbon Capture is shown in Figure 2.1 which will be detailed in the next sections.

2.1 Technology Readiness Level

In the evaluation of the technologies collected in this report the Technology Readiness Level (TRL) scale is applied. The scale was first developed by NASA to measure the maturity of a given technology.

Figure 2.2.2: Technology readiness levels



In the context of Carbon Capture the TRL levels are evaluated against the maturity of a full-scale system specifically for this application. This means that even though the technology is considered mature in another context and/or at a smaller scale, the technology will in this report only be rated TRL 8 or 9, i.e. mature, in case a full-scale CO_2 relevant plant is in operation.

Each technology in this report are scored on this scale as is shown in the fact sheets.

2.2 CO_2 is a valuable commodity

The International Energy Agency [4] published a report in September 2019. The following sections are copied from this report:

> *Globally, some 230 million tonnes (Mt) of carbon dioxide (CO_2) are used every year. The largest consumer is the fertiliser industry, where 130 Mt CO_2 is used in urea manufacturing, followed by oil and gas, with a consumption of 70 to 80 Mt CO_2 for enhanced oil recovery. Other commercial applications include food and beverage*

production, metal fabrication, cooling, fire suppression and stimulating plant growth in greenhouses. Most commercial applications today involve direct use of CO_2.

New pathways involve transforming CO_2 into *fuels, chemicals and building materials. These chemical and biological conversion processes are attracting increasing interest from governments, industry and investors, but most are still in their infancy and face commercial and regulatory challenges.*

The production of CO_2-based fuels and chemicals is energy-intensive and requires large amounts of hydrogen. The carbon in CO_2 enables the conversion of hydrogen into a fuel that is easier to handle and use, for example as an aviation fuel. CO_2 can also replace fossil fuels as a raw material in chemicals and polymers. Less energy-intensive pathways include reacting CO_2 with minerals or waste streams, such as iron slag, to form carbonates for building materials.

2.3 Technology fact sheets

A number of mature or upcoming technologies is needed to capture, store or utilize CO_2 on large scale. In the following sections these technologies are highlighted in the form of Fact Sheets introducing each of these. The following technologies have been considered:

Table 2.1: List of Fact Sheets

Technology		TRL
Capture		
1	Absorption	9
2	Adsorption	6-7
3	Cryogen distillation	5
4	Calcium looping	6-7
Logistics		
5	Pipe transport	9
6	Land transport	9
7	Sea transport	9
Storage		
8	Storage under ground	9
9	Carbonization under ground	7
Usage		
10	Direct sales	9
11	Production of algae	4-6
12	Methane	8
13	Methanol	8
14	Jet fuels	5
15	Other carbon based products	1-9
16	Growth accelerator in green houses	9
Other technologies		
17	Alkaline electrolysis	9
18	SOEC electrolysis	7

Technology		TRL
19	PEM electrolysis	8-9
20	Fixation in building materials	6-8
21	Pyrolysis, biochar BECCS	7

The Fact Sheets will give a brief overview of the technology in question with emphasis on evaluation of the maturity of the technology, relevance for large scale Carbon Capture and presentation of cases and references. The technologies are grouped in five areas as shown in the table above and are presented in each of the following sections.

The technologies are presented separately as the building blocks to a CCS/CCU setup. It should be noted that even though the technologies very well can be seen as building block with only few interfaces between the process steps, the real value is in the integration of the systems in order to optimize the plant in regards to cost, energy usage, waste streams, storage capacity etc.

2.4 Carbon capture technologies

Carbon dioxide can be extracted from a flue gas through different technologies. The basic technologies are well known chemical unit operations and have been available for many years. Still, there are only few examples of commercial large-scale plants for the purpose of extracting carbon dioxide from flue gas.

Table 2.2: Main technologies for carbon capture

Technology	Description	Pros	Cons
Absorption	CO2 is captured by an amine solvent, a liquid comprising of water and amines, which is being used to absorb the CO2 from the flue gas and then rereleased in a disorber for further processing or storage	Well-known technology from refineries. Many suppliers and references	Replenishing the amin can add to OPEX. Care must be taken to avoid amin emissions
Adsorption	Adsorption on an active surface and release at a different temperature or pressure	Simple process setup, expected low operating cost	Difficult to scale to large plants. Limited capture efficiency. Risk of degradation of adsorbent. Limited large-scale experience
Cryogenic	Cooling the flue gas below to liquify CO_2 and thus separation	Possibilities of high overall efficiencies, especially with integration with other CCSU system components and district heating	New technology, not proven
Membrane filtration	Using semi-permeable membranes for selectively fetching CO_2 from the flue gas	Simple process setup, low operating costs	Only demonstrated small-scale, difficult to scale-up, low capture efficiency. Mostly relevant for smaller scale

Technology	Description	Pros	Cons
Calcium looping	A process involving capturing CO_2 by carbonation of calcium oxide and subsequently calcination to lime stone. The net product is captured CO_2 and also calcium oxide useful for cement	High potential for integration in cement production. Possible future high efficiency. Low toxicity	High temperature process (>900°C). Mostly relevant for cement producers.

As with other flue gas treatment technologies a carbon capture plant has a significant size and area footprint, which can be a hurdle for retrofitting in existing plants. The piping and ducts must carry the full volume of flue gas which in itself requires space. The absorption process requires high vertical scrubber towers[1], and the adsorption plant would likewise require a large footprint.

The captured CO_2 must be treated and compressed for transportation and storage, which is known technology. CO_2 is usually cooled, pressurized and then stored as a liquid.

The capture of CO_2 requires energy in the form of heat and electricity and produces waste heat streams at lower temperature levels, which possibly could be utilized in a district heating system, if available nearby. This is an important consideration for implementing carbon capture in cities, as a possible utilisation of low temperature excess heat in district heating networks could be important for the feasibility of the plant.

The concentration of CO_2 in a flue gas from a combustion process is 10%-15%. Another relevant source could be from biogas plants, where the biogas consists of around 30%-50% CO_2, and where the upgrade of biogas to grid quality would already involve separating the CO_2 as a separate stream. The capture of CO_2 from large biogas plant could thus be cheaper than capturing from a flue gas.

[1] A typical scrubber will be in the order of 30-45 metres high. Some upcoming technologies from e.g. CompactCarbon and Aker Solutions present a much smaller plant size, but these technologies are still on pilot level

Fact sheet #1: Absorption amine process

TRL 9

Description

CO_2 is absorbed from the flue gas by passing the flue gas through an amino acid scrubber. The CO_2 rich solution is then heated and transferred to a stripper, which causes CO_2 to be released in a gaseous state. The extracted gaseous CO_2 can be compressed and transferred or stored in pipes or vessels, see Figure 2.3.

Different types of amines can be applied in the process, and some suppliers have their own proprietary substances.

The process is well-known from the refinery industry, and full scale plants have demonstrated that the process can be used for extraction of CO_2 from flue gases.The typical plant consists of the following three main parts: 1) a "front-end part" including a high characteristic absorber tower and lower "stripper" vessel, 2) a "back-end part" including cleaners, coolers and compressors, and 3) a CO_2 storage vessel.

Energy requirements for the process comprise cooling, heating and electricity. Integration of heat streams must be optimized for the specific plant.

This technology is currently the preferred technology for large scale carbon capture from flue gas based on maturity and cost.

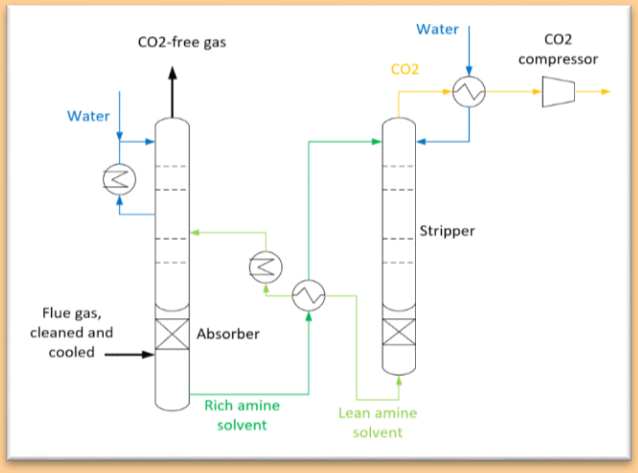


Figure 2.3: Sketch of an amine absorption system

Figure 2.4: Amine absorption plant for carbon capture on waste incenera-tion plant at AVR in Duiven, The Netherlands. Photo: NIRAS A/S

Cases

Several suppliers offer commercial solutions, albeit most experiences are with smaller plants.

Case 1 - Fortum Oslo Varme AS, Klemetsrud, Norway
Pilot plant tests on-going since January 2019, extracting CO_2 from flue gas from waste incineration. Next step is upscaling to full-size plant. Efficiency proved above 90 %.

Case 2 - Saga Municipal Government, Saga, Japan
Plant in commercial operation since 2016, extracting CO_2 from flue gas from waste incineration. Capacity of 10 ton/day. Contractor is Toshiba.

Case 3 - AVR Waste-to-Energy plant, Duiven, the Netherlands [5]
CO_2 capacity of 100 kt/yr. Production start August 2019 (see Figure 2.4)

Fact sheet #2: Temperature swing adsorption

TRL 6-7

Description

The temperature swing adsorption (TSA) process captures CO_2 by adsorbing the CO_2 on a solid material such as a zeolite or activated carbon. By reconditioning the adsorbant in a continuous temperature cycle a fairly low-cost process flow can be obtained.

One plant configuration is to continuously move a granular solid adsorbent from an adsorbent reactor to a regenerative reactor where steam is used to regenerate the adsorber and release the CO_2.

In another plant configuration the adsorber is made in the shape of a rotating disc similar to large scale air pre-heaters for power plants. A section of the absorber is then rotating through the regimes of absorption of CO_2 from the flue gas, release of the CO_2 with low pressure steam, and a number of regimes for regeneration of the adsorbent. The TSA process requires more flue gas cleaning and conditioning than the amine process.

Even though feasibility studies show that the technology could be feasible in large scale [3], this technology is not yet demonstrated as a full scale carbon capture plant.

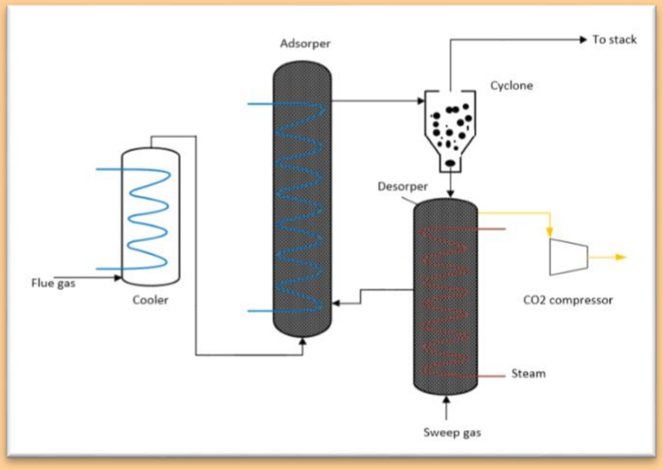


Figure 2.5: Sketch of a temperature swing adsorption system

Figure 2.6: Picture of temperature swing adsorber from Inventys (inventysinc.com)

Cases

Case 1 – Inventys, Alberta, Canada

Inventys 11 kt/yr CO_2 capture demonstration plant to be built in Alberta, Canada (2019).

References

[3] IPCC, "Carbon dioxide capture and storage," 2015.

Fact sheet #3: Cryogenic carbon capture

TRL 5

Description

Cryogenic carbon capture is a technology developed by the American company SES. In the process, flue gases are cooled below the sublimation point of CO_2 of -78,5 °C. This causes a deposition of the CO_2 to solid form. The CO_2 is then extracted and reheated under pressure in order to take liquid form. The process requires a cryogenic refrigerant cycle in order to achieve the low temperatures. However, most of the cooling heat is recovered in the process by heating of the flue gas and CO_2 downstream of the extraction. The same type of process is well-known from nitrogen production for atmospheric air.

The energy consumption of a full scale cryogenic process is expected to be only half of a similar absorption process, which will be a significant reduction in the cost of carbon capture.

Despite the potential benefits of cryogenic technology, more research, development and demonstration of the technology is needed before it can be used commercially, but this could over time become the preferred technology for carbon capture.

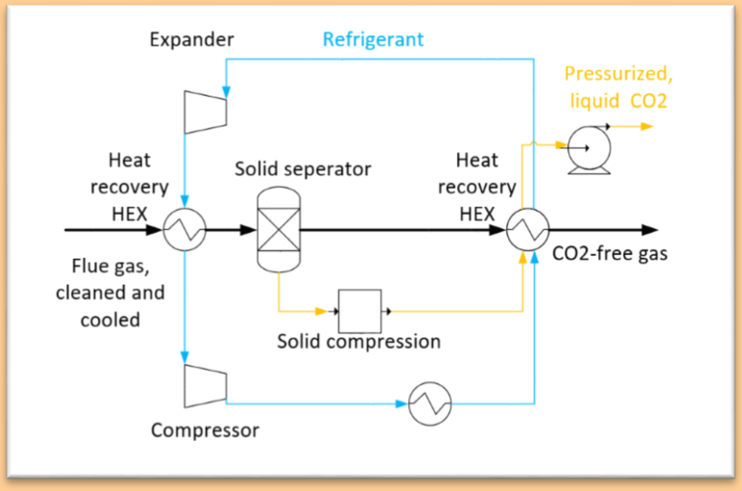


Figure 2.7: Sketch of a cryogenic carbon capture system

Figure 2.8: Picture of a cryogenic carbon capture system (from: https://sesinnovation.com/technology/demonstrations)

Cases

Case 1 – Sustainable Energy Solutions (SES) demonstration plant, Atlanta, United States [6]
CO_2 from a cement kiln is captured with the cryogenic carbon capture technology of SES. The captured CO_2 is utilized for concrete curing.

References

[6] Sustainable Energy Solutions, [Online]. Available: https://sesinnovation.com/company_info/newsinfo/.

Fact sheet #4: Calcium looping

TRL 6-7

Description

In the Calcium Looping process Calcium is used as a reversible sorbent for reacting with CO_2 in the flue gas forming $CaCO_3$ and subsequent releasing CO2 again when calcinated to CaO. The process requires high temperatures (650°C to 900°C) and will require a continuous make up feed of calcium carbonate (e.g. limestone) due to the decreasing reactivity through multiple calcination-carbonation cycles. The waste sorbent (calcium oxide) may be used for cement manufacturing or flue gas desulfu-rization.

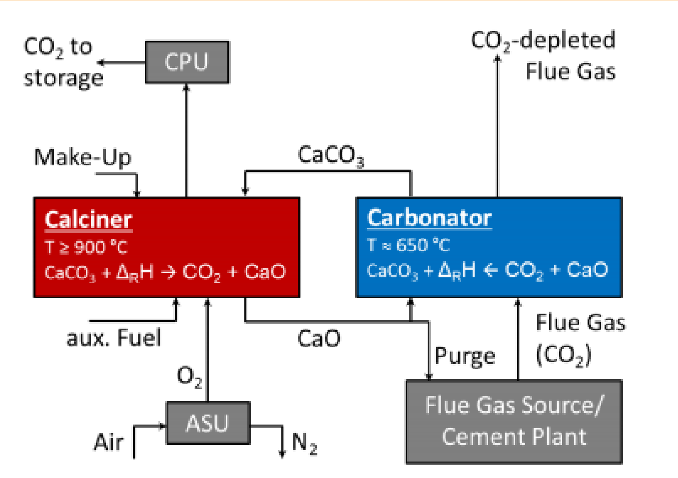


Figure 2.9: Sketch of a calcium looping system

The process is still not fully developed and demonstrated in full scale, but is seen as a future better alterna-tive than the standard amine absorption process. The technology has the potential for higher efficiency and lower toxicity than amine process.

Reactor types may for example be fluidized bed technology, which has already been demonstrated in large scale. Heat for the calcination process may be produced by direct heating in an oxygen fired calcinator or by indirect heating.

Latest studies show confidence to scale up to full scale industrial size and to integrate in energy storage or with cement production.

Cases

Case 1 – Pilot plant at University of Stuttgart, Germany [1]
Pilot plant of 200 kW_{th} capturing CO_2 from power plant flue gases.

Case 2 – Pilot plant at the Technische Universität Darmstadt [7]
Pilot plant of 1 MW_{th} capturing CO_2 from a coal fired furnace.

Case 3 – Pilot plant at La Pereda power plant, Spain [8]
Retrofit of a 1,7 MW_{th} system for a coal fired power plant.

Case 4 – Pilot plant at the Industrial Technology Research Institute, Taiwan [9]
Pilot plant of 1,9 MW_{th} capturing CO_2 from the flue gases of a cement plant.

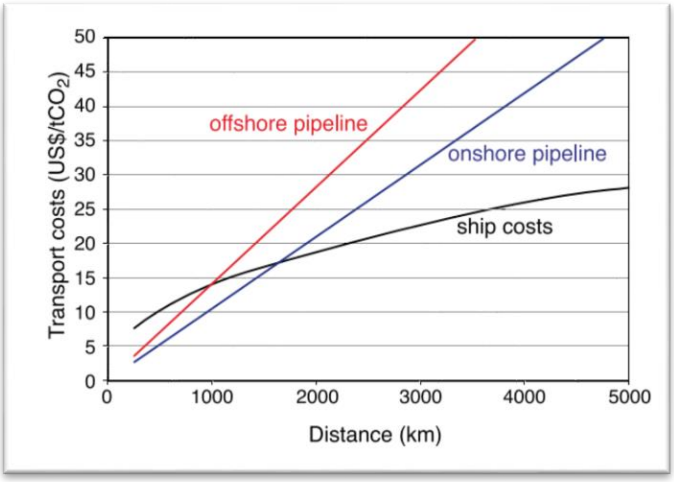
References

[7] J. Hilz, M. Helbig, M. Haaf, A. Daikeler, J. Ströhle and B. Epple, "Long-term pilot testing of the carbonate looping process in 1 MWth scale," *Fuel,* vol. 210, pp. 892-899, 2017.
[8] Project-scarlet, [Online]. Available: http://www.project-scarlet.eu/wordpress/wp-content/uploads/2016/05/07_SCARLET-1PWS_2016-04-21_Experiences-from-La-Pereda-pilot-plant-J.-C.-Abanades-Spanish-Research-Council-CSIC-INCAR.pdf. [Accessed 11 November 2019].
[9] M.-H. Chang, W.-C. Chen, C.-M. Huang, W.-H. Liu, Y.-C. Chou, W.-C. Chang, W. Chen, J.-Y. Cheng, K.-E. Huang and H.-W. Hsu, "Design and Experimental Testing of a 1.9MWth Calcium Looping Pilot Plant," *Energy Procedia,* vol. 63, pp. 2100-2108, 2014.
[10] Cleanker Project, [Online]. Available: www.cleanker.eu. [Accessed 11 November 2019].
[11] Flexical Project, [Online]. Available: www.flexical.eu. [Accessed 11 November 2019].

2.5 CO_2 transport

The transport of CO_2 is a necessary chain in the Carbon Capture future. The location of the CO_2 storage or the CO_2 utilisation plant is rarely adjacent to the CO_2 emitter. The transport of CO_2 requires cooling and/or pressurizing, but the solutions are quite well-known. Pipeline transport have been used for decades for Enhanced Oil Recovery, truck transport is well established on local smaller CO_2 markets, and ship transport is known from similar use for Liquified Natural Gas tankers.

Figure 2.10: Cost of CO_2 transport Source: [3][IPCC15]



As is the case with transport of other commodities the cost of ship transport is favourable over larger distances compared to pipeline transport or trucks (see Figure 2.10). Land transport is not shown in the figure but is not competitive with the three other modes of transport except for short distances below e.g. 100 km.
The establishment of a pipeline requires a significant investment, but will be the cheapest transport alternative in operational cost. The best choice of transport methods varies with the location and local conditions of the source of CO_2.

There are no established standards for the properties of CO_2 for transportation. The purity, temperature, pressure, dryness of the gas is to be agreed for each case.

Table 2.3: Comparison of CO_2 transport options

Technology	Description	Pros	Cons
Pipe transport	Similar to transport of natural gas onshore or offshore	Feasible for large quantities. Low operating cost.	Large investment. Difficult to build new pipeline in populated areas. Requirements to underground conditions
Land transport	Bulking by truck or train. CO_2 must be liquified	Flexible, low capital cost	Large operating costs

Technology	Description	Pros	Cons
Sea transport	Sea transport by dedicated CO_2 carrier with pressurized tanks (liquid CO_2)	Flexible compared to pipeline. Feasible over long distances. Possible to add new producers/consumers of CO_2	Medium operating costs. Medium capital cost. Possibility of rebuild of existing ships

Fact sheet #5: Pipe transport

TRL 9

Description

Transportation of CO_2 by pipeline is similar to well-known systems transporting natural gas. The CO_2 is either transported as a compressed gas or in liquid form. Unlike natural gas the CO_2 is not explosive, but still it represents a choking hazard from leaks. The CO_2 is heavier than air and when a leak occurs the gas will collect in low-lying areas. If the piping is routed through densely populated areas an odourizer (added smell) could be added to the gas for added safety.
The best choice of pressure and thus whether the CO_2 is gaseous or liquid must be determined in a feasibility study per case.
The CO_2 gas is not corrosive in its pure and dry form and can e.g. be transported in steel pipes of the existing X65 quality known from off-shore oil/gas installations.
A piping system can be used to connect multiple CO_2 producers and consumers. In that case a common specification of the CO_2 quality must be agreed. Such piping systems exist in the United States for EOR purposes and in the Netherlands for utilization of the CO_2 in green houses.

Figure 2.11: Picture of a CO_2 pipeline under construction. Source: NIRAS A/S

Figure 2.12: OCAP CO_2 pipeline system in Rotterdam, The Netherlands. Source: ocap.nl

Cases

Case 1 - Alberta Carbon Trunk Line [12]
A USD 470 million 240 km pipeline for Enhanced Oil Recovery in Alberta, Canada under installation

Case 2 – OCAP pipeline, Rotterdam, The Netherlands [13]
The OCAP pipeline is distributing CO_2 from oil refinery and a fertilization plant to 580 greenhouses in the area for growth enhancers.

References

[12] Alberta Carbon Trunk Line, [Online]. Available: https://actl.ca/.
[13] OCAP, [Online]. Available: https://www.ocap.nl/nl/images/OCAP_Factsheet_English_tcm978-561158.pdf.

Fact sheet #6: Land transport

TRL 9

Description

Transportation of CO_2 by road or train is an established business in many parts of the world. CO_2 is used in many industrial processes - especially within the food and beverage segment. CO_2 transport trucks are usually dedicated to CO_2 only to avoid contamination.

CO_2 is liquified (cooled and pressurized) for minimizing volue during trucking or train transport.

Transportation of CO_2 by truck is limited to local transport (usually less than 100 km) because of the relative high transport cost compared to the product value.

Much of the CO_2 transported by bulk is "food grade" and is used in e.g. carbonated soft drinks.

The bulk gas supplier companies can usually handle a larger part of the logistics including local storage facilities at the destination.

Figure 2.13: Picture of a CO_2 transportation truck (from www.AC-PCO₂.com)

Cases

CO_2 bulk transport is available in many areas of the world from local suppliers. Examples include AVR MWS plant in The Netherlands [5] where trucks distribute CO_2 to local greenhouses. In Klementsrud, Norway the feasibility of CO_2 trucking or pipeline is being investigated

References

Fact sheet #7: Sea transport

TRL 9

Description

Transportation of CO_2 by ship is relevant for a majority of the CO_2 emitting plants with access to the sea and will give access to e.g. underground storage.

The CO_2 is pressurized and in liquid form, which means a pressure of at least 57 bar at 20 °C or refrigerated at lower pressure. The optimum pressure depends on a complete analysis of the logistics chain. A consensus on the most feasible transport temperature and pressure is not agreed on yet.

Figure 2.14: Picture of CO_2 *transportation vessel (from https://www.anthonyveder.com/fleet/coral-carbonic)*

Today, CO_2 is already transported by ship in smaller applications. Upscaling of the CO_2 volume will require larger vessels. Existing larger gas carriers (LPG or LNG) can be converted into CO_2 carriers. Otherwise, new vessels specialized for CO_2 transport can be designed. Different companies are already working on suitable concepts.

Transportation by ship is typically feasible for long distance transport due to lower investment costs and higher degree of flexibility compared to pipelines.

Cases

Case 1 - Northern Lights, Norway

The Northern Lights storage project in Norway is specifying a dedicated ship for CO_2 transport. Expected to be 7500 m^3 capacity at 19 bar.

Case 2 - Coral Carbonic

First purpose-built CO_2 tanker from 1999, 1250 m^3 capacity, see Figure 2.14.

2.6 Carbon storage

Fossil fuels are carbon-based compounds which have been stored underground for millions of years, and which we are now in the industrial age releasing to the atmosphere. In the same way as gaseous and liquid hydrocarbons have been stored in crevices underground for millions of years, it is also possible to return the carbon in the form of carbon dioxide to the same type of geology to store the carbon more or less indefinitely.

Table 2.5 lists the main storage technologies to be considered for CO_2 storage. Other technologies such as storing CO_2 in minerals above ground from industrial by-products could also be a future technology, but is not considered here, as a feasible solution in relevant quantities has not been found. Also Enhanced Oil Recovery, where CO_2 is used to enhance the extraction of oil in an oilfield will not be considered here, as it inherently is not a solution to lower the global carbon footprint.

Table 2.5: CO_2 *storage overview*

Technology	Description	Pros	Cons
Direct storage	Drilling new wells or using depleted gas/oil wells to store CO_2 under ground indefinitely. Possible both on-shore and off-shore.	Well-known technology from oil extraction. Possible to reuse infrastructure.	Requires the right geological formation. Will always be a net expense, except for the certificate value of the stored CO_2. The responsibility for the long term monitoring of CO_2 storage is unclear.
Carbonation underground	The process of creating carbonates by reacting CO_2 with metal-oxides. This can happen underground in certain geological formations	The resulting carbonates are stable on a geological time scale	The natural process needs to be accelerated by e.g. heat and is thus quite energy intensive. Still under development. Only applicable in specific locations

The possible options for storing CO_2 underground are already mature [14] and new storage facilities can be developed within a short time span. The issues in regards to CO_2 storage is more on the cross-border agreements (the London Protocol [15]) and clear solutions to the long term liability issues on who would monitor the storage and be responsible for any leaks many years after the storage has taken place.

Indicative pricing from upcoming projects in the North Sea is €30-€50 per ton CO_2 for storage underground including sea transport from regional sources when available incentives and credits are included.

Together with amine based carbon capture from flue gas, the storage of CO_2 in depleted oil and gas fields is the most obvious path to significantly reduce the CO_2 footprint from cities right now. The technologies are in place and the cost per ton of CO_2 is soon within reach for many CO_2 emitters.

Fact sheet #8: Storage under ground

TRL 9

Description

Underground storage of CO_2 is possible both off-shore and on-shore. All relevant technologies are known from the oil industry.

The first off-shore CO_2 storage plant was established in 1996 at the Sleipner field in Norway. The CO_2 is captured on the offshore platform from the extracted gases, and compressed and reinjected in geological layers below the sea bed at a rate of up to 900 kt/yr [16].

An example of an upcoming offshore carbon capture and storage (CCS) project involving the complete CCS supply chain is the Northern Lights project [17]. CO_2 will be captured from industrial sites near Oslo from where it will be shipped to an onshore temporary storage and subsequently transported via pipeline to the storage facility, see Figure 2.15.

There are several existing CCS projects involving on-shore storage of CO_2. Historically, the CO_2 has been used for enhanced oil recovery (EOR), however, in the last decade multiple non-EOR CO_2 storage facilities have entered into operation.

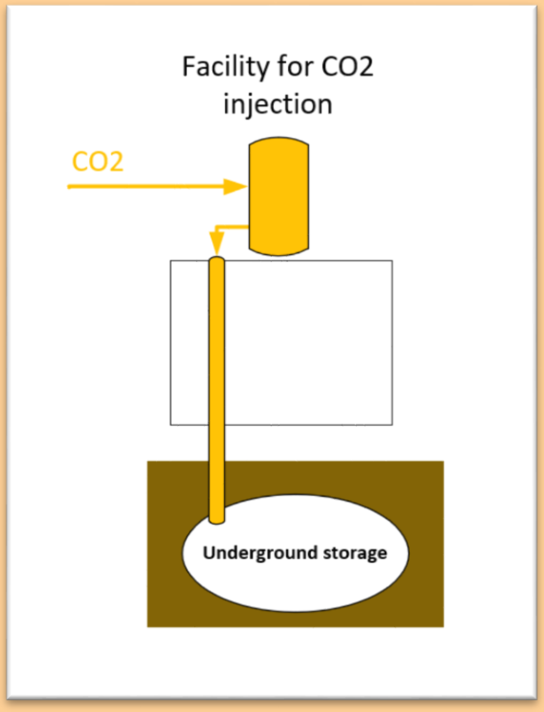


Figure 2.15: Sketch of a facility for underground storage of CO_2

Cases

Case 1 - Examples of offshore CO_2 *storage facilities in operation*
Sleipner in Norway (up to 900 kt/yr) [16], Snøhvit in Norway (up to 700 kt/yr) [18], K12-B in the Netherlands (up to 20 kt/yr) [19], Tomakomai in Japan (up to 200 kt/yr) [20].

Case 2 - Examples of onshore CO_2 *storage facilities in operation:*
Gorgon in Australia (up to 4,000 kt/yr) [14], Illinois in United States (up to 1,000 kt/yr) [14], Quest in Canada (up to 1,000 kt/yr) [14].

References

[14] Global CCS Institute, [Online]. Available: https://CO₂re.co/FacilityData. [Accessed 8 November 2019].
[16] A.K. Furre, O. Eiken, H. Alnes, J. Nesland Vevatne and A. Fredrik Kiær, "20 Years of Monitoring CO_2-injection at Sleipner," Energy Procedia, vol. 114, pp. 3916-3926, 2017.
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[19] TNO, [Online]. Available: https://www.tno.nl/media/1581/357beno.pdf. [Accessed 8 November 2019].
[20] Midwest Carbon Sequestration Science Consortium, [Online]. Available: http://www.sequestration.org. [Accessed 8 November 2019].

Fact sheet #9: Carbonation under ground

TRL 7

Description

Traditional underground storage of CO_2 relies on impermeable subsurface structures, which can withstand the buoyancy effects of the stored CO_2. Using this method of CO_2 storage, there is a risk that the CO_2 escapes the storage for example via fractures [23].

Carbonation underground is a method for CO_2 storage which eliminates the risks associated to CO_2 leakage. The concept involves the dissolving of CO_2 in water and subsequent injection in basalts. By injection of the CO_2-water mixture in basalts containing, for example, magnesium and calcium ions, the CO_2 reacts with the rock material to form carbonate compounds. The result is permanent storage of CO_2 in solid rock material.

The technology has been demonstrated in the Carbfix project at the Hellisheidi power plant in iceland [23]. The further development of the technology is carried out in the ongoing project GECO [24].

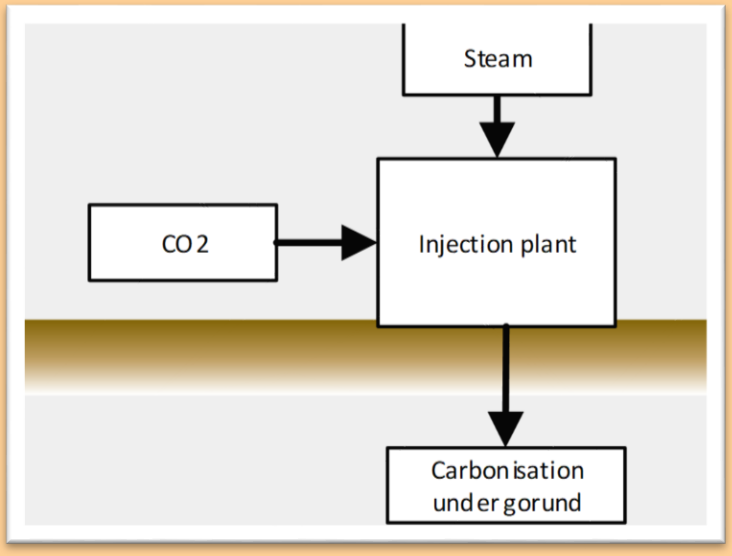

Figure 2.16: Sketch of a facility for underground CO_2 storage with carbonation

Cases

Case 1 - Carbfix project, Iceland

Carbonation under ground has been demonstrated in the Carbfix project. Part of the CO_2 and H_2S emissions from a geothermal power plant are captured and injected in underground basalt formations where it mineralises. Approximately, 10 kt/yr of CO_2 is captured and stored [23].

References

[23] Carbfix Webpage, [Online]. Available: https://www.carbfix.com. [Accessed 8 November 2019].
[24] GECO Project Webpage, [Online]. Available: https://geco-H2020.eu. [Accessed 8 November 2019].

2.7 Carbon utilisation

2.7.1 CO_2 as a commodity

CO_2 is primarily a waste product from combustion, but is also a commodity used for several applications on todays market:

- In green houses for increasing the growth of flowers and vegetables
- For food packaging in order to keep foodstuff free of oxygen
- For soft drinks and beer
- For welding
- Algae production
- Chemical industry

When CO_2 is traded as a commodity it is primarily based on capture from fossil based sources although a few plants in the Netherland's are based on capture from waste incineration, one in Denmark based on CO_2 from biogas and several breweries have their own capture from the fermentation processes. A large part of the distributed CO_2 is a by-product from the production of ammonia or fertiliser. As this CO_2 is already a waste product, the benefit for the climate of introducing a source of bottled/bulked CO_2 based on renewable sources would be limited.

2.7.2 CO_2 as a building block

While the use for CO_2 "as is" as a commodity is limited and does not necessarily reduce the CO_2 emissions, CO_2 can also become a building block for producing synthetic fuels such as methane, methanol, fuels like jet-fuel and basic chemicals for the plastic industries etc. In all these pathways CO_2 is the source of carbon combined in a synthesis with hydrogen which again can be either produced by fossil material or by green electricity through electrolysis of water (split of water into hydrogen and oxygen). The need for hydrogen in this process is large. E.g. the production of 100.000 t of methane needs about 50.000 t of hydrogen and about 275.000 t of CO_2. An electrolysis plant that has the capacity of producing 50.000 t/year of hydrogen needs a windfarm in the magnitude of 350-450 MW. For jet-fuel the consumption of hydrogen is even higher.

Example: A typical European waste incineration facility would emit 500.000 tons of CO_2 per year and produce 30-70 MW of electricity from the waste. If the plant wants to capture all the CO_2 and utilise as e-fuels, an electrolysis plant to produce hydrogen would need to produce in the order of 100.000 ton Hydrogen per year to match the CO_2. This would require 10-20 times more electricity than the plant produces in its turbines. If the new fuels are to be sustainable, the power has to come from renewable sources, such as hydro, sun or wind.

2.7.3 Synthetic fuels

The CO_2 used for producing synthetic fuels (also called e-fuels) will eventually be released in the atmosphere when the synthetic fuel is burned in the intended application. The value for the CO_2 reduction for the climate is therefore not in the direct storage of CO_2 as is done in Carbon Capture and Storage, but rather in the substitution of the fossil fuel that otherwise would have been burnt.

In a fossil-free future we will not be extracting carbon from fossil fuels anymore, and carbon as a building block will be a scarce commodity. At this point CO_2 utilisation will be a necessity in order to produce carbon based products, e.g. plastics.

It is still not clear which renewable fuels that will be the preferred solution to the future need for fossil fuel substitution. The world's largest shipping company Maersk has announced that they envision their large fleet of ships will most likely be fuelled by ethanol, methanol, methane or ammonia created from renewable sources[2] and also state that the biggest challenge to reach this is not in the ships but in the renewable production of these fuels on shore. Most likely the future fuels will be a mix of these fuels and possibly also pure hydrogen, as they all have their advantages in different uses.

The future use of synthetic fuels should be limited to areas where it is impossible to use electricity directly and where electricity storage technologies is difficult to implement, such as in air and sea transport. As an example one of the obvious fuels to produce from CO_2 and hydrogen is methane (CH_4), which can readily substitute natural gas in the existing distribution infrastructure. But still the green (synthetic) methane is costly to produce both in energy and in cost. Instead, the better solution would be to minimize the use of natural gas altogether and install heat pumps or renewable heat sources. The CO_2 and hydrogen should then be reserved to produce liquid fuels such as methanol or jet-fuels.

2.7.4 Carbon utilisation fact sheets

In the following Fact Sheets the possible uses of CO_2 are described. The maturity of these technologies is less than the technologies presented earlier on carbon capture and carbon storage. The utilisation of CO_2 for higher value products would generally require either a large scale multi-refinery or synergies between several industries, as the CO_2 emitter is rarely in the position to handle the full production chain.

Table 2.6: Overview of utilisation technologies

Technology	Description	Pros	Cons
Direct sales	Selling CO_2 in the market for direct use	CO_2 has a positive value in the market	Limited size of market. The available CO_2 in the market is already mostly "green" thus little CO_2 reduction potential
Algae production	Increase algae growth by adding CO_2. Algae is useful for feed and fuel	Possible synergies with food production and/or waste water cleaning. Possible future intensive farming	Very large areas needed for industrial size CO_2 consumption. Still expensive. Mostly suitable for sunny regions in warm climates
Methane	Producing methane (a.k.a synthetic natural gas) by combining CO_2 and hydrogen	A well-known process. Can be used in existing natural gas infrastructure.	Requires large amounts of hydrogen and thus electricity. Less attractive as a fuel for transport. Needs compression and cooling to store in tanks
Methanol/ethanol	Methanol (and ethanol) is a building block for many	Is liquid at ambient temperature, thus easy to store. Useful	Requires large amounts of hydrogen and thus electricity. Lower energy yield

[2] https://www.maersk.com/news/articles/2019/10/24/alcohol-biomethane-and-ammonia-are-the-best-positioned-fuels-to-reach-zero-net-emissions

Technology	Description	Pros	Cons
	chemical compounds. Can be produced by synthesis of CO_2 and hydrogen.	as fuel for transport. Possible use in shipping. Easily stored. Known technology	than methane. More complex process than methane production
Jet fuel	Fuels of higher hydrocarbons derived from CO_2 and H_2	A possible path to CO_2 neutral air transport. Known technology. Possibility of premium price compared to fossil fuels	Requires large amounts of hydrogen and thus electricity. Complicated process on top of methane and/or methane synthesis. Large scale plant needed for profitability.
Other carbon based products	Incorporating CO_2 in carbon based chemicals (e.g. plastics, fibres, textiles) substituting fossil oil products	Potential for greener products where CO_2 is captured in the product.	Requires close synergies between CO_2 producer and consumer unless intermediate (methanol or methane) is transported between the sites. More costly than using fossil carbon sources.
Growth accelerator in green houses	Adding CO_2 to the air in a green house to boost the growth of the plants	Green house owners will pay a positive price for the CO_2. Easy implementation. Known technology.	Most CO_2 added to the greenhouse will end up in the atmosphere almost immediately. No CO_2 reduction effect, unless substituting a fossil CO_2 source in the green house. Very seasonal demand.

Fact sheet #10: Direct sales

TRL 9

Description

An option for utilization of the captured CO_2 is direct selling if a market is available. High purity CO_2 can be used for welding and in the food industry[3]. Other markets such as growth enhancer in greenhouses have less stringent quality demands. CO_2 in bulk is a commodity available world-wide.

The method of transport and state of the CO_2 (liquid or gas) is to be considered when selecting direct sales. Usually CO2 is sold in the local market because of the relative high transport cost. A direct pipeline is relevant for short distances and sea transport is relevant for long distances.

It should be noted that adding CO_2 from carbon capture for selling in the open market will substitute existing suppliers. Most existing CO_2 sources are already fairly green, e.g. as a waste product from the production of fertilizers or from fermentation, which means that the CO_2 reduction value of selling CO_2 from carbon capture could be limited and could be seen as greenwashing.

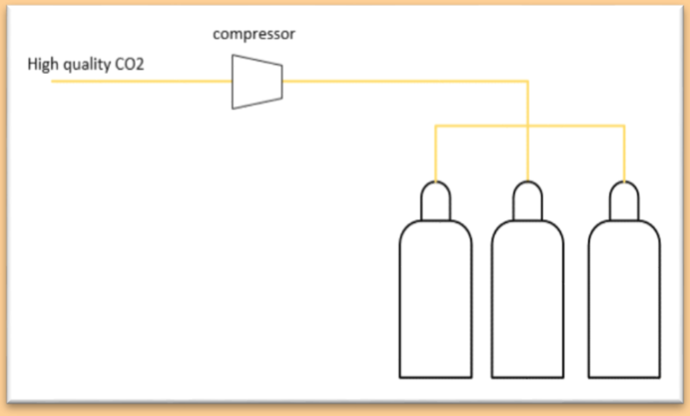

Figure 2.17: Sketch of a CO_2 storage process

Figure 2.18: Picture from a soda production line (Source: Coca Cola Hellenic)

Cases

Case 1 – Danish market, Denmark

The Danish market is around 70-80.000 tons/year originating primarily from ammonia production.

Case 2 – Local CO_2 grid, the Netherlands [13]

In the Netherlands, a local CO_2 grid has been established. The CO_2 is captured from refineries and chemical plants. During the growth season, CO_2 is directly sold for greenhouse farming.

References

[13] OCAP, [Online]. Available: https://www.ocap.nl/nl/images/OCAP_Factsheet_English_tcm978-561158.pdf.

[3] Example of CO2 food grade specification can be found at https://www.sintef.no/globalassets/project/cemcap2/12112017---fact-sheet---co2-food.pdf

Fact sheet #11: Algae production

TRL 4-6

Description

Algae are microorganisms which are characterized by fast growth and their ability to consume CO_2.

There are currently trial production sites around the world facilitating algae growth based on organic residues, CO_2 and light. Examples of algae facilities are open dam systems or pipe based systems (see Figure 2.19).

The algae are used for producing certain proteins, oils and heat. Algae-based biofuel production is promising, since it does not require the use of agricultural land and can use water sources which are unfit for agricultural use. However, the space requirement per ton of CO_2 reduction is high and the need for sunlight limits the feasibility in tempered climates.

The CO_2 reduction thus stems from the indirect savings from substituting CO_2 intensive products (e.g. feedstock, proteins) to the CO_2 neutral algae.

Figure 2.19: Picture of in-pipe algae growth system (from https://www.ecoduna.com/en/company/our-usp/)

Cases

Case 1 – Kalundborg Forsyning, Denmark [25]

In Kalundborg, Denmark a demonstration plant with algae in glass pipes within a greenhouse has been built. The algae are used for waste water treatment, while consuming nutrients such as phosphor, nitrogen, and CO_2.

References

[25] Ingeniøren (in Danish), [Online]. Available: https://ing.dk/artikel/algeanlaeg-skal-rense-kalundborg-virksomheders-spildevand-132297. [Accessed 11 November 2019].
[26] All About Algae, [Online]. Available: http://allaboutalgae.com/benefits/

Fact sheet #12: Methane production

TRL 8

Description

Methane is used globally for various purposes including heating, road transport, and marine transport. Furthermore, there is an existing infrastructure for methane including land-based gas distribution grids and ships dedicated to the transport of liquified natural gas.

The production of methane is possible from hydrogen and CO_2 in a methanation unit.

Methanation can be used in the upgrading of biogas to natural gas. Biogas is a mixture of methane and CO_2. In order to utilize biogas in the natural gas grid the CO_2 needs to be removed or converted to methane. If the CO_2 is reacted with hydrogen to form methane, maximum utilization of the biogas achieved.

Typically, methanation is carried out in an exothermal chemical reaction at 200-300 °C. Another possible methanation pathway is via biological conversion. One example of this is the technology of Electrochaea, which is based on a single celled microorganism, converting hydrogen and CO_2 into methane.

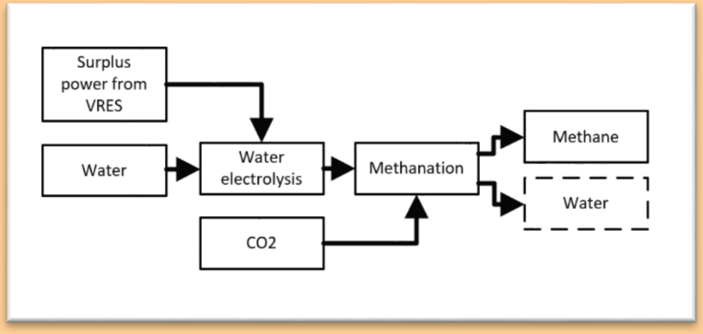

Figure 2.20: Methane production pathway based on CO_2

Figure 2.21: Picture of the GoBiGas plant (from https://www.goteborgenergi.se/om-oss/vad-vi-gor/forskning-utveckling/gobigas)

Cases

Several suppliers offer commercial solutions, albeit most experiences are with smaller plants.

Case 1 - GobiGas, Sweden [27]

GoBiGas (Gothenburg Biomass Gasification, see Figure 2.21) in Sweden is in a combined plant gasifying residue from wood and wood chips. The produced syngas is then upgraded using methanation. For distribution the plant is connected to the Swedish natural gas grid.

Case 2 - BioCat project, Denmark [28]

The BioCat project is based on biological conversion of H_2 from electrolysis and CO_2 from a biogas into methane, which is sent to the natural gas distribution grid.

Case 3 – Qvidja bioenergy facility [29]

A facility based on thermal gasification of wood to produce hydrogen to a biological reactor creating methane

References

[27] Göteborg Energi, [Online]. Available: https://www.goteborgenergi.se/om-oss/vad-vi-gor/forskning-utveckling/gobigas. [Accessed 8 November 2019].

[28] Electrochaea, [Online]. Available: http://www.electrochaea.com/technology/. [Accessed 8 November 2019].

[30] Danish Energy Agency, [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf. [Accessed 8 November 2019].

Amsterdam, Copenhagen,
Helsinki, Oslo, Stockholm

13 December 2019

www.niras.com

Fact sheet #13: Methanol production

TRL 8

Description

The traditional method of producing methanol is based on the reforming of lower order hydrocarbons (for example methane or propane) into a syngas (a mixture of H_2, CO and CO_2) which is synthesized to methanol, see Figure 2.22

An alternative and renewable production pathway for methanol is based on CO_2 and H_2, where the H_2 is produced from electrolysis, see the sketch. The process requires the compression of CO_2 and H_2 to 85 bar prior to the methanol synthesis process. After the methanol synthesis follows a distillation process for separating water and methanol [30]. The process is more complex than the methane synthesis.

Methanol is used in the production of plastics and chemicals and can be used as a fuel for fuel cells and for marine diesel engines. In 2015 the global methanol demand was 91 billion liters [32].

Methanol has a lower energy content than methane, but is liquid at ambient conditions and thus easier to store and transport

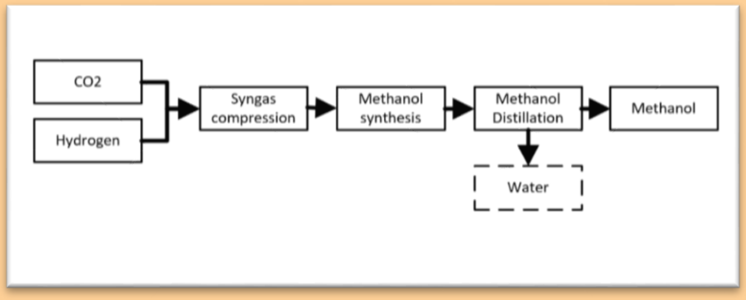

Figure 2.22: Methanol production pathway based on CO_2

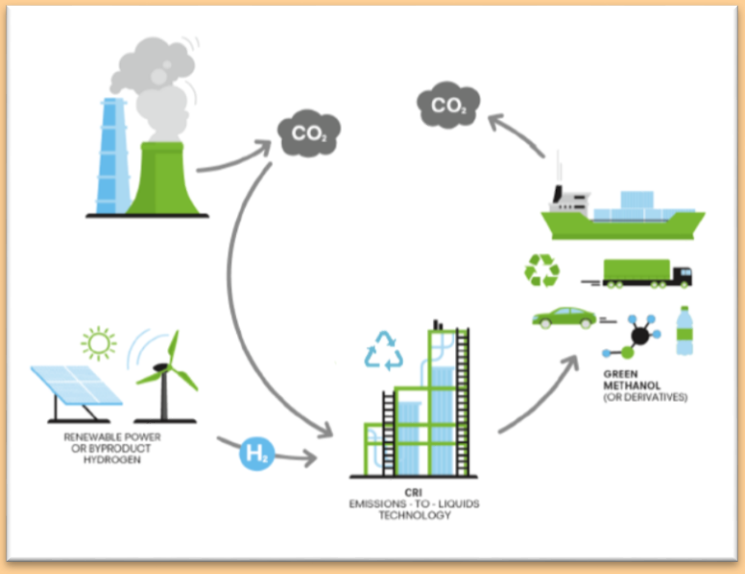

Figure 2.23: Sketch of carbon life cycle in relation to Carbon Recycling International (from https://www.carbonrecycling.is/circlenergy)

Cases

Case 1 - Carbon Recycling International, Iceland [33]

The methanol production facility of Carbon Recycling International in Iceland is currently (fall 2019) the only existing renewable methanol production facility. The methanol is produced based on H_2, which is produced from electrolysis using renewable electricity, and CO_2, which is captured from a geothermal source. The production capacity is 5 million liters of methanol per year.

References

[30] Danish Energy Agency, [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf. [Accessed 8 November 2019].
[31] Haldor Topsøe, [Online]. Available: https://video.topsoe.com/webinar-using-CO2-to-boost-methanol-production?source=spot%3a20004560. [Accessed 8 November 2019].
[32] Methanol Institute, [Online]. Available: https://www.methanol.org/the-methanol-industry/. [Accessed 8 November 2019].
[33] Carbon Recycling International, [Online]. Available: https://www.carbonrecycling.is. [Accessed 8 November 2019].

Fact sheet #14: Jet fuel production

TRL 5

Description

Jet fuel is highly standardized and regulated fuel for aviation, traditionally produced from fossil oil. Jet fuel production pathways need to be certified by the American Society for Testing and Materials (ASTM). Among the certified pathways for the production of sustainable jet fuel, the Fischer Tropsch process and the alcohol to jet pathways are the most promising options, which enable the integration of CO_2.

The inputs to the Fischer Tropsch process are CO and H_2 (syngas). It is possible to utilize CO_2 for the production of CO ($2CO_2$ => $2CO + O_2$), for example in a reverse water gas shift reactor or in a SOEC. The output from the Fischer Tropsch process is a mix of products including waxes and various liquid fuels, see Figure 2.24. The Fischer Tropsch pathway was certified by ASTM in 2009 with up to 50 % blend-in with conventional fuels.

The price of "renewable" jet fuels is expected to be 2-3 times the price for fossil based jet fuels, as the airlines will also need to reduce their carbon footprint. For aviation there are currently no other feasible alternatives for reducing CO_2 emissions from air transport. This fuel is expected to give the highest price for CO_2 utilisation.

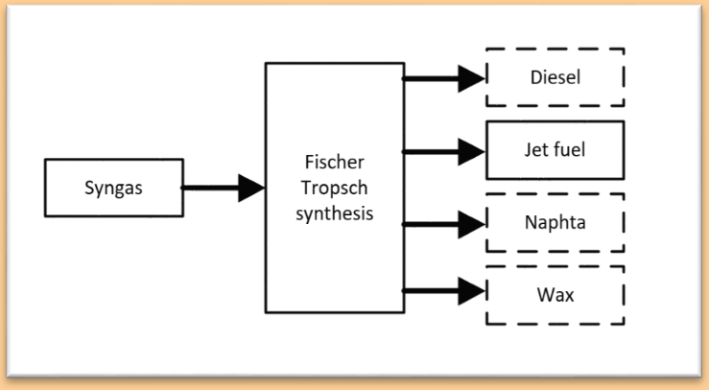

Figure 2.24: Fischer Tropsch synthesis

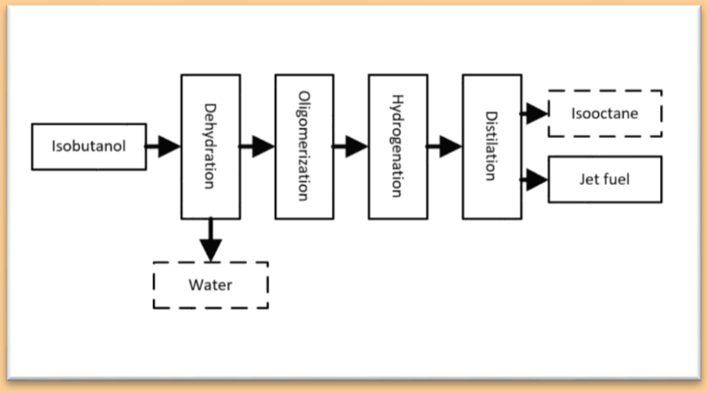

Figure 2.25: Conversion of isobutanol into jet fuel

Cases

Case 1 - Fulcrum Bioenergy, USA [34]
Fischer Tropsch facility used for the production of jet fuel based on municipal solid waste.
Case 2 - Gevo, USA [35]
Alcohol to jet facility used for the production of jet fuel based on straw and wood residual.

References

[30] Danish Energy Agency, [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf. [Accessed 8 November 2019].
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[37] Nordic Energy, [Online]. Available: https://www.nordicenergy.org/wp-content/uploads/2016/09/FULLTEXT_Sustainable_Jet_Fuel_for_Aviation.pdf. [Accessed 8 November 2019].

Fact sheet #15: Other carbon based products

TRL 1-9

Description

It is possible to integrate the use of CO_2 in a range of carbon based chemicals.

CO_2 is used in the chemical industry for the production of urea based fertilizers. Other applications for CO_2 in the chemical industry are in the production of common chemicals such as methanol, ethylene, and propylene.

In the polymer industry, it is possible to integrate the use of CO_2 in the production of plastics, foams, fibres, textiles, etc. The use of CO_2 for polymer production results in reduced consumption of fossil based raw materials with limited additional energy input, see Figure 2.26.

The increased focus on renewable production is expected to increase the interest in CO_2/H_2 based products leading to a larger market with higher prices.

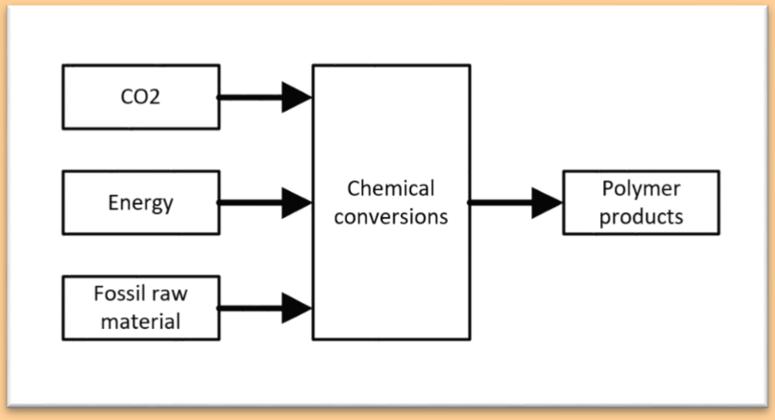

Figure 2.26: Polymer production pathway based on CO_2

Cases

Case 1 - Covestro, Germany [38]
Substitution of crude oil with CO_2 in the chemical and plastics industries. Examples of products: soft foam mattresses and sports floors.

Case 2 - Asahi Kasei Chemicals, Taiwan [39]
CO_2 is used in the production of polycarbonates and ethylene glycol.

Case 3 - Novomer, United States [40]
Polycarbonate polyol production with up to 50 % (weight) CO_2 content.

References

[38] Covestro. [Online]. Available: https://www.covestro.com/en/company/strategy/attitude/CO₂-dreams. [Accessed 8 November 2019].
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[41] International Energy Agency, [Online]. Available: https://www.iea.org/publications/reports/PuttingCO₂touse/. [Accessed 8 November 2019].

Fact sheet #16: Growth accelerator in green houses

TRL 9

Description

Growth of produce in greenhouses is depending on the concentration of CO_2 within the greenhouse. Increasing the concentration of CO_2 leads to higher yields of produce. The CO_2 is traditionally sourced from an on-site gas heater or gas engine. With an external supply of CO_2 the greenhouses can omit the use of the gas engines.

The need for CO_2 in green houses is highly seasonal and only relevant during the growth season.

Only selected countries have a greenhouse industry large enough to make this feasible in larger scale.

Figure 2.27: Picture of a greenhouse (Source: pxhere.com)

Figure 2.28: Picture of tomato crops

Cases

Case 1 - AVR Duiven, the Netherlands

AVR Duiven in the Netherlands is a waste incineration plant supplying CO_2 captured from flue gases to greenhouses. A long term contract is negotiated with Air Liquide as the distributor to the green houses. TPI - Tecno Project Industriale was in charge of constructing the facilities.

Case 2- Linde Gas, the Netherlands

Linde Gas in the Netherlands supply CO_2 gases to 580 greenhouses in the Rotterdam area. It amounts to 400,000 ton of CO_2 per year collected from the Shell refinery. [13]

References

[13] OCAP, [Online]. Available: https://www.ocap.nl/nl/images/OCAP_Factsheet_English_tcm978-561158.pdf.

2.8 Other related technologies

2.8.1 Electrolysis

Where the storage of CO_2 underground is a short-time path with fewer stakeholders and technologies in play, the usage of CO_2 in fuels etc. is on the other hand a multiple step process in a more complex setup. In most of the usage cases for upgrading CO_2 to a higher calorific value fuel such as methane or methanol, a source of energy and hydrogen is needed. The most relevant source of hydrogen is from electrolysis of water. A few different technologies for this is described below:

Table 2.7: Comparison of electrolysis technologies

Technology	Description	Pros	Cons
Alkaline	The classic technology involving splitting of liquid water below 100°C	Well known established technology. No noble metals	Limited efficiency. Still expensive because of lack of scale, but increased demand for large scale plants will drive the price down. The technology is bulky and has limited potential for radically lower price
Solid Oxide Electrolysis Cells	The reverse of a Solid Oxide Fuel Cell splitting the water to hydrogen and oxygen over a high temperature membrane. Temperature >600°C	Possible high efficiency at the lowest price. Heat for evaporation can be external. No noble metals. Can convert CO_2 to CO as well	Immature technology, currently limited lifetime and higher cost than alkaline and PEM
PEM electrolysis	Low temperature <300°C	Possible high throughput/small footprint.	Use of noble metals makes it (still) expensive. Still in demonstration phase for large scale

The scalability of the mentioned electrolysis technologies is rather similar, as all three technologies will scale by adding multiple smaller units into larger building blocks. For all three technologies the price is still high, which could come down when the demand for large scale electrolysis grows. SOEC technology has the largest potential for lowering cost (no expensive parts) and obtaining the highest efficiency, but the technology is still not available in large scale.

The cost and size of such an electrolysis plant is as large as the carbon capture plant itself and is thus a significant part of the business case. Furthermore, the electricity demand to run the hydrogen production is very high, as this is where the energy (the calorific value) to the fuel is created. Typically the yearly cost of electricity amounts to half the capital investment in the electrolysis plant.

The dimensioning of the electrolysis plant should be carefully considered. Even though hydrogen production capacity is expensive and hydrogen is expensive to store in larger quantities, it could possibly make sense to have a electrolysis plant capable of delivering more hydrogen than what is needed for the steady flow of

CO_2. Some buffer capacity could give the flexibility in turning down hydrogen production when the electricity is most expensive over a day or over a week.

Fact sheet #17: Alkaline electrolysis

TRL 9

Description

Renewable production of hydrogen can be achieved through alkaline electrolysis, where electricity from renewable sources is used for splitting water into O_2 and H_2, see Figure 2.29.

Alkaline electrolysis has a long history in the chemical industry, and the fairly simple technology is well-known.

Excess heat from the production can be utilized for district heating. The operational temperature of commercially available alkaline electrolysis cells is around 60 °C – 100 °C. The electricity to fuel energy efficiency is around 61 %.

The size of the plant needed for large scale hydrogen production for CCU is larger than current applications, but the scalable nature of the technology means that the upsizing is of less concern. The technology is bulky and economy-of-scale when scaling up is limited.

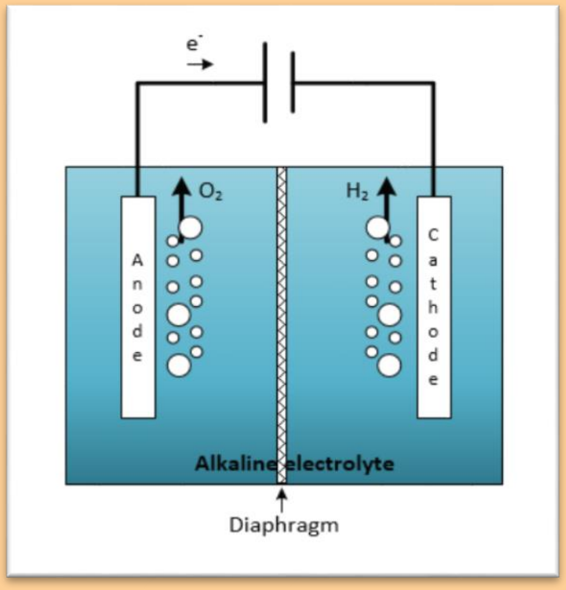

Figure 2.29: Sketch of the working principle of alkaline electrolysis (from https://www.sciencedirect.com/topics/engineering/alkaline-water-electrolysis)

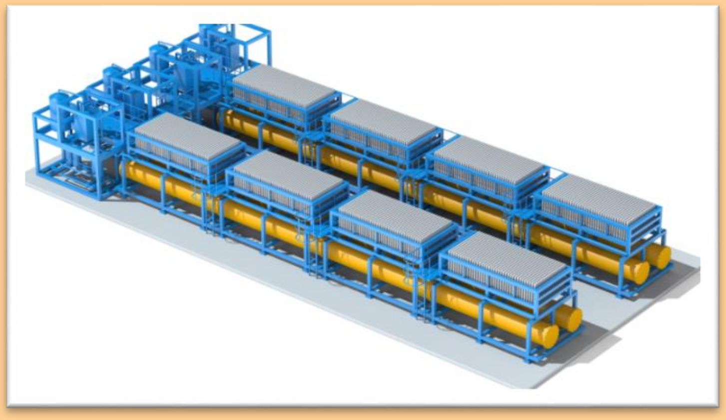

Figure 2.30: ThyssenKrupp 20 MW module (from https://www.greencar-congress.com/2018/07/20180728-tk.html)

Cases

Case 1 - NEL Hydrogen alkaline electrolysis system at ASKO Midt-Norge AS, Norway [42]
In 2017, ASKO midt-Norge (a grocery wholesaler) installed a 570 kW electrolyser system for the production of hydrogen for distribution trucks and forklift trucks.

Case 2 – ThyssenKrupp alkaline electrolysis system, Germany [43]
As part of the Carbon2Chem project, Thyssenkrupp has in 2018 installed a 2 MW alkaline electrolysis plant near their steel mill facility in Duisburg, Germany. The electrolysis plant is planned to be an integrated part of a carbon capture and usage system.

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Fact sheet #18: Solid oxide electrolysis

TRL 7

Description

In a solid oxide electrolyser cell (SOEC) water, in the form of steam, reacts with electrons at the cathode (negative electrode) to form H_2 and O^{2-} (oxide). The oxide travels through the cell to the positively charged anode, where it reacts to form oxygen.

The SOEC process requires both electricity and heat and the relative amounts depend on the cell operation temperature. The operation temperature is typically between 700 °C and 1000 °C. The energy (heat plus electricity) input to fuel energy efficiency is around 68 % [30]. Unlike alkaline electrolysis some of the energy need for reaction can be supplied as heat, making higher overall efficiencies possible.

SOECs are also capable of electrolysis of CO_2 into CO. The SOEC can also co-electrolysis of water and CO_2 at the same time. The combined electrolysis produces a syngas, which is the basic building block for producing liquid fuels. This gives an advantage and a possible simpler setup if used for syngas production.

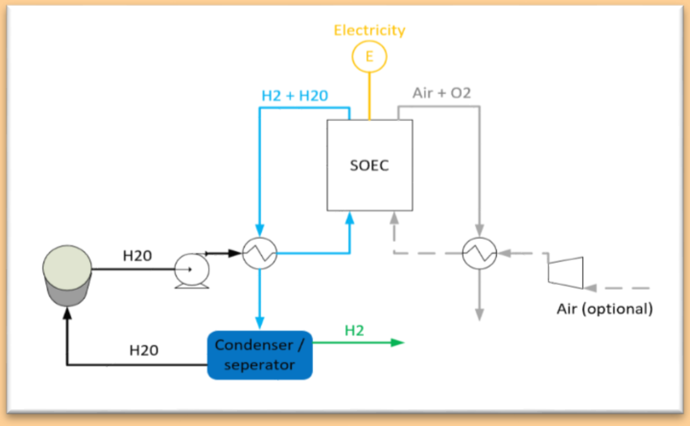

Figure 2.31: Sketch of a SOEC system

Figure 2.32: Picture of a Sunfire SOEC unit (from https://hydrogeneurope.eu/member/sunfire)

Cases

Case 1 – Sunfire SOEC at Salzgitter Flachstahl, Germany [44]

As part of a Horizon 2020 project, Sunfire has delivered a 150 kW electrical input SOEC module at Salzgitter Flachstahl. Steam for the SOEC module is obtained from waste heat from a smelting process, and hydrogen is supplied to a local hydrogen pipeline.

References

[30] Danish Energy Agency, [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf. [Accessed 8 November 2019].
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Fact sheet #19: Proton exchange membrane electrolysis

TRL 8-9

Description

A proton exchange membrane electrolyser cell (PEMEC) or PEM for short is built up around the proton membrane. Typically the electrodes are in direct contact with the membrane.

The PEM cells have good part load capabilities and is able to cope with transient variations in electrical input. Another benefit of the PEM cells is the direct production of high-pressure hydrogen without mechanical compression.

The PEM cell operates at temperatures around 50 °C – 100 °C or up to 300°C, which makes it possible to utilise the heat released for district heating. The electricity to fuel energy efficiency is around 61 % [30].

The PEM cells uses iridium in the anode material which is one of the rarest metals on Earth.
The PEM electrolysis is comparable in performance with alkaline electrolysis in many ways but with faster demand response. The choice of technology should be based on commercial considerations for a specific project.

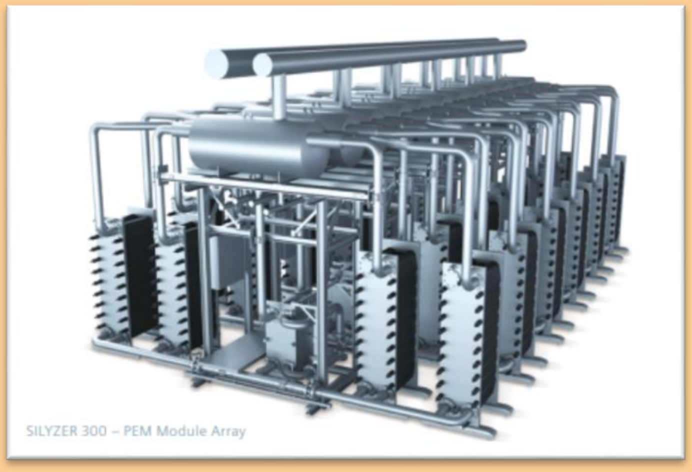

Figure 2.33: Graphical 3D-illustration of a Siemens PEM module (from https://new.siemens.com/global/en/products/energy/renewable-energy/hydrogen-solutions.html)

Cases

Case 1 – Proton Onsite PEM cells at Guangdong Synger Hydrogen Power Technology, China [45]
In 2016, a 13 MW plant has been delivered by Proton Onsite to Guangdong Synger Hydrogen Power Technology. The hydrogen will be used for fuel cell driven busses.

Case 2 – Siemens PEM cells at Stadtwerke Mainz, Germany [46]
In 2015, the 3.75 MW PEM cell facility at Stadtwerke Mainz has been producing renewable hydrogen based on wind energy.

References

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Fact sheet #20: Fixation in building materials

TRL 6-8

Description

CO_2 can be stored in building materials either through concrete curing with CO_2 or by using CO_2 as a raw material for building aggregates.

Concrete curing is traditionally carried out using water, but the use of CO_2 enables the permanent carbon storage in low-energy carbonate compounds, see Figure 2.34. An additional benefit of CO_2-curing is that the properties of the concrete are improved compared to water based curing.

Building aggregates can be produced by reacting CO_2 with waste materials such as ash, cement dust, and steel slag, see Figure 2.35. The product of the reaction is limestone, which can be used as building aggregates.

In both paths CO_2 is captured and permanently stored in the building materials, thus acting as both a utilization and storage technology.

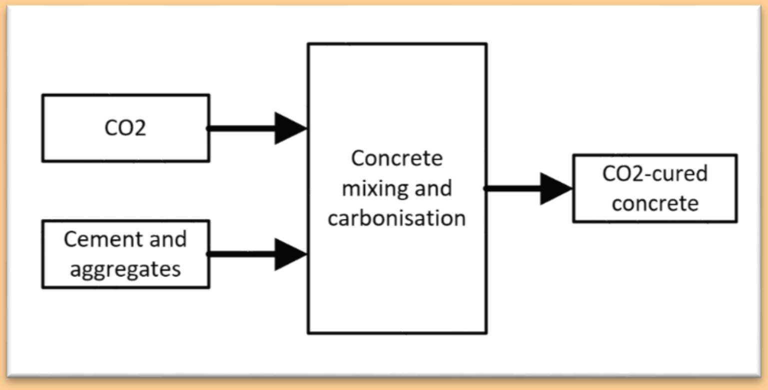

Figure 2.34: Production pathway for CO_2-cured concrete

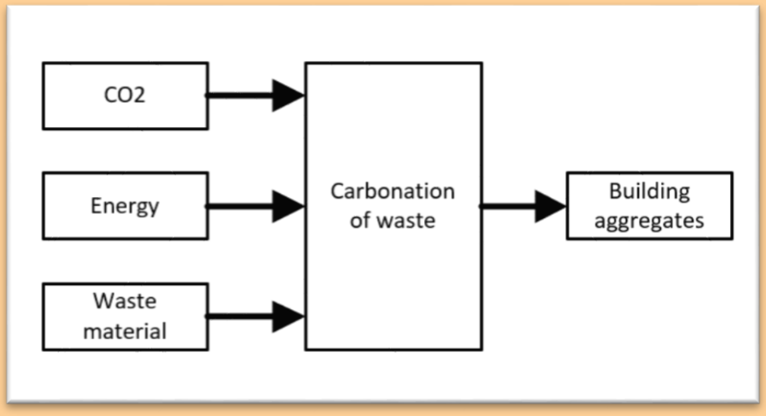

Figure 2.35: Production pathway for building aggregates based on CO_2

Cases

Case 1 - CarbonCure, Canada [47]
Provides a technology for concrete producers enabling the CO_2 curing of concrete.

Case 2 - Carbon8, United Kingdom [48]
Provides solutions for valorizing industrial waste materials and CO_2 into limestone used as building aggregates.

References

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2.8.2 Biomass related Carbon Capture

BECCS (bioenergy with carbon capture and storage) is the process of extracting and storing carbon from biomass. One path for this is the combustion of biomass in the form of renewable part of household waste or woody biomass and then storing the CO_2 from the flue gas afterwards as described in the Capture and Storage Fact Sheets above.

Example: In a waste incineration plant the municipal waste as feedstock is a mix of bio-based waste from renewable sources and non-bio-based waste from fossil sources. In Denmark the average share of fossil CO_2 *in the flue gas from a waste incineration plant is around 30%. The rest of the produced* CO_2 *is considered from renewable sources. The plant would need to capture 30% to become* CO_2 *neutral, but if the plant manages to capture more than the fossil share of* CO_2*, the plant can become net-*CO_2 *negative. This can also be categorized as BECCS.*

Another path of BECCS is the pyrolysis (partial oxidation) of biomass, whereby only a fraction of the carbon is burnt for heat or electricity production while the remaining high carbon content is deposited in the ground as biochar or similar. As many biomass feedstocks can be regarded as almost carbon neutral it is possible to have a setup where such a plant could actually be carbon negative by storing carbon under ground while maintaining a sustainable reforestation of the biomass feedstock. This technology is briefly described in Fact Sheet #21.

There are other technologies in the area of biomass for carbon capture. An example is the use of biomass thermal gasification as a source for H_2 for further utilisation of CO_2. In a demonstration plant in Finland [29] an oxygen blown thermal gasifier supplies hydrogen to a biological reactor with microorganisms with the ability to combine hydrogen and CO_2 to methane. The CO_2 source for this could be a stream of flue gas stream or biogas. The end product is renewable methane, and so this concept is then not Carbon Storage, but rather Carbon Utilisation. The technology is quite different from the CO_2 processing technologies in the rest of this report and would require another focus to be described in detail.

2.8.3 BECCS in cities

BECCS in the form of pyrolysis and similar technologies could be an important part of the solution for the future green energy and it has the potential to be applied in smaller scale closer to the biomass feedstock and to the receivers of biochar. The smaller scale makes it relevant to urban environments with the use of local biomass sources. These sources could also include fuels such as Waste Derived Fuels and local waste wood sources from parks and recreational areas. However, the small scale systems based on several process steps and mechanical handling of biomass makes them prone to high operational costs.

The choice of solution depends on the local conditions and biomass sources. The feasibility of a biomass conversion system as described should also be considered in a wider context involving improving the waste stream cycles, and creating local value in the form of jobs and activity.

Fact sheet #21: BECCS and pyrolysis of biomass

TRL 7

Description

Bio-energy with carbon capture and storage (BECCS) is a method of converting biomass to useful energy while storing carbon. One way of achieving this is with pyrolysis.

In biomass pyrolysis, biomass is heated in an oxygen-free or oxygen-deprived environment. The products can be syngas, bio-oils, and/or bio-char depending on the pyrolysis process temperature and reaction times.

The bio-char has a high carbon content and thereby a significant potential for long term carbon sequestration when plowed into agricultural soil acting as soil improvement and carbon sequestration.

By combustion of produced syngas it is possible to provide the heat required for the pyrolysis reactor and supply excess heat for district heating.

The value of biochar as a fertilizer depends on the circumstances of production method and the use in the soil. The long term sequestration of carbon by this method is measured in hundreds or thousands of years, but not indefinitely.

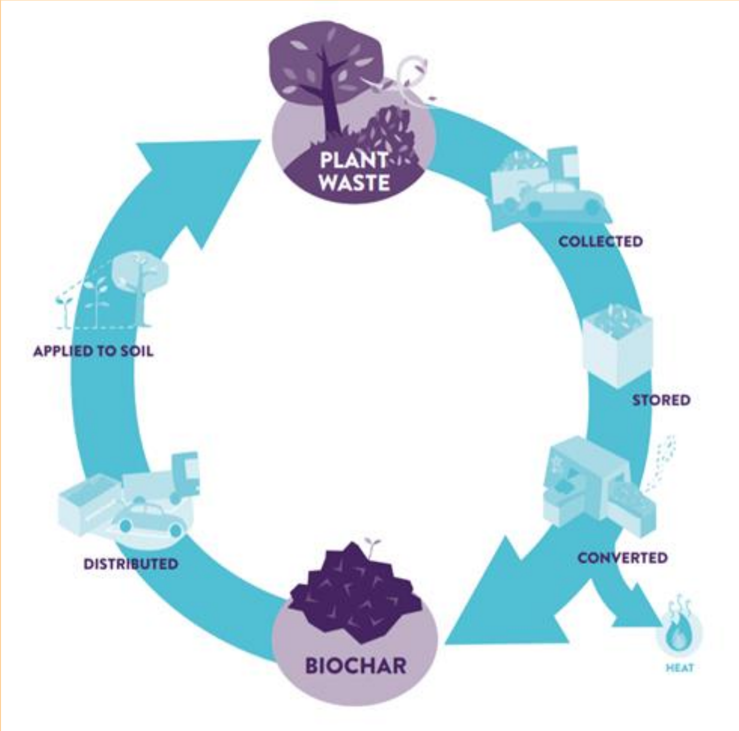

Figure 2.36: Biochar cycle, illustration from Stockholm Biochar Project (from https://www.bbhub.io/dotorg/sites/2/2017/03/Replicating-in-Stockholm.pdf)

Cases

Case 1 – Stockholm Biochar project [49]

Plant waste is collected from Stockholm citizens and used in a pyrolysis process where district heating and biochar is produced. The biochar is used by citizens and local authorities for improving soil qualities in gardens and public spaces.

References

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2.9 Summary of technical catalogue

The technologies described above are snapshots of the current state of development. The area of CCU/CCS is in rapid development at the moment with many new possibilities showing up through new companies and technologies. The report does not list all relevant companies and demonstration projects. The technologies mentioned above are expected to be the most relevant mature technologies and examples, but many other activities are ongoing worldwide. One important indicator is still the TRL level as described in the Fact Sheets above, where it is up to the stakeholders to choose which risk profile they are willing to take.

Additionally, the timeline for implementing some of the less mature technologies can be long, and can be too long to fulfil the near term goals set by a city or another entity. Also, the urgency of fighting the climate changes now, points to the implementation of some of the mature technologies instead of waiting for the development and upscaling of upcoming technologies.

For the choice of solutions the integration of the different parts of the system (capturing, local storage, heat and electricity demand, transport, storage and/or utilisation) is important. Heat integration and other synergies are important to explore in order to gain the most benefit and the lowest cost. The best choice of technology will depend on local conditions and should be subject to a thorough feasibility study.

3 Projects

At present several potential storage schemes are under development in Europe.

3.1 Northern Light in Norway/North Sea

The Northern Light project is under development in a consortium of Equinor, Shell and Total [52].

The overall concept is to establish an infrastructure to receive and store liquified CO_2 at the west coast of Norway from where it is pumped in a pipeline to a well some 150 km from the cost and then pumped into an aquifer deep in the ground as illustrated in the following figures:

Figure 3.1: Northern Light overview. [52]

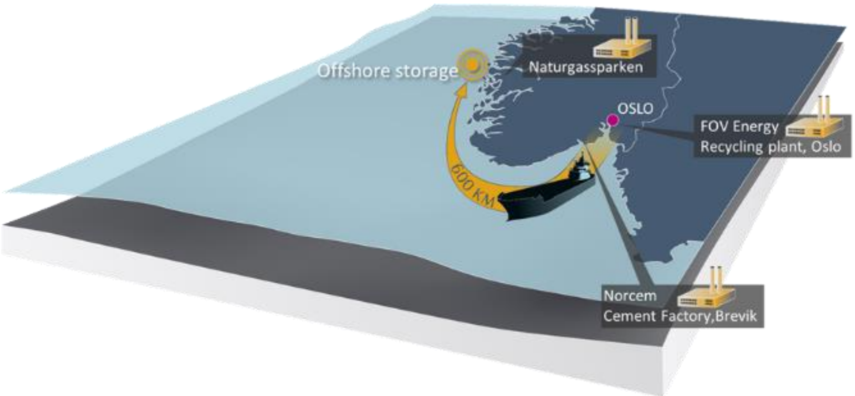


Figure 3.2: Northern Light concept [52]

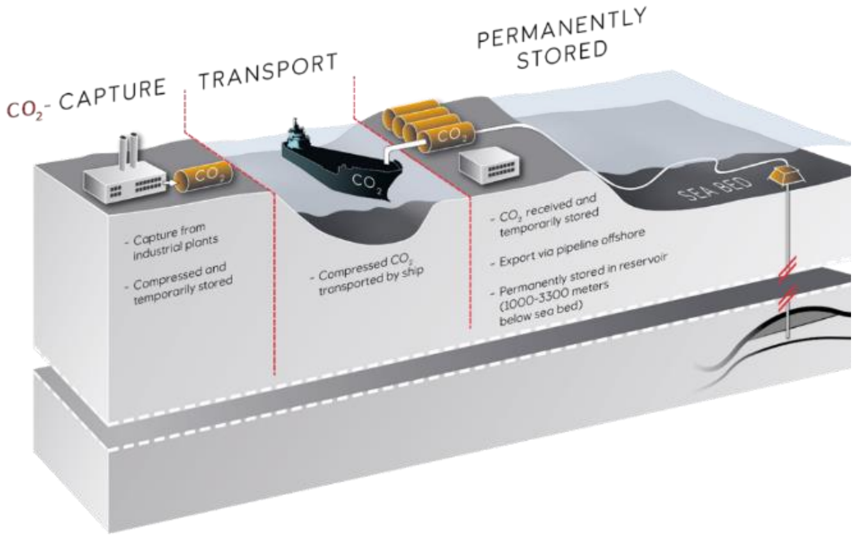


Figure 3.3: Northern Light port concept [52]

The project development is in progress and the consortium is aiming at having an agreement with the Norwegian Government in 2020. The initial capacity of the system is estimated at up to 5 mio. tonne per year, and they have MoU´s (Memorandum of Understanding) with several suppliers for CO_2, being the Fortum Waste incineration plant near Oslo, a cement factory in Norway, Stockholm Exergi and others.

3.2 Arthos in the Netherlands

One of the interesting areas for carbon capture is the North Sea Channel District and the extended harbor area of Amsterdam. Decarbonization is currently part of national strategies and subsidy program. Projects including carbon usage for circular purposes, and CO_2 infrastructure has been considered in terms of extending a pipeline from the harbor of Rotterdam towards the harbor of Amsterdam, passing along the greenhouses in "Westland area" where carbon is used for the growth of fruit and vegetables. Also, a new pipeline is considered as an underground connection to an empty gas fields in the North Sea, as a possibility site to store carbon.

A feasibility study is being conducted at AEB Amsterdam, the largest waste-to-energy facility with a point source of 450,000 ton per year of CO_2. Tata steel has a large steel production and might be a candidate for even more CCS for the system.

3.3 Porthos in the Netherlands

Port of Rotterdam Authority, Energie Beheer Nederland B.V. (EBN) and N.V. Nederlandse Gasunie are working on the construction of a CO_2 transport and storage infrastructure between the Port of Rotterdam and a depleted gas fields beneath the North Sea. The total length of the CO_2 infrastructure is around 55 km. The storage will take place in fields 21 km off the Dutch coast.

Initiators

Port of Rotterdam Authority, EBN and Gasunie are thee organisations that play an important role in the Dutch energy landscape. In this project, each external organization offers specific experience and expertise. Port of Rotterdam Authority with its knowledge of the local situation and market, EBN with its expertise of the deep subsurface and Gasunie as gas infrastructure and transport expert.

Porthos in the Port of Rotterdam

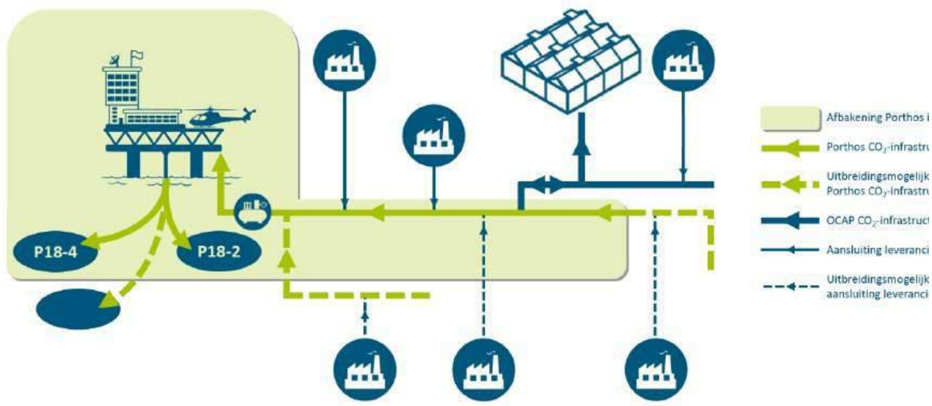
Porthos stands for Port of Rotterdam CO_2 Transport Hub and Offshore Storage. The three initiating parties are working together to prepare this project in which CO_2 from the industry will be captured, collected in a transport pipeline and then stored in gas fields deep beneath the NorthSea seabed. Some of the CO_2 can be used in the South Holland greenhouses to ensure faster plant growth.

Porthos and Europe

Porthos has been granted Project of Common Interest (PCI) status by the European Commission. A PCI project is an energy infrastructure project that has obtained preferred status on behalf of the European Commission. This also means that permit applications are more streamlined and the applications are made simultaneously as one total package of permits.

The project is illustrated below:

Figure 3.4: Porthos overview. Source: rotterdamccus.nl



3.4 Other Possibilities in the North Sea

Besides the ones described above it is likely that some of the operators of oil and gas fields in the North Sea will have the infrastructure and capabilities to use these at fields that are no longer productive or in the final stage to be able to convert their business to storage in the more or less empty reservoirs. In addition the Danish GEUS (geological research institute) has also pointed out the possibility for several potential locations in the Danish underground on-shore.

3.5 Carbon Capture projects in the pipeline

Besides the several projects mentioned in the previous sections ARC – the waste incineration plant in Copenhagen is at present investigating the possibility of capturing up to 500,000 ton per year of CO_2 for further transportation and storage, most likely to be at one of the schemes in the north Sea. Part of the analyses is a focus on usage of the CO_2 for methanization, production of methanol or even jet-fuel all in combination with hydrogen produced by green electricity (wind power) through electrolysis. These production to be a future possibility in combination with the storage of the majority of the total amounts.

In The Netherlands the privately owned Waste-to-Energy plant AVR in Duiven have started operation on a 12 ton/hr / 60.000 ton/yr Carbon Capture plant based on amine absorption. The absorber is standard monoethanolamine (MEA) in order not to be restricted to proprietary absorbents, which many plant suppliers will require for optimum operation. The captured CO_2 is transported by trucks and sold to the nearby greenhouses and industry, but the market is highly seasonal. The larger Rozenburg plant near Rotterdam, which is also operated by AVR, is also in the process of establishing Carbon Capture with an expected higher capacity.

Also in the Netherlands is the municipality owned Waste-to-Energy plant in Twence in the process of expanding their Carbon Capture capabilities. Currently they have a pilot scale carbon capture plant based on absorption, which produces CO_2 for an on-site production of sodium-bicarbonate. This substance (baking powder) is used at the plant for the Sulphur cleaning of the flue gas, but it is also a commodity, that can be sold. The plant has made a contract for the establishment of a new Carbon Capture facility with a yearly capacity of 100.000 ton CO_2 to be installed 2020. The CO_2 will be trucked from the plant and sold to local greenhouses and industries.

4 Recommendations on usage

Utilization of captured CO_2 is obviously tempting as an alternative to sequestration. However, for carbon accounting purposes there are challenges in most utilizations, as they will ultimately lead to the reintroduction of CO_2 to the atmosphere in most cases. Usage is not an activity to be undertaken by cities, but may encouraged by them and may be included in their carbon accounting.

If captured CO_2 is sold commercially, it will replace CO_2 from other sources, many of which will produce and emit CO_2 anyway, as the CO_2 is a byproduct of other processes, for example fertilizer production. In this case, there is no emission reduction from utilization of captured CO_2. There are some instances where captured CO_2 can be claimed to substitute fossil sources (for example direct combustion of natural gas to fertilize Green Houses, but for most cities such pathways are not available).

In order to achieve an emissions reduction from utilization of captured CO_2, the most viable avenue seems to be the production of hydrocarbons to substitute fossil sources – until these are no longer an option. In the short term (until fossils are not an option), cities may thus count captured carbon that is processed to hydrocarbons as emission reductions, but that will require the development of accounting methodologies that prove such a substitution. A few such methodologies exist within the CDM system, for example for methane substitution[4] or substitution of CO_2 of fossil origin with CO2 from renewable sources[5].

In the long term, carbon capture may become part of a carbon cycle, which involves production of hydrocarbons from captured CO_2, and recapture after the use of the hydrocarbons as for example jet fuel by extraction from the atmosphere (BECCS for example). As there are few other options for aviation than synthetic fuels, and as biomass resources may be insufficient as basis for complex hydrocarbons (including plastics), it is recommended that cities follow and support developments in electrolysis (to produce hydrogen) and hydrocarbon synthesis based on CO_2 and Hydrogen.

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