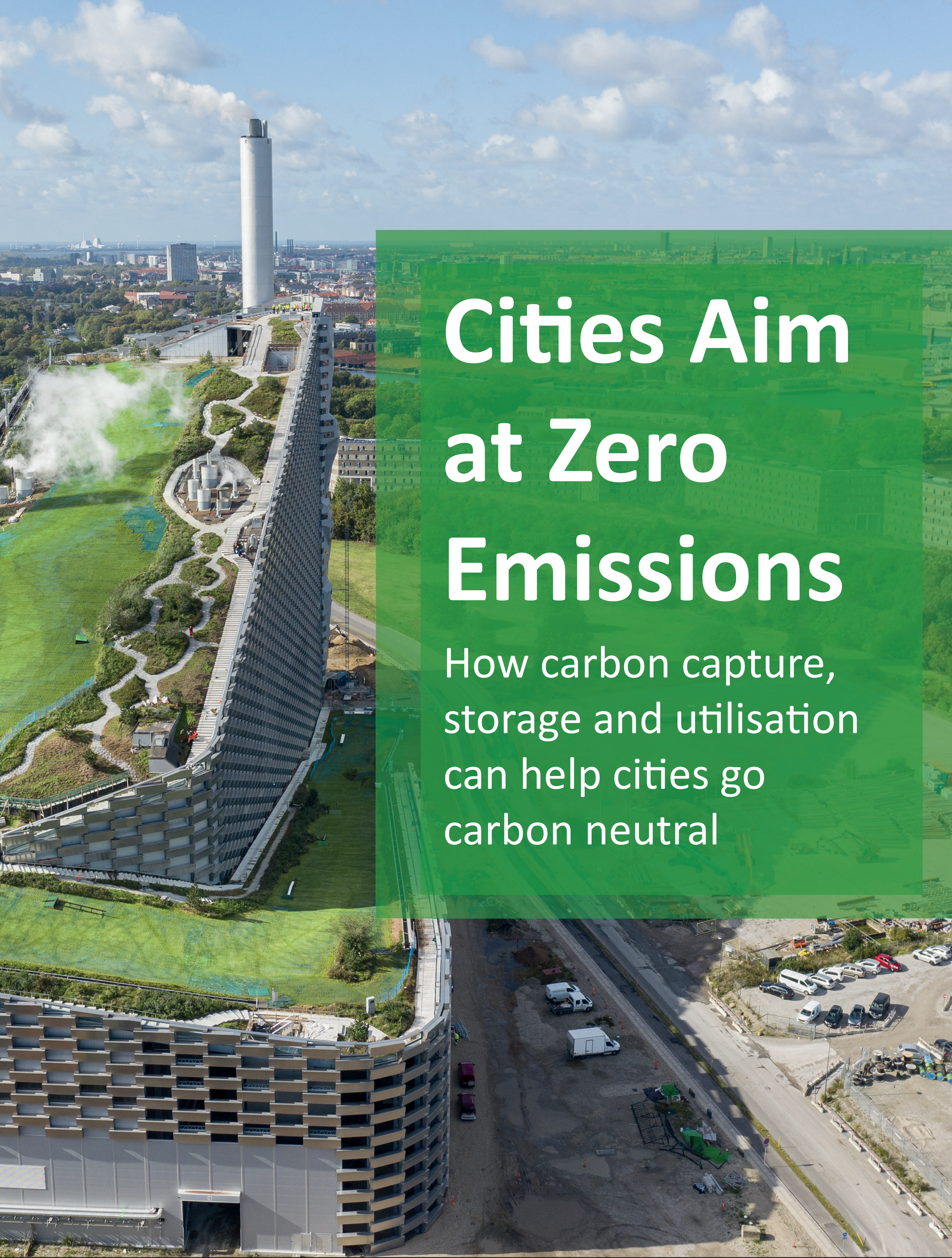

Cities Aim at Zero Emissions

How carbon capture, storage and utilisation can help cities go carbon neutral

CNCA
Københavns Kommune
BELLONA
City of Amsterdam
Helsinki
Oslo
Stockholms stad

Foreword

This report is written by the Bellona Foundation and the City of Copenhagen in collaboration with Amsterdam, Helsinki, Oslo and Stockholm. The topic is carbon capture, storage or usage in relation to cities mitigating their climate impact. It explores the whys, ifs and hows associated with the technologies. Discussions will shed lights on the different barriers and drivers for carbon capture from a city perspective, and illustrate the potential and possible actions based on real examples.

The publication marks the end of a one-year project collaboration between the five cities mentioned above. All of them have advanced climate plans with ambitious targets, and they perceive carbon capture as a possible solution to ensure these plans succeed. These cities already experience the challenge of becoming carbon neutral without applying this technology on their centralized heating sources.

Behind the development of this report there are 10 individual background notes and a screening of the different technologies related to carbon capture. These are written by the Bellona Foundation, the consultancy Niras and the City of Copenhagen. All of these end-products have been conducted on behalf of needs highlighted by the cities to enhance them moving closer to implementation of carbon capture, storage or usage. Over the course of 2019, the cities used the first half for framing their needs related to the subject, and the econd part was used for studying literature and the state of the art with Bellona and Niras.

The Carbon Neutral Cities Alliance (CNCA) has made this project possible through its Innovation Fund. The CNCA Innovation Fund was created in 2015 to invest in high-potential, city-led projects that develop, test, implement and amplify deep decarbonization strategies and practices. These projects accelerate deep decarbonization around the world by showing the “art of the possible” in urban climate policy.

Until now, the discussion on carbon capture has rarely been mentioned in cities context. But if cities are to live up to the Paris agreement and succeed with their ambitious climate targets, it may become a reality. Therefore, we hope this publication will inspire other cities to consider carbon capture as a climate solution. The report will answer a lot of the initial questions asked in other cities, and propose actual actions for how a carbon capture facility may become reality. As carbon capture still is perceived as a niche technology, our work will be of relevance of all kinds of stakeholders who seek to gain new knowledge on the whys, ifs and the hows.

Enjoy the reading.

Carbon Neutral Cities Alliance

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. CNCA is a project of the Urban Sustainability Directors Network.

It is possible for cities to achieve their interim carbon reduction targets through incremental improvements to exsting systems. However, achieving carbon neutrality will require radical, transformative changes to core city systems.

The Alliance aims to address what it will take for leading international cities to achieve these deep emissions reductions and how they can work together to meet their respective goals more efficiently and effectively."

If we lack space, I would rather delete the existing paragraph "It is possible for cities to achieve their interim carbon reduction targets through incremental improvements to existing systems. However, achieving carbon neutrality will require radical, transformative changes to core city systems.

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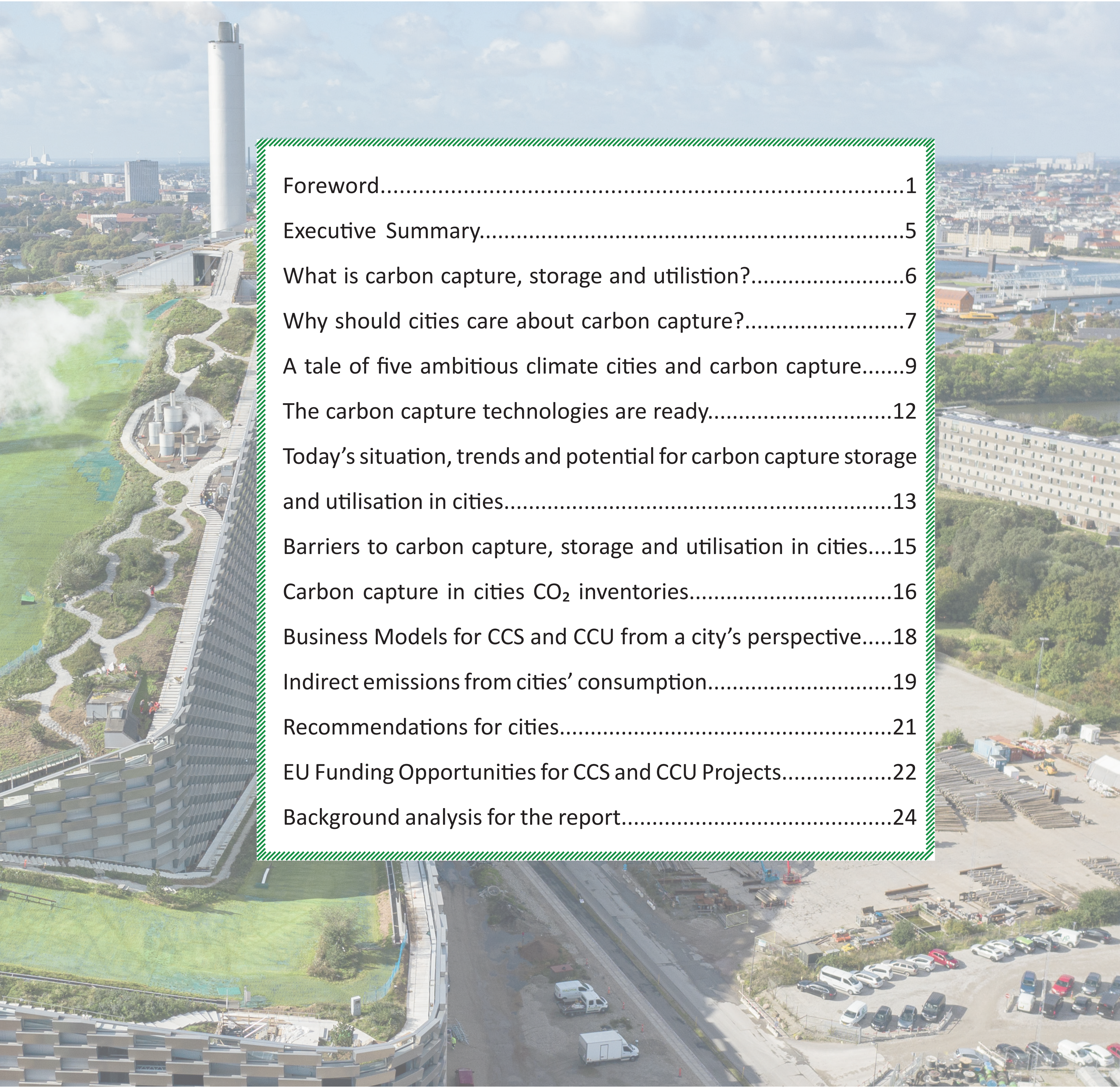


Executive Summary

Today, cities account for 75 per cent of global CO_2 emissions, more than half of the world's population, and 80 per cent of global gross domestic product. For a city, some emissions are direct deriving from sources like fossil-fuelled transport, central heating and cooling, power production, burning wood in stoves and waste handling. But a large portion of the emissions are indirect – our use of electricity, our food consumption and in particular our material world. Everything that makes up a city – roads, buildings, plastic bottles and escalators - is produced emitting CO_2.

Cities have a huge responsibility related to reducing their climate impact and setting the pathway towards the fossil free society. More and more cities develop ambitious climate targets, and though progress has been made, it will become difficult to reach carbon neutrality with currently available measures and within their sphere of influence. Here, carbon capture from local sources can play an important role as a readily accountable measure.

Some believe that carbon capture technologies are a solution for the future, but the truth is, that currently 19 facilities are implemented globally, and four more are under construction. They capture and store a total of about 25 million tonnes CO_2 annually, and this number is expected to increase to about 40 million tonnes CO_2 annually as new projects under construction will soon begin to operate.

There are no immediate technical barriers to carbon capture and storage, as evidenced by the operating full-scale projects world-wide. The main barrier is cost, which for most situations is still considerably higher than any CO_2 tax or emissions fee. Furthermore, there exist specific regulatory barriers that differ from country to country. Regarding carbon capture and utilisation, it is more complex to identify specific barriers due the diversity of utilisation technologies.
Cities can be drivers for infrastructural hubs for new climate technologies, and cities can directly ensure that new innovations can enter the market, and increase their own attractiveness for inward, clean investment. Cities can deploy carbon capture, transport, utilisation and storage. They can also help create the necessary market and infrastructural frameworks.

The following recommendations are starting points for cities that want to engage with these carbon capture technologies:

1. Map your emissions
2. Assess viability of carbon capture, transport and storage
3. Assess viability of carbon capture and utilisation
4. Get access to funding
5. Plan strategically for future expansion
6. Use public procurement to establish a first market for clean products
7. Drive consumption change through campaigns and levying

Cities have the power to affect these. As hosts to CO_2 emitting facilities (e.g. combustion and industrial process plants) that represent highly concentrated sources of CO_2, it is technically feasible for cities to (retro)fit such facilities with CC. Also, the CO_2 emissions from indirect sources (e.g. cement and steel) can be reduced through procurement requirements. Therefore, carbon capture storage and carbon capture utilisation will be an important technology for many cities, if they are to reach their ambitious climate target of carbon neutrality.

What is carbon capture, storage and utilisation?

The concept of carbon capture, storage or utilisation (CCSU) consists of three elements; (1) carbon capture (CC) from a flue gas stream or directly from the air, (2) transportation of CO_2, and (3) either store (CCS) the CO_2 permanently, or convert and utilise it to make fuels or other products (CCU). These different elements are described shortly below, however further detail can be found in the report *Screening of Carbon Capture Technologies* conducted by NIRAS for this project.

Carbon capture

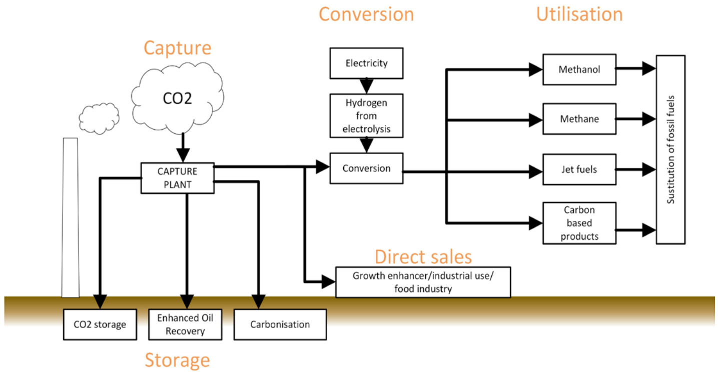
There are multiple ways to separate and capture CO_2, either directly from the air or at point sources. Between the many different technologies capable of capturing CO_2, the one that has the highest technological readiness level (TRL) and lowest cost is a post-combustion method called absorption. This is a process where an amine (an organic derivative from ammonia), or other chemical which readily binds to CO_2, is added to the flue gases in a 'scrubber'. The technology is proven and has already been installed on several full-scale facilities.

Transportation of CO_2

Facilities that emit CO_2 are rarely located near a geological storage site or usage facility, and therefore transport is necessary. There are three different ways of transporting the carbon; trucks, pipelines or ships. In general, it can be said that the costliest method and with least capacity is trucks. Road transport can be a flexible solution and provide the best solution for some facilities (e.g. small ones). The most optimal forms of CO_2 transportation would commonly be by ship or pipelines. Shipping is a flexible mode of transportation, but requires easy access to a harbour. It is best suited when the CO_2 must be transported over long distances. Transportation by pipelines often has the largest capacity and is cheap to operate, but can be expensive to construct, and difficult to plan for in urban and dense areas.

Storage and negative emissions

When the CO_2 is captured it can be stored in the deep underground, both onshore and offshore. Storage technologies are well evolved and have been proven secure for storage of CO_2. The CO_2 is injected into the underground, e.g. in porous rock formations. These can be in saline aquifers, depleted oil and gas fields or other formations suited for this activity. When stored deep underground the CO_2 will behave as a liquid due to the higher pressure there. Using CCS will ensure that no CO_2 will enter the atmosphere. Moreover, if CO_2 from bio-energy is captured and stored (BECCS), e.g. biomass fuelled power plants, it will result in so-called negative emissions.



Overview of the different carbon capture, storage and usage technologies.

This can be explained due to the fact that biomass absorbs CO_2 when it grows, and when the biomass burns, the CO_2 returns to the atmosphere, which is currently classified as CO_2 neutral. If instead the CO_2 is captured and stored after combustion, it will thereby prevent it from entering the atmosphere again and result in negative emissions. The climate mitigation impact of biomass is, however, dependent on sustainability of the biomass source as well as the timeframe that is used when one measures the impact.

Utilisation

The utilisation of CO_2 is broadly divided in to two categories; direct use or conversion. Direct use includes processes where CO_2 is used directly for commercial purposes (e.g. in beverages). Conversion refers to processes where CO_2 is converted and utilised in new products e.g. chemical or fuels. When the CO_2 is used for production of synthetic fuels, the CO_2 is combined with hydrogen to form hydrocarbons that can substitute fossil fuels. The production of synthetic hydrocarbons requiresa significant amount of electricity, which must be produced from renewable sources if synthetic fuels can achieve any emissions reductions. Producing fuels from CCU only delays CO_2 emissions, and can therefore only provide emissions reductions when they replace fossil fuels. The main example application for this is the aviation sector which has no available substitutem for liquid hydrocarbon fuels.

Why should cities care about carbon capture?

Today, cities account for 75 per cent of global CO_2 emissions, more than half of the world's population, and 80 per cent of global gross domestic product. Furthermore, United Nations forecast that by 2050 more than two-third of the world's population will live within cities.

Cities have a huge responsibility to reduce their climate impact and to set the pathway towards a fossil free society. Luckily, more and more cities commit themselves to ambitious climate targets, develop strategies and value real actions towards reducing their carbon emissions. Examples are energy efficiency, investing in renewables, and 'greening' mobility.

Current measures won't be enough

Even though progress has been made, some cities are realizing that current measures to reduce CO_2 emissions are not enough to reach carbon neutrality within their sphere of influence. Here, carbon capture from local sources can play an important role as a readily accountable measure.

Furthermore, on a longer horizon, the achievement of the targets of the Paris Agreement requires so-called negative emissions, which make carbon capture and storage an essential tool to extract CO_2 from the atmosphere when connected to bio-energy facilities.
Carbon capture and utilisation for the production of so-called synthetic hydrocarbons may also be an important part of CO_2 management cycles in this future.

In order to meet these challenges, a multitude of solutions must be implemented – carbon capture is only one such solution. The point here is the mix of solutions – recognizing that there is no single silver bullet, as concluded by IPCC mitigation analysis.

City skyline including chemical plant (photo: pxfuel)

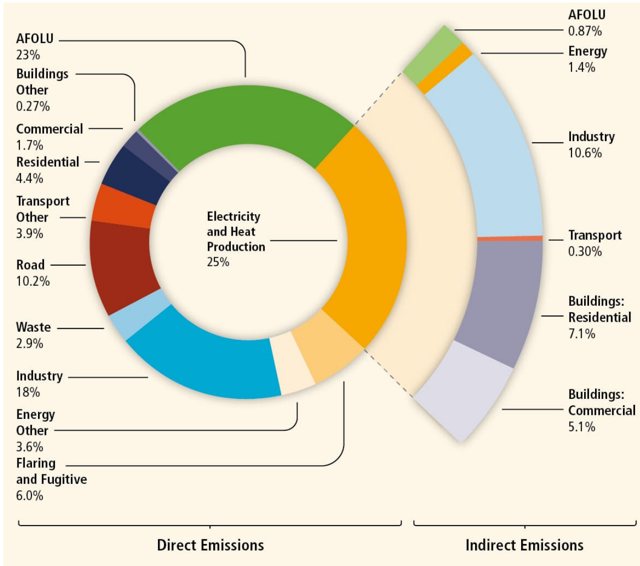


Figure 1 The source of the problem – Greenhouse gas emissions. The figure shows where the total GHG emissions in 2010 (49.5 $GtCO_2eq/yr$) came from. The pullout from the figure distribute the CO_2 emissions from electricity and heat production according to their final energy use. The figure is from the IPCC 2014 Fifth Assessment Report. Chapter 1: Figure 1.3

Carbon emissions in cities

Europe's largest emitting sectors are the energy, road transport, and industry, followed by residential, agriculture, and maritime and air traffic. Advances in reducing emissions and implementing new, cleaner technologies are being made, particularly in the energy, residential and graduallyin the road transport sectors. Through renewable electricity, improved building efficiencies, and electrification and transformation of mobility, some of the largest emittingsectors have the means available to reduce CO_2 emissions dramatically over the coming decades.

Of the three remaining sectors, industry is the largest and - from a climate perspective - most crucial sector as it produces goods and materials essential for climate action in other sectors. Particularly heavy industry that produce basic materials, such as cement, steel and chemicals, are fundamental to climate technologies, including renewable electricity, housing insulation and new modes of mobility. For a city, some emissions are direct deriving from sources like fossil-fueled transport, central heating and cooling, power production, buning wood in stoves and waste handling. But a large portion of the emissions are indirect – our use of electricity, our food consumption and in particular our material world. Everything that make up a city – roads, buildings, plastic bottles and escalators - is produced emitting CO_2.

Cities have the power to influence these. As hosts to CO_2 emitting facilities (e.g. combustion and industrial process plants) that represent highly concentrated sources of CO_2, it is technically feasible for cities to (retro)fit such facilities with CC. Also, the CO_2 emissions from indirect sources (e.g. cement and steel) can be reduced through procurement requirements.

Key arguments for why cities should care about carbon capture

The technology is proven and ready to be implemented to achieve carbon neutrality and negative emissions.

Ambitious climate cities can accelerate innovation and roll-out of technology by showcasing solutions.

The last 10-20 per cent of CO_2 emissions in cities will be difficult to neutralize from energy efficiency and renewable measures alone.

Closely tied to local utilities e.g. waste-to-energy and power plants and having the opportunity to collaborate.

Having more ambitious targets than the national government and being at a more advanced stage in the transition.

A tale of five ambitious climate cities and carbon capture

Carbon Neutral City Alliance members Amsterdam, Copenhagen, Helsinki, Oslo and Stockholm all have progressive climate plans and some of the world's most ambitious targets. Until recently, most cities have focused on reducing the energy consumption, introduced more renewable energy, and promoted low-carbon mobility. But as the most ambitious cities progress, it becomes evident that more radical solutions are necessary to reduce the remaining carbon emissions.

Before the start of the project each of the five cities had already begun working on how carbon capture could become reality. Working with carbon capture is highly complex, and there exist numerous barriers and questions related to the technology from a city perspective. Instead of each city dealing with these alone it was perceived supportive to collaborate on the subject.

In this section the similarities between the cities will be emphasized arguing for their reasoning behind their interest in carbon capture. Furthermore, to inspire other cities a short description of each city will be provided in relation to their climate plan and work with carbon capture until now.

Demographic similarities between cities

The five cities are located in the northern parts of Europe, with Amsterdam and Helsinki being located respectively as the most southern and northern city (see Map 1). Some of the demographic resemblances include the size of population and geographical area, local economy, and average age (see Table 1) as well as features such as political opinion, mentality and religion.

One of the more important similarities for the cities is the climatic zone with the cold winters that cause a significant heat demand and similar energy patterns, which have led to energy systems relying on point sources including waste incineration and combined heat and power plants burning bio energy.

There is shared understanding of reducing CO_2 emissions from these point sources that have led to starting this project. Both removing the CO_2 from the fossil parts of the heat production, and further remove CO_2 from the biogenic energy leading to negative emissions.

Map 1: Overview of Europe and the location of the five cities.

Amsterdam

Amsterdam has set an ambitious goal of reducing emissions by 95 per cent in 2050 and is planning on completely phasing out natural gas by 2040. The city is emitting 50 per cent more CO_2 today compared to 1990 levels, and the largest sector for emissions are electricity and the building environment, which therefore also is where the largest focus on reduction is. CCSU is debated both in national and local politics, and carbon storage is considered a necessity for reaching short and mid-term goals. On a longer term, carbon utilization is considered as an important building block for the production of synthetic fuels to reduce emissions in aviation. These technologies have been introduced in the Roadmap Amsterdam Climate Neutral 2050. CO_2 infrastructure has been considered on terms of extending the current OCAP pipeline, which is a CO_2 pipeline spanning from the Rotterdam harbour to the harbour of Amsterdam and is mainly used for accelerating plant growth rates in greenhouses.

Table 1: Demographic data on the five cities.

City	Population	Economy (GDP in USD bil.)	Avg. Temp. (C°)	Avg. Age
Amsterdam	860.124 (2018)	154	9,2	37,7
Copenhagen	602.481 (2017)	127	8,4	35,4
Helsinki	631.965 (2016)	77.1	5,1	40,1
Oslo	672.061 (2017)	74.4	6,3	37,3
Stockholm	962.154 (2017)	143	7	42

Industrial activities in the Amsterdam harbour (Photo: Henk Monster)

Also, a connection pipeline from both the Rotterdam and Amsterdam industrial areas towards deployed gas fields in the North Sea for storage is considered.

From 2021 onwards a new national regulatory framework of climate policies is introduced. The industry - including the waste incineration sector - will be charged for emitting CO_2. At the same time, a broad subsidy scheme for CO_2 reduction technologies will be implemented.
Amsterdam's waste incineration has conducted a feasibility study for a reduction of 500.000 tonnes CO_2 per year, roughly a third of its total CO_2 emissions. At this moment the city of Amsterdam is the only shareholder of the waste incineration. In 2019 the City Council decided to sell the waste incineration and is preparing an auction for 2020. The city remains its ambition to realize CC on the waste incineration – in cooperation with the future owner.

Copenhagen

In 2009 the City Council set an ambitious target to become carbon neutral by 2025. A large part of the target will be met by a transition in the energy production, especially due to an increasing number of renewable sources like wind turbines and photovoltaics. Recently a new waste-to-energy plant and biomass fuelled combined heat and powerplant (CHP) have been established. After the new CHP will be fully up and running in 2020, the last coal fired CHP will be taken out of service.

A mid-term evaluation of the Climate plan concluded that a gap of 200.000 tonnes of CO_2 will occur with current progress, therefore this technology is suggested as a new initiative to reach the goal. Copenhagen is currently collaborating with the local waste incineration plant on a carbon capture solution. The emissions from the plant are approx. 480.000 tonnes of CO_2 per year. It is estimated that around one third of the CO_2 is from the fossil fraction in the waste, and the remaining two thirds derives from incineration of the biogenic fraction.

Current legislation, however, makes it impossible to store CO_2, even though studies have been conducted on undergroundstorage. The city is in dialogue with universities, energy utilities, and the Geological Survey of Denmark and Greenland. The next step is to further work with Danish stakeholders to mature a carbon storage project.

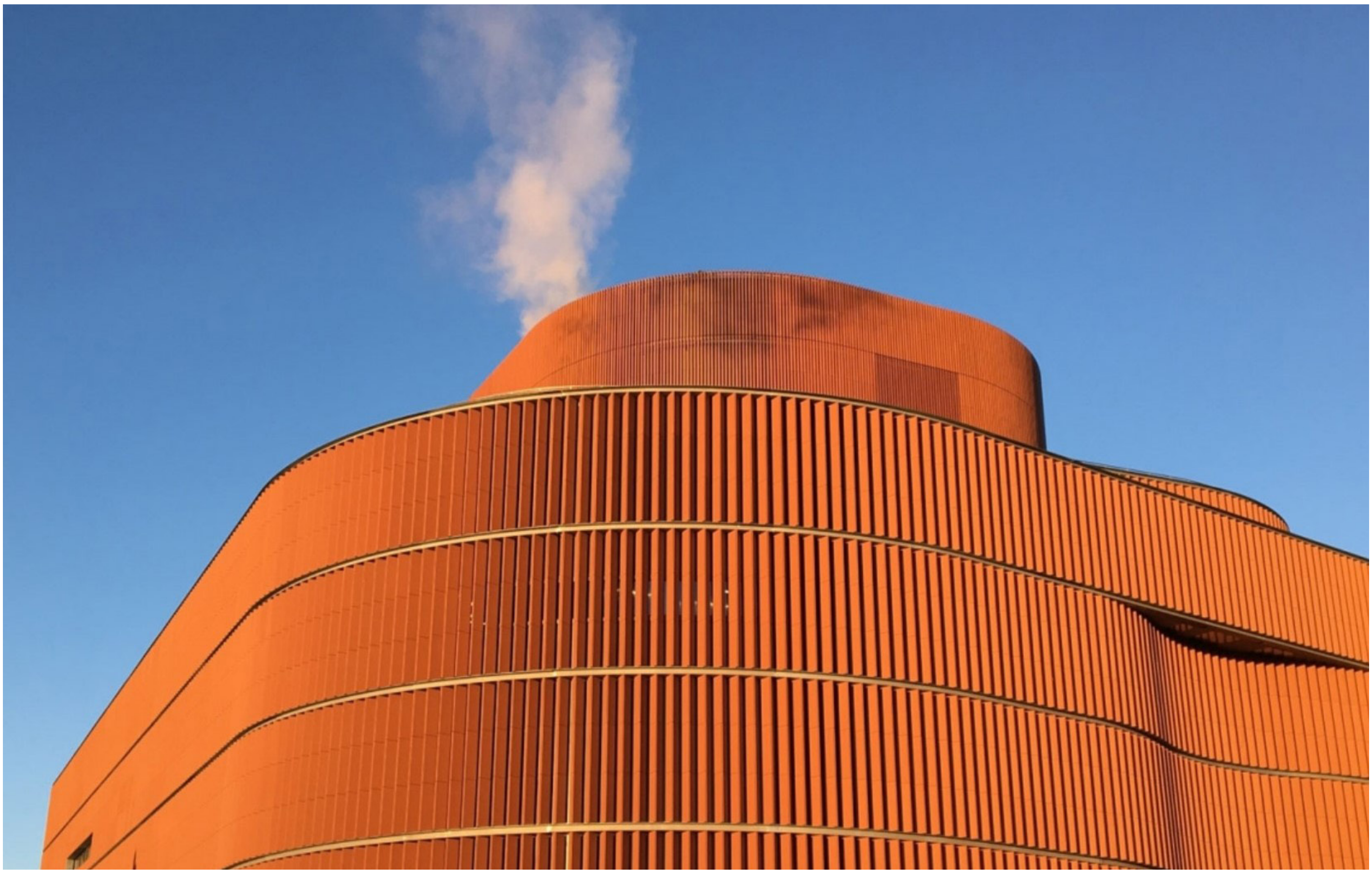
Helsinki

Their goal is to be carbon neutral by 2035 and reduce emissions by 80 per cent compared to 1990 levels. The largest emitting sector is heating, with 56 per cent of overall emissions. The city aims to reduce emissions by 80 per cent and compensate for the last 20 per cent. The reduction of emissions per capita accumulates to 47 per cent compared to 1990 already, despite a growing population. The city is looking into all possibilities for compensating for the last 20 per cent of emissions, and carbon capture and storage in combination with biomass is considered a promising solution for this compensation, and a mean to produce negative emissions. They are also looking in to increasing the number of carbon sinks outside the city. Currently there is no program or incentives to introduce CCS, but the possibility of CC with the city owned energy company, Helen, are now being studied. Finland has very limited storage capacties.However, Helsinki is exploring opportunities for both storage and utilisation of CO_2.

The Klemestrud Plant in Norway (Photo: Fortum Oslo Varme/Einar Aslaksen)

Oslo

Oslo experienced an increase of 8 per cent CO_2 emission from 1990 to 2009 and has a goal to reduce direct GHG emissions by 95 per cent by 2030. The transport sector is responsible for 55 per cent of emissions, and waste incineration about 25 per cent. It is very difficult to reduce the emissions from waste incineration by other measures than CCS and with a climate target of 95 per cent reductions by 2030, CCS on waste incineration becomes a key mitigation measure for Oslo. National level government in Norway has made a commitment to realize at least one full-scale CCS facility with the goal of having this operational by 2024. Currently the Norwegian Parliament is aiming to make an investment decision in the fall 2020. The Klemetsrud waste incineration plant is one of two potential projects in this process. The waste treated at the plant consists of approximately 50 per cent biological carbon. This means that a CCS facility at the plant will remove more than 200.000 tonnes of CO_2 from the carbon cycle every year in addition to the 200.000



Värtaverket, the Biomass Power Plant in Stockholm (Photo: Gottlieb Paludan Architects / Urban Design)

of CO_2 of fossil carbon. A carbon capture pilot has been carried out at the Klemetsrud and it was proven that 90 per cent of the 400.000 tons of CO_2 can be captured. This means that the project could generate about 200.000 tonnes of negative emissions each year.

Equinor is the operator of the Northern Lights consortium, which also includes Shell and Total. They will build an open access transport and storage infrastructure for CO_2 that provides capacity beyond that required for the two potential capture sites in Norway. The government granted permission to store CO_2 in a saline-filled formation southeast of the Troll field in the North Sea, which is one of the largest fields in Europe. This marks an importantmilestone in Norway's future CCS climate agenda.

Norway has a relatively long history of CCS dating back to 1996. Equinor is currently operating two storage reservoirs where more than 20 million tonnes of CO_2 have been stored to date, giving them more than 20 years of experience in the field. Equinor, Shell and Total have through the planning process in the Northern Lights project found new storage capacity of a total of 32.5 million tonnes.

Stockholm

Stockholm have reduced their emissions by about 40 per cent since 1990 and have a goal of becoming fossil free by 2040. The system boundary is emissions from energy use within the geographical city. Currently a new climate action plan for 2020-2023 is being developed, which includes a carbon budget for 2020-2040. To compensate for the remaining emissions in the transport and energy sector in 2040 the city is planning on implementing emissions reductions solutions such as BECCS and biochar.

In the city's financial 2019 budget, carbon capture in combination with biomass is declared a promising measure to reverse climate change. BECCS implemented on several different point sources in Stockholm has an estimated potential for emissions reductions of 1.300.000 tonnes of CO_2 per year. The local utility district heating company Stockholm Exergi, owned partly by the city, has begun planning a BECCS project that could be operating in 2024/25. In December 2019 Stockholm Exergi started Sweden´s first test facility that captures carbon dioxide from bio-cogeneration. However, Sweden is not seen to have storage possibilties and the plan is therefore to send the CO_2 to Norway.

The carbon capture technologies are ready

All essential components of both carbon capture storage and carbon capture utilisation are commercially available. Full-scale commercial operation of full-chain CCS and CCU is implemented at 19 facilities globally, and four more are under construction. They capture and store a total of about 25 million tonnes CO_2 annually, and this number is expected to increase to about 40 million tonnes CO_2 annually[1] as new projects under construction will soon begin to operate.

The number of full-scale projects is growing, and more applications of CC facilities is spreading to new industrial and energy production processes. There are currently seven suppliers of CC technologies that have delivered facilities to full-scale operations[2]. New entrants promise innovative technology for new applications and have demonstrated their potential at a smaller scale[3]. Some of these have developed solutions that captures CO_2 from industrial flue gases, and others aim to capture CO_2 directly from the atmosphere, independent of industrial point sources.

Technologies that convert captured CO_2 into other materials and products, spanning solid carbonate minerals, liquid and gaseous synthetic hydrocarbons, plastics and more are available. While many of the CCU products are aimed at niche markets, the interest in solutions that converts CO_2 into synthetic hydrocarbons is significant. Even though no CCU-based synthetic fuels facilities are in operation, the main technology components are in commercial operation in South Africa, which produces about 140 thousand barrels of synthetic fuels daily, however based on a coal gasification and catalytic synthesis process. A similar example is the production of synthetic methane at large scale at a coal gasification plant in South Dakota (USA), delivering its captured CO_2 to oil fields in Canada for enhanced oil recovery (CO_2EOR).

Thousands of CO_2 injection wells are in operation, though most are in service in the commercial CO_2EOR industry in North America. The same technology used for CO_2 injection wells for CO_2EOR is used to permanently store CO_2 in deep geological formations. Systems for preventing and fixing leaks from storage sites through fit-for-purpose monitoring have been developed to satisfy special regulations of CO_2 storage sites in the EU, North America and more. Storage of CO_2 in offshore deep geological sites have been commercially operated on the Norwegian continental shelf since 1996.

Several independent research projects have confirmed the security of the storage operations. A total of about 22 million tonnes of CO_2 have been stored at two offshore sites on the Norwegian continental shelf.

Transport of CO_2 by pipelines has been a commercial activity since the 1970s, and thousands of kilometres of CO_2 pipelines are currently in operation. Ship transport of commercial deliveries of CO_2 in Northern European began in the 1980s. Road transport of CO_2 by lorries and rail has been a commercial industry since the 1950s. In conclusion, components related to carbon capture technologies are ready.

The CO2 capture pilot plant at the Fortum Oslo Varme plant, showing the absorber and desorber towers. (Photo: Fortum Oslo Varme)

[1] The Global CCS Institute (2019). Annual Report. https://www.globalccsinstitute.com/

[2] Shell Cansolv, Mitsubishi Heavy Industries, Fluor, Aker Solutions, Siemens, have all delivered commercially licensed CO_2 capture solutions. Some project developers are applying open-source, non-licensed technology solutions.

[3] Climeworks, Carbon Engineering, Global Thermostat, CO_2 Solutions, Lanzatech, Carbon Clean Solutions and many more.

Today's situation, trends and potential for carbon capture, storage and utilisation in cities

Cities are striving for zero CO_2 emissions. They own direct CO_2 emissions from waste-to-energy (WtE) plants and other combined heat and power (CHP) plants. Carbon capture and storage complements limitations of feasibility, scale, costs and time associated with other climate action tools. While CCS is sometimes considered as an expensive end-of-pipe solution, it is the cheapest option for deep decarbonisation for several industrial sectors at current commodity prices[1].

CO_2 emissions from large point sources in cities can virtually be eliminated by installation of CC and then permanent storage of the captured CO_2. Cities can also contribute to lowering emissions and accelerate implementation of CO_2 capture outside the city boundaries, by setting strong procurement requirements to materials with low or zero embedded emissions. Prime examples of this are cement and steel produced with CCS or other very low or negative emissions solutions.

Industry and "negative emissions"

Up to 19 per cent of Europe's total CO_2 emissions are industrial, coming mostly from cement, chemical and steel production[2]. Even when comprehensive energy efficient solutions are implemented, and all energy supply is renewable, there will still be CO_2 emissions from the production process itself: cement is produced from calcium carbonate ($CaCO_3$) – a process which separates out calcium oxide and leaves CO_2 as a residual by-product. Steel is produced by adding carbon, which removes the oxygen in the ore by creating CO_2. It should be noted that steel can also be produced by replacing fossil inputs with renewable hydrogen. However, this would require enormous increases in availability of renewable electricity to produce the hydrogen.

Removal of CO_2 from the atmosphere, referred to here as 'negative emissions', can be achieved by installing CCS on sources that emit biogenic CO_2. Many cities have major sources of biogenic CO_2 emissions in their heat and power production as well as waste treatment and incineration. These sectors make up together about 30 per cent of biogenic CO_2 emissions in the Nordic countries. This level and distribution of existing biomass use, combined with the storage potential in the North Sea, create ideal conditions to form a partnership that could lead the way in the development of BECCS as a negative emissions solution.

Amager Bakke, the waste-to-energy plant in the city of Copenhagen (Photo: Amager Resource Center/Ehrhorn/Hummerston)

[1] Arnout de Pee, Dickon Pinner, Occo Roelofsen, Ken Somers, Eveline Speelman, and Maaike Witteveen. June 2018. Decarbonization of industrial sectors: The next frontier. Published online by McKinsey&Company. https://www.mckinsey.com/industries/oil-and-gas/our-insights/decarbonization-of-industrial-sectors-the-next-frontier

[2] European Environment Agency. 2017. "GHG emissions by aggregated sector". Database. Available: https://www.eea.europa.eu/data-and-maps/daviz/ghg-emissions-by-aggregated-sector-1#tab-dashboard-02

An Electric Vehicle Charging Station (Photo: Wikicommons)

Electrification of road transport may lead to negative emissions

Cities own, operate and lease fleets of vehicles. The aggregate CO_2 emissions from these can be significant. Several technology strategies are available to reduce these emissions. One technology solution is already widely implemented, namely, use of biomethane as fuel in transport. Many cities already produce biomethane from sorted organic waste and municipal sewage treatment. The biomethaneis then used as a fuel substitute for diesel, leading to low-emission transport services for municipal buses and other municipal vehicles. However, the scope of this strategy is limited by availability of organic wastes in the various treatment systems. In Northern European cities, this resource is in general fully utilised. In other words, further emissions reductions in cities will need to employ additional solutions for the cities' own transport.

Electrified transport is gaining wider acceptance for personal vehicles. At the same time there has been made even more progress in electrifying municipal bus transport, which is poised to outcompete biomethane buses based on the lower (and still falling) total life-cycle cost of ownership for electric buses. This trend is anticipated to spread to other heavy vehicles operated by municipalities. Consequently, cities will likely have a surplus of biomethane in the future. A potential alternative use can be to supply existing (or new) electric power and district heating production.And where such facilities have CCS installed, this will make the use of biomethane better than CO_2 neutral.

Utilisation of CO_2 may be a part of the solution

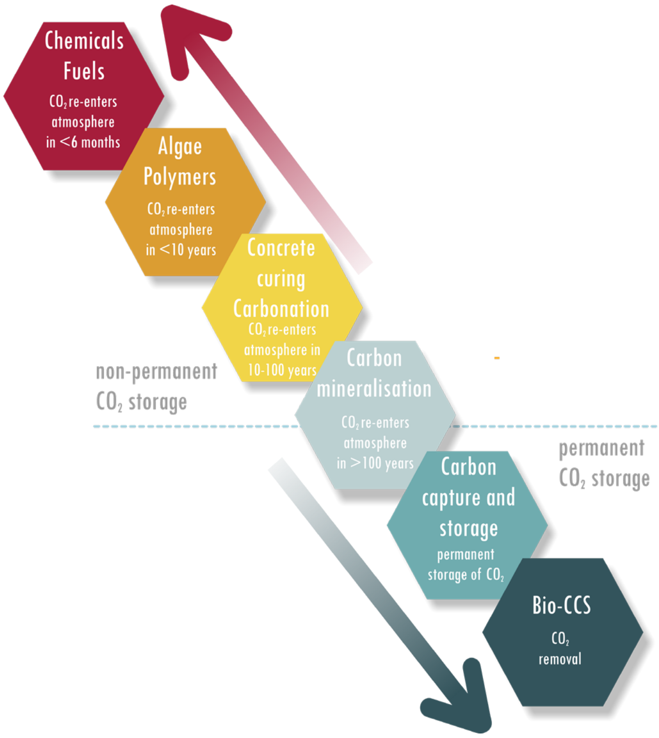
While CCS can provide permanent emissions reductions, it is capital-intensive and requires affordable access to geological storage. The next best option to CCS can, in isolated cases, be carbon capture and usage (CCU). Under specified circumstances CCU can provide commercially viable emissions reductions benefits.

For most CCU applications, notably synthetic hydrocarbons, the input CO_2 from the capture facility is re-released weeks or months after it has been captured. For these CCU cases, a project must satisfy the following requirements:

1. The captured CO_2 that is used in the CCU application must be biogenic or from direct air capture (DAC).

2. If hydrogen is required for the CCU process, it must be produced using renewable electricity.

The most relevant case for CCU with early re-release of the captured CO_2 appears to be for producing synthetic aviation fuels. This is because this sector will likely be the most difficult to directly decarbonise. A few CCU solutions mineralize the CO_2 in a permanent, solid form. These cases could lessen the two requirements above, depending on the overall life cycle accounting of the captured and used CO_2.



Unlike CCS and bio-CCS, some CCU products such as fuels or chemicals do not provide long-term storage of CO2. This retention time of the carbon in the product, along with other factors, needs to be taken into account during the assessment of the climate change mitigation value of a given CCU or CCS technology (diagram adapted from ZEP, 2017).

Barriers to carbon capture, storage and utilisation in cities

As earlier mentioned, carbon capture, storage consist of three main components. The total chain of CCS starts with the capture plant operator, which sends the captured CO_2 to the transport system operator. The last link is the CO_2 storage site operator, which receives the CO_2 from the transport operator. Transfer of ownership or responsibility from one link in the chain to the next is specifically regulated by law in many jurisdictions. In those that lack this, it is a barrier to CCS project development.

In the European Union (EU), this has mostly been covered by fit-for-purpose directives. The key issues regarding the transferral process along the CCS chain relates to liability in the event of leakages. According to the EU Emissions Trading System (ETS), any leakages must be accounted for in reporting and for some cases compensation and prescribed repairs. Leakage risks to site employees and third parties must also be evaluated and mitigated according to regulations regarding public and worker safety.

Barriers related to installation and construction

There are no immediate technical barriers to CCS, as evidenced by the 19 operating full-scale projects world-wide. The main barrier to CCS is cost, which for most situations is still considerably higher than any CO2 tax or emissions fee. Therefore, the commercial motivation is low or absent in the isolated perspective of choosing the least-cost alternative, which for many large point sources, is to continue emitting. But the technology solutions are improving, and new innovations are rolling out that promise to make CCS more cost-effective. So, in the near term the main barrier to CCS is recovering its costs.

Other barriers are related to specific CCS projects at specific sites. There must be physical space for the new capture equipment, which can often have a similar or larger area footprint than the plant from which they capture CO_2. For installations already in tight spaces, this presents new challenges. More compact capture systems are being developed that may help.

The captured CO_2 must be transported to the storage site. This entails both pipelines and ships. The risk issues of pipeline operations are site specific, according to the terrain and third parties near the pipeline route. Regulatory processes are in place in most jurisdictions to handle this, but for some potential projects, the high level of residual pipeline risk may be a showstopper. Enhanced pipeline safety solutions may be required to overcome this.

Specific EU regulatory barriers

For CO_2 transport across national borders and storage under the seabed, the London Protocol is recognised as the governing international agreement. The London Protocol Parties at their annual meeting (LC41/LP14) in October 2019 approved a Resolution for Provisional Application of the 2009 CCS Export Amendmen. This Provisional Application allows countries to agree to exportand receive CO_2 foroffshore geological storage. This removes a previous barrierto CO_2 storage hosted by a different country than the location of the CO_2 capture plant. In EU-regulated states, the following official laws and directives apply:

- EU ETS Directive (2003/87/EC) & its Monitoring and Reporting Guidelines (2010/345/EU)
- Liability Directive (2004/35/EC)
- CCS Directive (2009/31/EC)

The key starting factor for a storage project is the local and regional subsurface geology, which must be suitable for CO_2 storage over long periods with high security. Some EU member states have decided (as is their prerogative) to impose a moratorium on CO_2 storage in their jurisdiction on land. EU member states with continental shelves (offshore) may still allow storage under appropriate conditions there. The CCS Directive (2009/31/EC) is the main regulating document for EU member states in their CO_2 storage site approval and oversight.

Barriers for utilisation

The situation with potential barriers for carbon capture and utilisation projects overlaps with CCS in the issues described above for their CC and transport components: available space and risk management of potential system/pipeline/lorry leakage events. The issue of barriers to deep geological storage is not relevant for CCU. Regarding the commercial barriers to CCU, because this technology solution does not currently aim to directly reduce emissions, this is not a factor in their commercial evaluation. However, the potential to monetize the captured CO2 as part of the CCU product or service, allows for some income to recover costs of the CCU infrastructure. This must beconsidered on a case-by-case, site and market-specific basis, as these will determine whether a specific CCU project will provide sufficient return for its owners and investors. In other words, the main barrier for a specific CCU project may be its too-low inherent rate of return on invested capital.

Also, for the different utilisation technologies there may exist barriers related to the specific product, that relate to construction, commercialization and the use of the product. E.g. in urban areas it may be difficult to produce synthetic fuels due to size and local risk.

Carbon Capture in cities CO_2 inventories

The number one incentive for cities to work with carbon capture is the potential for CO_2 reductions, and it is therefore highly important that the technology can be included in cities CO_2 inventories. Due to carbon capture and utilisation being more complex in the accounting this section explores CCS in cities CO_2 inventories.

During the last decades the city inventory and accounting methods have varied significantly. To allow for more credible and meaningful reporting, greater consistency in GHG accounting is required. The Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) responds to this challenge and offers a robust framework that builds on existing methodologies for calculating and reporting city-wide GHG emissions. The GPC is the most commonly used reporting system for cities, and all reporting is done on a voluntary basis. World Resources Institute, C40 Cities Climate Leadership Group and Local Governments for Sustainability (ICLEI) have partnered and created the GPC.

When preparing the inventory, the GHG emissions from city activities shall be classified into six main sectors: 1) Stationary energy, 2) Transportation, 3) Waste, 4) Industrial processes and product use (IPPU), 5) Agriculture, forestry, and other land use (AFOLU) and 6) Any other emissions occurring outside the geographic boundary as a result of city activities.

Carbon capture and storage in the GPC accounting guidance

According to the GPC guidance the GHG emissions should be reported for each sector and sub-sector. Emissions sequestered by carbon capture and storage systems shall be excluded from emission totals for applicable sectors. However, cities may report these separately.

The guidance doesn´t indicate how the separate reporting shall be done. The reporting of CCS is important in the inventory and accounting as it supports the 5 principles which the GPC is built on, especially completeness and accuracy (three others; consistency, transparency and relevance). The GHG Protocol has started preparing guidance on reporting requirements for CO_2 storage, and it is recommended that the guidance should be used by GPC and the cities when it is finalized.

Through the United Nations Framework Convention on Climate Change (UNFCCC) it is possible to have CCS methodologies, for instance under the United Nations (UN) approved carbon market, Clean Development Mechanism (CDM), but it will require a specific methodology for CCS is being developed and approved.

In the GPC there are no requirements to specific methodologies to be used, and therefore dependent on the type of CCS, a methodology for calculation of stored CO_2 can be developed. It is recommended to follow UNFCCC guidance of how to develop methodologies.

View of Düsseldorf, located in the Ruhr-Westphalia Industrial Region in Germany (Photo: Daniela De Lorenzo)

Production of steel inside the Salzgitter steel plant, Germany (Photo: Daniela De Lorenzo)

CCS installations are often larger scale and can involve several point sources and cities' attentionshould therefore be given to a potential risk for inaccurate counting.

Biogenic carbon capture and storage in the GPC accounting

According to the 2006 IPCC Guidelines for National Greenhouse Gases Inventories it is allowed to recognise negative emissions from BECCS. Through both the Australian Greenhouse and Energy Reporting Act (NGER) and the Canada GHG Reporting Programme (Canada GHGRP) it is possible to report negative emission from the application of BECCS.

Through the UNFCCC it is possible to have BECCS methodologies for instance under the UN approved carbon market, CDM, but it will require a specific methodology for BECCS, which is still being developed and approved. The reporting of BECCS would be similar to CCS, except that there would also be removals from the atmosphere associated with it. Both CO_2 from removals and storage should be separately reported.

The GHG Protocol has attention to BECCS and will in a forthcoming guidance elaborate on reporting requirements for carbon removals as well as storage. It is recommended that the guidance should be used by GPC and the cities.

What does this mean for cities?

The advantage of GPC is that many cities have already used the manuals and guidelines in the reporting, and city reporting can also feed into the national reporting. The GPC will have an inventory and reporting at the same high standard as under the Paris Agreement. Both CCS and BECCS will contribute to GHG emission reductions and all reporting will comply with the GPC principles.

- For CCS the CO_2 permanently stored should be reported separately.

- For BECCS the CO_2 from removals and storage should be reported separately.

The GHG Protocol will soon develop a guidance and standardson how companies/organizations should a ccount for CO_2 removals and storage in GHG inventories, which will address CCS and BECCS.

Business models for CCS and CCU from a city's perspective

Carbon capture and storage and carbon capture utilisation are two technology pathways that share the same starting point. Thesole aim of CCS is to avoid CO_2 from entering the atmosphere by storing it in the deep underground or in stabile, non-toxic minerals. CCU technologies seek to reuse the captured CO_2 as a product in itself or as a feedstock for new products.

It is this difference in final destination of the CO_2 that largely defines how cities can recover their costs related to new CCS or CCU facilities, both when it comes to investments and operational (CAPEX and OPEX).

From a cost perspective, both pathways must deal with comparatively high CC costs. These costs range from just 20 Euros per tonne of CO_2 to hundreds of Euros depending on the CO_2 source. Initial capital investments into transport infrastructures and storage hubs appear significant. However, their overall cost per tonne of CO_2 over multiple years of use are predicted to approach the ten Euros per tonne range or lower[1].

Utilisation can have a business appeal

The business appeal of CCU lies in the attempt to give value to, by selling what is considered a mere waste product that should otherwise be disposed. Captured CO_2 can be utilised to make a range of potential products. As the vast majority of CCU products re-emit the CO_2 at their end of life, their climate benefit lies primarily in the assumed displacement of fossil CO_2 sources.

The CCU solution with the highest potential climate benefit is using CO_2 as a reactant to produce other materials, and in which the CO_2 is converted into a by-product mineral that is stable and non-toxic. One example of this is identified for converting the mineral anorthosite to aluminium oxide (Al_2O_3, also referred to as alumina). This is the last step before the production of metallic aluminium. The mineral by-product of the CCU-enhanced alumina production is calcium carbonate ($CaCO_3$).

One CCU solution currently attracting increased interest is using CO_2 as the source of carbon to produce synthetic hydrocarbons. This technology has been evaluated by numerous investigators. A common observation is that it has a narrow set of conditions in which it can produce some limited climate benefits. However, if done sub-optimally, it risks actually increasing CO_2 emissions compared to using fossil fuels. If done optimally, synthetic fuel production will require significant new capacity of renewable electricity to run the process. The cost structure for a synthetic hydrocarbons project based on captured CO_2 is distinct. Here the highest cost item is for the electricity required to produce the other main ingredient for synthetic fuels, namely hydrogen produced by electrolysis. Hence this technology concept is often called e-fuels (short for electrofuels).

For both of these CCU example cases, it appears theoretically possible for cities that own and operate CO_2 capture facilities to sell their CO_2 at production cost to thirdparty developers of these two types of CCU solutions.

Amager Bakke seen from in the city center of Copenhagen (Photo: Amager Resource Center/Dragør Luftfoto)

Carbon capture and storage is purely a climate action

For CCS, the biggest challenge is to fairly and practically recover the total costs, since no income is possible from selling the captured CO_2. With no apparent product or servicebeyond climate action, the cost of the process is best transferred to the outputs of the respective industry, and therefore borne by the consumer or service user. High-level analysis shows that it is plausible to spread the incremental costs of a CCS implementation across the full range of users or customers for a number of cases for CCS. For a waste-to-energy installation, district combined power and heating plant, cement plant or steel plant, the CCS add-on will result in modest cost increases for services or for the total finished project using the low-emissions cement or steel, e.g. in using CCS-enhanced cement in a new commercial building.

From a city point of view, the business case perspective is indirect rather than direct. By signalling they are willing to pay slightly more, and by mandating zero or near-zero carbon building materials, cities can use their immense consumer and procurement power to create a business case for materials manufacturers and for construction companies that use these materials.

[1] Zero Emissions Platform (2011). The costs of CO_2 transport and storage. http://www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html

Indirect emissions from cities' consumption

Cities not only own and operate large point sources of CO_2 emissions that serve their citizens, they are responsible for large indirect emissions through purchases of materials forconstruction projects and transport services. Municipal governments are often the most active purchaser of new buildings and infrastructure in a city.

Proactive procurement for cities

Municipalities are some of the cement, steel and petrochemical factories' most important customers, particularly for cement and steel for city buildings and transport infrastructure. As such, municipalities can reduce their so-called scope 3 emissions by mandating procurement priority to low-embedded-emissions products and materials.

Excavation site along one of the Amsterdam canal water (Photo: Flickr/ Fons Heijnsbroek)

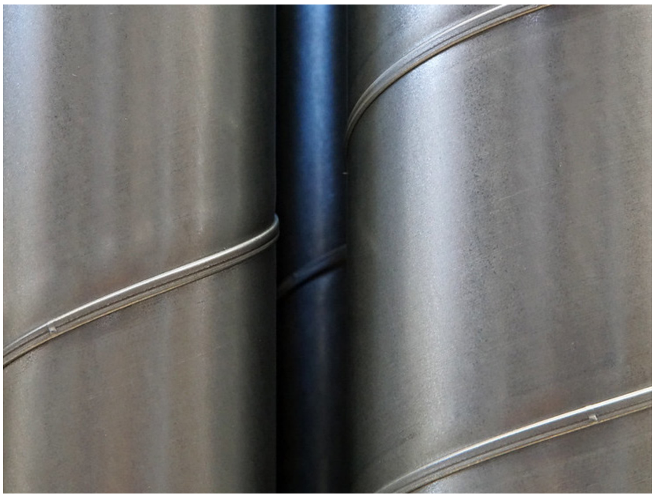
Several existing certification regimes already promote suppliers of products and solutions with improved sustainability and environmental profiles. Common for these are that they are voluntary, and they use third party verification specialists to certify projects. The building and construction industries currently use the BREEAM, LEED and CEEQUAL certification programmes for rating the sustainability of complete, integrated buildings. In addition, there are nume rous products and single-parameter certification systems that may be relevant[1].

These are designed to promote defined sustainability principals, measured according to the life cycles of all embedded components, construction methods used, operational needs of energy, and other materials for the structures. The third-party certification supplier assesses evidence that a given structure should receive a rated or classified grade according to inter alia embedded greenhouse gas content of all the used material and components. Municipalities can then specify the necessary grade certificate that reflects use of low-emissions cement, steel, structural wood, etc., some of which can be produced with a CCS solution. In this way, a market can be created that allows higher-priced cement, steel, sustainably harvested lumber, etc. to be procured by building contractors to satisfy specifications for new municipal buildings, civil works and infrastructure.

Cases for which the CCS price is already right

For cement and steel, the immediate solution to cost recovery of CCS is to reflect the levelised cost of specific CCS site implementation in the prices of their products. Under current conditions, this will make their cement or steel uncompetitive per unit of raw materials with suppliers that have not implemented CCS.

At the same time, using low-carbon steel and cement in the construction of a house would only increase the overall cost by a couple percent points. The price effect t of CCS-cement has been estimated to about 1% more for the total cost of the finished structure[2]. This despite the current estimates that CCS will effectively double the cost of producing cement. A similar analysis shows steel produced with CCS yields a comparable result[3].



Stainless Steel Produce (Photo: Flickr/ Rosmarie Voegtil)

[1] https://www.wbdg.org/resources/green-building-standards-and-certification-systems
[2] Rootzén, J.; Johnsson, F. (2016) "Managing the costs of CO2 abatement in the cement
[3] Rootzén, J.; Johnsson, F. (2016) "Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry". Energy Policy 98 pp. 459-469.

In order to provide a first market through public procurement, early movers might have to bear part of this marginal cost burden. There are several low-threshold tools to revise procurement procedures, to allow CCS-enhanced products to remain competitive. These include raised minimum standards for materials through building codes, guarantees of origin and sector-wide minimum market shares of enhanced products[4]. The common feature of these is that costs for CCS are shared along the broader value chain of producers and consumers. This is similar to the way the electrical grid is financed. All users share costs of local, incremental expansionand improvements in the grid. In this way, capacity can be effectively expanded to accommodate new users that would otherwise be unable to pay the entire, isolated cost up front of the new infrastructure that they need.

Examples of cities making moves

Currently, there is no zero-carbon concrete or steel production in Europe. However, a mix of political and market signals can go a long way to incentivise manufacturers to change their production processes. The City of Oslo, Norway, is presented here as an example. It is second largest property owner and developer. With 3,6 billion Euro planned in construction and building related investment over the next four years, the city has stated that it will set higher demands in terms of sustainability. If a group of cities makes joint statements of ambition, this is likely to bolster manufacturers' confidence in a near-future market for zero-emission cement and steel.

In the long term, one can anticipate the cost gap between low-carbon and conventional products to narrow, close and flip. This is due to cost improvements on the CCS technology side and increasing CO_2 price levels in the EU Emission Trading System (ETS), and regulatory frameworks that increasingly revoke the license to emit. Avoidance of CO_2 taxes will be part of the cost recovery and risk assessment and therefore investment decision.

Oslo Skyline (Photo: Flickr/Sigurd Rage)

4 Holmås, Heikki, Anne Katrine Birkeland, Stig Jarstein, Øystein Holm, Magnus Røsjø and Kaja Breivik Furuseth (2019). 'Hvordan gjøre CO2 -fangst og -lagring lønnsomt? -hvordan nye virkemidler kan utvikle markeder for lavkarbonprodukter'. (in Norwegian) Multiconsult. 10. april 2019 / 05. Document code: 10209499-TVF-RAP-001.

Recommendations for cities

Cities and municipalities can be at the forefront of driving investments into deploying carbon capture, transport, utilisation and storage. They can also help create the necessary market and infrastructural frameworks. By establishing themselves as drivers for clean products and infrastructural hubs for new climate technologies, cities can directly ensure that new innovations can enter the market, and increase their own attractiveness for inward, clean investments. The following recommendations are starting points for cities that want to engage with these low-carbon technologies.

Map your emissions

Begin by mapping centralised emissions sources such as power plants, industry, and waste incinerators. What is the service provided? Can it be replaced or avoided? Is the plant likely to remain active in the foreseeable future? What is the ownership structure?

The aim of the mapping process is to identify the most persistent emitters that will require CC to fulfil the city's climate target. If there are many such emitters in the region, this is a reason to cooperate with industries as well as with other municipalities.

Assess viability of carbon capture, transport and storage

In Europe, the Netherlands, the United Kingdom and Norway are all developing offshore CO_2 storage capacity with the possibility to store CO_2 from third countries. Ships and river barges can transport CO_2 from the emissions source to offshore storage sites. Cities and industrial sites that have access to port facilities are good candidates for ship and barge transport. For very large volumes, CO_2 transport via pipeline is more cost-efficient.

Assess viability of CO2 capture and use

CO_2 uses are very diverse, from so-called synthetic fuels to the mineralisation of building products. It is not simple to characterise the requirements and inputs needed. For example, if the aim is to produce synthetic fuels to replace conventional fossil fuels, projects must characterise CO_2 sources as well as the expected availability of renewable electricity. In order to assess the climate benefit, a full life-cycle analysis including the origin of the carbon/CO_2 as well all relevant CO_2 emissions should be conducted.

Get access to European funding

European Union funds are available for capture, transport, utilisation and storage. The Innovation Fund will open for proposals of projects in 2020. EU funding mechanisms under the Connecting Europe Facility can fund transport and storage infrastructure. Rotterdam is one of several recipients of EU funding that helps mature designs for shared CO_2 networks. For cities that aim to benefit from this funding, planning CO_2 projects with an international and European dimension should be a priority.

Plan strategically for future expansion

CO_2 networks can benefit CO_2 storage, CO_2 utilisation and atmospheric CO_2 removal. CO_2 infrastructure established by an initial CCS project, can also provide high purity CO_2 streamsfor piloting of utilisation technology, and further for expansion to full-scale operations as sufficient resources become available. Dialogue with other cities and regions will help map infrastructure needs and potential for expansion to relevant emitters in the area. Expanding CO_2 infrastructure capacity on an ad-hoc basis later can be significantly more expensive than adequately sizing the initial investment.

Use public procurement to establish a first market for clean products

Cities are major consumers of construction materials like steel and cement. City leaders can engage private investors through building permit approval requirements. But as major property owners and developers, they can also introduce requirements for their own construction projects.

Ambitious cities should enter a building materials procurement partnership for major public construction work. This could be established city networks like CNCA or C40. This will create an incentive among companies to become the first manufacturers of low-carbon steel and cement.

Drive consumption change through campaigns and levying

Campaigns about responsible consumption can have a far-reaching impact on shifting consumer behaviour. This can be combined with levies on unsustainable practices. One very relevant example for cities is waste management. Following the waste hierarchy of "prevent, reuse, recycle", charging a levy for e.g. non-recyclable plastic waste that needs to be incinerated, can directly be reinvested in the CO_2 capture technology necessary at the waste incinerator. this is a reason to cooperate with industries as well as with other municipalities.

EU funding opportunities for CCS and CCU projects

The European Union Emissions Trading System (EU ETS) was introduced to put a steadily decreasing cap, on the total amount of CO2 and other GHGs emitted in certain sectors of the European economy. The platform is a market for emissions allowances (European Union Allowances, EUAs). The EU ETS currently operates in 31 European countries (the EU 28 plus Iceland, Liechtenstein and Norway).

Introduced in 2003 and revised last in 2017, the EU ETS covers approximately 45 per cent of the EU's total greenhouse gas (GHG) emissions. The EU ETS now covers about 14.000 installations across Europe, including more than 11.000 power stations and manufacturing facilities.

The EU ETS results so far

Since 2005, total emissions covered by the EU ETS have fallen by around 700 million tonnes CO_2 – equivalent to the emissions of around 86 million passenger cars (approximately 30 per cent of the total number of cars in circulation in the EU) for one year. Whilst this may sound like success, the EU ETS has failed to deliver the scale and pace of emissions reductions needed to deliver on EU's climate objectives, particularly since the ratification of the Paris Agreement.

Over the past decade, the EU ETS has been characterised by a low carbon price primarily resulting from a surplus in the availability of emissions allowances. This kept the EU ETS price from 2012 to 2018 at 9 Euros or lower. The EU ETS price started rising in Q4 2018, and has stabilised at around 25 Euros. While this has had some effects on general output from selected industry sectors, it is still too low to motivate investments in CCS. However, it is widely expected that the recent reforms to the EU ETS will lead to a steadily increasing CO2 price over the coming decade.

Recycling EU ETS revenues into climate mitigation investments

A key facet of the EU ETS in its early stages was the New Entrant Reserve fund (NER300), because 300 million ETS allowances were set aside and auctioned off, to create a fund for innovative renewable energy and CCS projects. The NER300 was notoriously difficult to access and, as a result, it did not get a single CCS project started. It was widely considered a failure.

Following reforms to the ETS ahead of Phase 4 (2021 – 2030) the NER300 was replaced with a new "Innovation Fund1" and redesigned with the aim of making the funds more accessible and impactful. The Innovation Fund remains available to CCS and innovative renewable energy projects alongside newly included small scale and industry projects. A Delegated Act providing the modalities of the Innovation Fund was adopted by the European Parliament and the European Council in June 2019. The Commission hopes to open a first call in 2020 with a view to the first disbursements being made in 2021/22.

EU funding opportunities for CCS

The table below provides a high-level overview of the various funding opportunities for CCS and CCU projects at the EU-level. In summary, the EU is able to provide funding (grants) and other financial products (loans, equity, guarantees, etc.) across most parts of the CCS and CCU chain, and at various different scales – from project development through to capital investment and operational penditure.

The European Parliament in Strasbourg (Photo: European Parliament)

Funding Programme	Summary
Innovation Fund (Responsible DG: CLIMA)	The ETS Innovation Fund is the main EU funding stream specifically available to support CCS projects. It can provide funding to both small and large-scale projects in different industrial sectors, including CO_2 transport and storage infrastructure projects. Up to 60 per cent of eligible costs can be covered with 40 per cent of funding available as pre-financing (unrelated to actual volumes of CO_2 stored). This so-called “Project Development Assistance” could potentially fund pre-FEED and FEED studies for a city-led CCS project. The Innovation Fund can cover both CAPEX and OPEX.
Connecting Europe Facility (CEF)	The Connecting Europe Facility (CEF) exists to support investment in cross-border energy and transport projects. Projects need to be first granted Project of Common Interest (PCI) status before an application to CEF can be made. Cross-border CO2 pipelines are considered to be a priority area (although cross-border impact needs to be demonstrated as opposed to the pipeline physically crossing borders) and up to 300 million Euros can be awarded to an individual project. Grants cover 50-75 per cent of eligible costs and, again, pre-FEED funding can be accessed to support feasibility and project development studies. The European Investment Bank can also offer various debt products to PCI projects.
Horizon Europe (Responsible DG: Research)	Horizon Europe is the successor to Horizon 2020 and has been agreed as part of the next Multiannual Financial Framework (EU Budget), beginning in 2021. Horizon Europe will take a ‘mission oriented’ approach to R&D challenges, including a mission on ‘Climate Neutral and Smart Cities’. Overall, Horizon Europe will make 100 billion Euros of RD&I funding available, and funding for both CCS and CCU projects will be made available as part of this.
European Regional Development Fund (Responsible DG: REGIO)	The ERDF aims to strengthen economic and social cohesion in the European Union by correcting imbalances between its regions. It focuses its investments on several key priority areas, two of which are ‘innovation and research’ and ‘the low carbon economy’. In more developed regions, at least 20 per cent of ERDF funds nationally must be spent on the low-carbon economy. Whilst the ERDF and Cohesion Fund Regulation specifically excludes funding for emissions reductions from sectors listed in Annex 1 of the ETS Directive, there is potential that CCS and CCU projects could still qualify if they contribute towards other areas such as the circular economy or can be categorised as research, development and innovation projects.
Cohesion Fund (Responsible DG: REGIO)	The Cohesion Fund is aimed at Member States whose Gross National Income (GNI) per inhabitant is less than 90 per cent of the EU average. It aims to reduce economic and social disparities and to promote sustainable development. The Cohesion Fund allocates a total of 63.4 billion Euros to activities under these categories: • Trans-European transport networks, notably priority projects of European interest as identified by the EU. The Cohesion Fund will support infrastructure projects under the Connecting Europe Facility; • Environment: here, the Cohesion Fund can also support projects related to energy or transport, as long as they clearly benefit the environment in terms of energy efficiency, use of renewable energy, developing rail transport, supporting intermodality, strengthening public transport, etc. As for the ERDF, whilst the Regulation specifically excludes funding for emissions reductions from sectors listed in Annex 1 of the ETS Directive, there is potential that CCS and CCU projects could still qualify if they contribute towards other areas such as the circular economy or can be categorised as research, development and innovation projects.
European Fund for Strategic Investments (EFSI) (Implemented and co-sponsored by the EIB)	Managed by the European Investment Bank and the Commission, EFSI comprises a 33.5 billion Euros programme made up of EIB capital and a guarantee from the EU Budget. It is able to provide a range of financial products (including loans, equity, guarantees and advisory services) to “strategic infrastructure” and renewable energy projects, including many types of CCS project. The principal aim of EFSI is to leverage an additional 500 billion Euros of private sector investment within the EU. According to the EIB website, Local authorities, public sector companies or other government-related entities may benefit from project loans or loans to finance research and innovation. Smaller projects may also be financed through EIB’s intermediated lending provided by partner institutions.

Background analysis for the report

The background analysis of this report can be found at https://carbonneutralcities.org/initiatives/innovation-fund/

Note 1 - City profile of the five cities and their ongoing work with CCSU
The first note creates an overview of the cities participating and their climate goals. All the cities are ambitious in their goals and approaches, this include the wish to look further into what carbon capture storage and utilisation offers as a solution for deep carbon emission reductions.

Note 2 – Measures to Encourage CCSU in cities
Cities can implement multiple measures to encourage CCSU both direct by investing in infrastructure and indirectly by public procurement. This note provides an overview of these measures and identifies certain aspects that can be important to consider regarding these measures, such as potential double accounting of reductions.

Note 3 – Barriers to CCSU from a city perspective
Some of the obstacles for cities to implement solutions included in the project are discovered based on experiences from the participating cities. Areas where adjustment or support is needed to accelerate the technologies are pointed out.

Note 4 – Carbon capture storage in city-based carbon accounting
Accounting methods for CCS and BECCS is reviewed, and some of the issues in connection to it on a city level are identified. The potential to use it as a tool for deep emissions cuts are included and data collection principles are discussed.

Note 5 – The role of CCS in transforming cities
In this note the importance of carbon capture and storage is underlined in the context of the Paris agreement and the IPCC. Both direct and indirect emissions from the city are explained further and the different sectors within the city are problematized. The role of carbon capture is made clear with explanations of how they combine with current technologies and what conditions must be met for it to be a viable solution. Lastly an overview of the participating cities' work with and potentials for carbon capture is given.

Note 6 – How to address emissions from industry from a city perspective
Industry's in the cities account for a large percentage of emissions and solutions for how this problem can be solved is needed. It gives a comprehensive walk through of these emissions and the challenges the industries face. In some industry sectors introducing renewable energy is not enough and the role and importance of carbon capture within the sector is underlined.

Note 7 – Barriers to transport and storage of CO_2 within the EU
Barriers to transport and storage are mostly legislative and this note identifies the different legislations. It focuses on the legislations that are relevant for the cities participating in this project. The changes that are needed to make transportation of CO_2 less problematic are discussed, this includes barriers that are not legislation but mainly lack of incentive.

Note 8 – Carbon Capture in the EU ETS
The connection between the carbon cap-and-trade system in the European Union (Emissions Trading System, ETS) and how carbon capture is accounted for in the system are described. The EU ETS is criticized on its inefficiency up until now in promoting carbon capture as a solution to the climate crisis but is simultaneous seen as future opportunity for funding solution and create incentive.

Note 9a – Potential business models for CCS and CCU
Different strategies on funding projects and possible ways to create financial incentives are described. The possibilities and challenges of these operations are discussed with the purpose of creating perspectives on the different solutions.

Note 9b – EU funding opportunities for CCS and CCU
European Union will play a significant role in creating the incentive and development for carbon capture. In this note the different funding opportunities are reviewed of what technologies the different schemes will fund.

Note 10 – Recommendations for cities
Multiple recommendations for the cities are developed in relation to carbon capture. They range from seeking funding to use public procurement as a tool to incentivise industry and the public. The importance of all these recommendations are underlined and their benefits are made clear.

Report: Screening of carbon capture technologies
A comprehensive screening gives an overview of the different technologies related to carbon capture, it assesses their potential, their downsides and their technological readiness level. It describes some of the existing projects around the world and the potential for using existing infrastructure in the North Sea to sequester CO2.