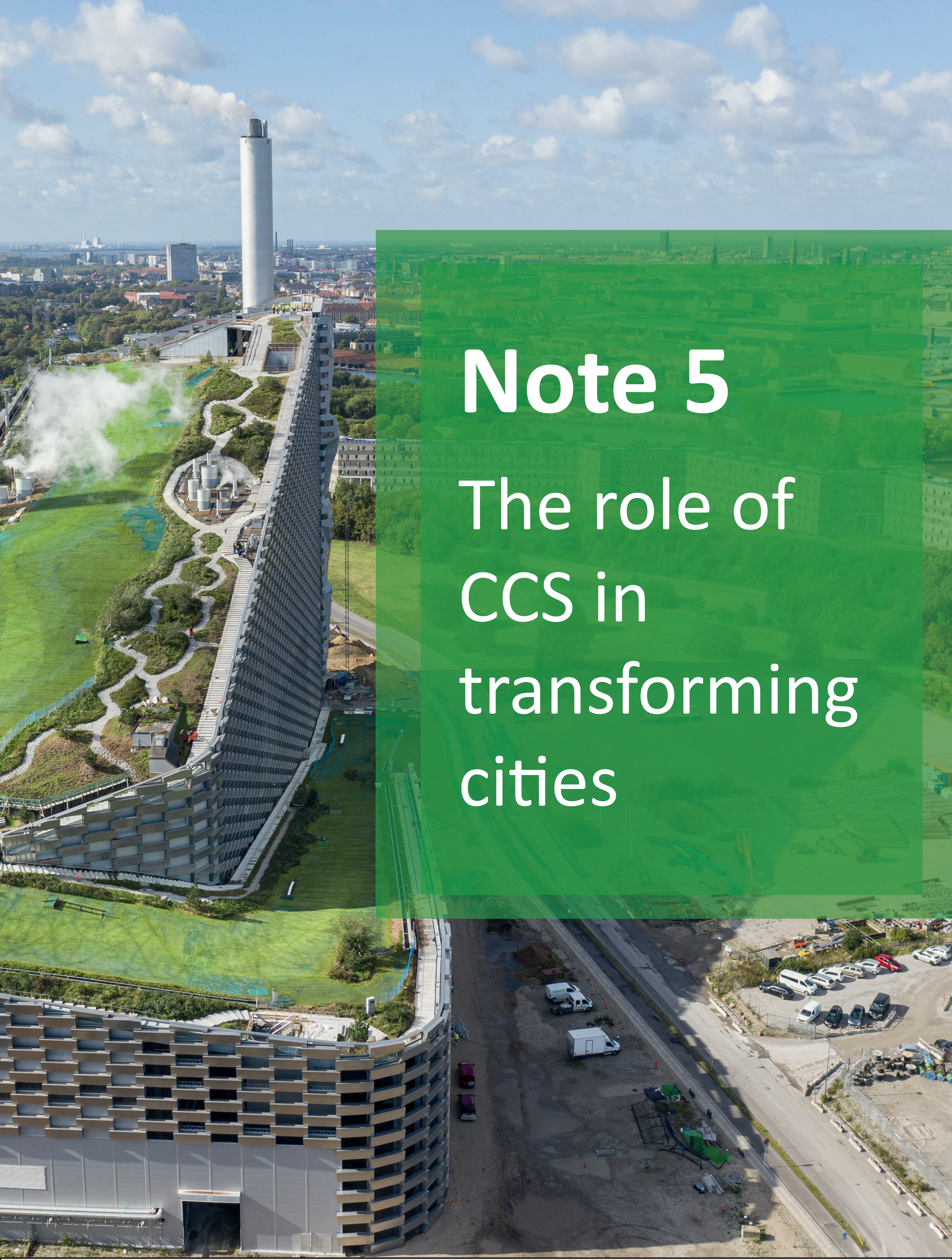

Note 5

The role of CCS in transforming cities

CNCA

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The role of CCS in transforming cities

1.0 Summary

Carbon capture and storage (CCS) is necessary in almost all scenarios considered by the UN Intergovernmental Panel on Climate Change (IPCC) that can limit warming of the atmosphere to no more than 2°C. The vast majority of scenarios satisfying this limit also include solutions where CO_2 is subtracted from the atmosphere (IPCC 2014: 151). Without the immediate, large-scale deployment of CCS technologies, the Paris climate targets will not be reached.

Cities are striving to become fossil-free with zero-emissions. And in all realistic transformation scenarios CCS is needed to achieve sufficient emission reductions. In particular, cities own direct emissions from waste-to-energy (WtE) plants and other combined heat and power (CHP) plants, which are avoided if CO_2 capture plants are installed and the CO_2 is permanently stored. Cities can also contribute to lowering emissions and accelerating implementation of CO_2 capture outside the city limits by demanding materials with low or zero embedded emissions in e.g. construction of buildings and infrastructure. The purpose of this note is to show the potential of CCS as a climate mitigation technology in five cities – Amsterdam, Helsinki, Copenhagen, Oslo and Stockholm.

Bio-CCS includes capture of CO_2 from energy production in e.g. CHP plants, process industries like cement and steel production (at facilities where biomass is used in the production process) and waste incineration. Both Stockholm and Helsinki have large point source emissions of biogenic CO2. These are fuelled by their significant domestic quantities of biomass. Even though Denmark lacks the large forested areas found in Sweden and Finland, Copenhagen produces some of its electricity and much of its district heating from biomass from straw, biogas, imported wood pellets and waste. All cities have waste-incineration plants where part of the emissions are biogenic.

As CCS will be needed in any case to reduce process CO_2 emissions, e.g. calcination of limestone in cement production, combining it with biomass used for process heat allows for a cost-effective implementation of bio-CCS. In addition to replacing fossil fuels and reducing emissions, sustainable biomass use in an industry with CCS results in carbon-negative products, i.e. products that lead to less CO_2 in the atmosphere than would otherwise be the case. It is therefore the only carbon dioxide removal approach with a marketable outcome. Such carbon-negative products (e.g. carbon-negative steel and concrete), have an existing value for society and an added value for the climate. Industrial sites already need CCS, so by complementing with biomass use, costs for achieving negative emissions are lowered. Hence, bio-CCS projects in the cities could provide a model of using both biomass and geological storage of CO_2 cost-effectively to its highest emissions mitigation potential (Serdoner 2018: 8).

These five cities are in an excellent position to play a key role in the development of CCS infrastructure (Johnson et al. 2017). Norway, Denmark and the Netherlands are well suited to develop a large-scale infrastructure for transport and geological storage of CO_2. Therefore, cooperation between these cities and countries on the development of CCS infrastructure needs to be promoted financially and politically.

2.0 Introduction

Global emissions rose by 2.7 per cent in 2018, resulting in 37.1 billion tonnes of CO_2 released in the atmosphere. In the USA, the average annual CO_2 emissions per person is 20 tonnes. In Europe, 4.45 billion tonnes of CO_2 are released every year, with the average European adding 24 kg of CO_2 into the atmosphere every day (Eurostat 2017).

CO2 emissions come from many different sources. From the food we eat to the homes we live in, almost every aspect of our lives includes emitting greenhouse gases to the atmosphere.

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

Of the three remaining sectors, which are lacking access to measures that would set them on a path towards zero emissions, industry is the largest sector. It is also the most crucial one, since it produces goods and materials essential for climate action in other sectors. Particularly heavy industries that produce basic materials, such as cement, steel and chemicals, are fundamental to climate technologies such as renewable electricity, housing insulation and new modes of mobility.

For a city, some emissions are direct emissions, from sources like fossil-fuelled transport, central heating and cooling, power production, burning wood in stoves, and waste handling. However, 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, and escalators - is produced emitting CO_2.

This note looks at reducing some of cities' largest direct emissions: those from waste incineration, power production and central heating/cooling. The city's indirect emissions that stem from the industrial sector are covered in more detail in Note 6.

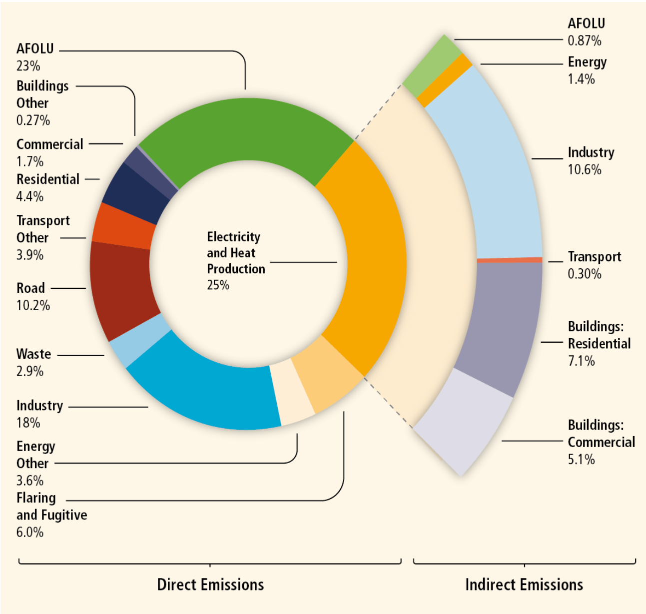

Figure 1 The source of the problem. The figure shows where the total GHG emissions in 2010 (49.5 GtCO2eq/yr) came from. The pullout from the figure distribute the CO2 emissions from electricity and heat production according to their final energy use. The figure is from the IPCC 2014 Fifth Assessment Report. Chapter 1: Figure 1.3

2.1 About the different scenarios – ambitions and solutions

Scenarios from the International Energy Agency (IEA) indicate that the potential for reduced CO_2 emissions through enhanced energy efficiency and increased renewable energy production is limited. According to the IPCC, a delay in CO_2 emission reductions can lead to dramatic consequences, and a new strategy for reducing CO_2 emissions as soon as possible is required. Carbon capture and storage (CCS) is a commercially available technology with potential for large reductions in CO_2-emissions. Therefore, the strategy for reducing global CO_2-emission must be a combination of (1) increased energy efficiency, (2) more renewable energy production, (3) a wide implementation of direct and permanent reduction of otherwise irreducible emissions by applying CCS. For a few isolated sectors, markets, geographical locations and products that need additional measures, applying Carbon Capture and Utilisation can be evaluated, since this can provide indirect emissions reduction where it displaces use of fossil fuels.

According to IPCC, the high confidence scenarios reaching atmospheric concentration levels of about 450 ppm CO_2eq by 2100 (consistent with a likely chance to keep temperature change below 2 °C relative to pre-industrial levels) include substantial cuts in anthropogenic GHG emissions by mid-century through large-scale changes in energy systems and potentially land use. But a common denominator for a large proportion of these scenarios – and the main reason[1] why IPCC in their Fifth Assessment Report (IPCC, 2014) refers to an emission reduction range of 40 to 70 per cent as opposed to the previously stated requirements of 50-85 per cent cuts – is that they rely heavily on Carbon Dioxide Removal (CDR) technologies. These are biomass-based processes that permanently store CO_2, and direct air capture facilities that also permanently store the captured CO_2. These are also referred to as negative emissions technologies.

Although there are multiple types of negative emissions technologies, one of the most promising (in terms of efficiency and scalability) is permanent geological storage of CO_2 from sustainable biomass (bio-CCS). Bio-CCS includes capture of CO_2 from energy production (BECCS), from process industries like cement and steel production (at plants where biomass is used in the production process to remove oxygen from the ore), and from waste incineration (Serdoner et al. 2018: 3).

Major sources of biogenic CO_2 emissions in the cities are heat and power production and waste treatment and incineration. 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 bio-CCS (Johnsson et. al. 2017) as a negative emissions solution.

2.1.1 Indirect industrial emissions

Up to 19 per cent of Europe's total CO_2 emissions are from industry. The bulk part of the emissions come from cement, chemical and steel production (EEA 2017). 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 that 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[2].

Note 6 takes a view on industrial emissions and describe this challenge in more detail. Furthermore, it will propose a few solutions relevant for a city's transformation in a low-emission society.

[1] Other reasons are a change of reference year from 2000 to 2010, the inclusion of all GHG emission (not only CO2) and the use of 2100 concentration levels instead of stabilization levels.

[2] It is possible to use hydrogen to reduce emissions from steel production. Sweden's Hybrit project is one example. However, one key limitation for this as a large-scale solution in the short, medium and possibly also long term is availability of hydrogen produced with low or no CO2 emissions.

2.1.2 Other indirect 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 food wastes and municipal sewage treatment. The biomethane is then used as a fuel substitute for diesel, giving emissions-neutral transport services for municipal buses and other municipal vehicles. However, the scope of this strategy is limited by the availability of organic wastes in the various treatment systems. In Northern European cities, this resource is in general fully utilized. 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. It is quietly making even more progress in electrifying municipal bus transport, which is poised to outcompete biomethane buses based on the lower (and still falling) life-cycle total 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. Where such facilities have CCS installed, this will make the use of the biomethane better than CO_2-neutral. In other words, the combination of biomethane and CCS can result in net removal of CO_2 from the atmosphere. This is further discussed in note 8 in terms of how CO_2 emissions are taxed or emissions reductions are incentivised.

For some cities, natural gas is the main source of heating in homes, offices, businesses and more. The CO_2 and other GHG emissions from combusting the natural gas and fugitive methane emissions from leaks in the natural gas distribution and end-user installations can be significant. While these systems are generally owned and operated by private interests, city governments have a voice in their oversight and in regulating and planning alternative forms of heating. Where there are clear low-emission alternatives to heating from distributed natural gas, cities should take the lead in organising their implementation.

2.1.3 Direct emissions from waste incineration in the cities

Waste incineration is the final step in waste management chains that begin with sorting and recycling. While other parts of the chain maximize the reduction and reuse of waste materials, incineration of the residual waste creates value by providing power and heat generation (Finnveden et al. 2013).Due to this added value, it is expected that a significant portion of the incineration capacity will continue to operate for many more decades. Sweden and Denmark have the highest per capita incineration capacity with about 590 kg/capita (European Commission 2017). Incineration of partially biogenic waste with CCS can provide an additional service to local communities that minimizes the plant's environmental impact. Pour et al. (2017) argue that, for each kilogram of wet municipal solid waste incinerated in a facility with CCS, one could remove 0.7 kg CO_2eq from the atmosphere. Even though waste incineration with CCS might be costly compared to CCS on larger emission point sources (Pour et al. 2017), it could deliver significant emissions reductions in a sector that holds high societal value.

2.1.4 Direct emissions from combined heat/power generation (CHP) in cities

The Nordic region uses lots of biomass for district heating, electricity generation and in industrial settings. Sweden, Finland and Denmark are at the forefront, with biomass providing 25 per cent, 26 per cent and 18 per cent of total energy supply respectively (Energimyndigheten 2017, Statistics Finland 2016). The region has existing biomass supply chains with a potential for significant CO_2 removal without any increase in biomass demand. It is estimated that Sweden alone emits 32 million tonnes of biogenic CO_2 from concentrated sources to the atmosphere every year (Schueler, V. et al. 2016). And according to Finland's official statistics, biogenic CO_2 emissions were 40 million tonnes in 2016 (Statistics Finland 2016), of which about 46per cent was from Finnish industry, heat and power sectors (Kouria et al. 2017).

Biomass is used in both large-scale district heating and in small-scale boilers – 61 per cent of all heat production in Sweden is from biomass (Energimyndigheten 2016). This type of heating can be combined with electricity production to optimize energy use (i.e. combined heat and power plants). Biomass is the fourth largest electricity source in Sweden, and new plants are in construction (Energimyndigheten 2016).

The opportunities for emission reductions at CHP plants are multiple; Energy recovery and storage, fuel switching and CCS are all means that can give significant emission reductions at plants in the cities. Finnish CHP plants used for district heating stood for 14 per cent of the total energy supply in 2017 (industrial CHP plants supply 10per cent of the total)[3]. Electricity and power production in Finland use approximately twice as much wood fuels as hard coal (Statistics Finland 2017)[4]. In Sweden 15 TWh out of 20 TWh of Sweden'selectricity production at CHP plants was fuelled by biomass (Energimyndigheten 2017)[5].

[3] Finland`s total electricity production is (2017) 65 TWh, consisting of hydro (17per cent), wind (6per cent), nuclear (25per cent), conventional power plants (4per cent) and CHP-plants 24per cent.

[4] Nevertheless; In 2018 coal use for electricity and heat in Finland was 22 TWh (Statistics Finland 2018)

[5] Sweden's electricity production (2017) is 160 TWh: hydro (41per cent), wind (11per cent), nuclear (39per cent) and CHP (9per cent).

However, Combined Heat and Power (CHP) units that burn solid biomass generally have low electric conversion efficiency due to the need to operate boilers at modest temperatures compared to fossil fuel boilers. This is because biomass has more corrosive trace components, and corrosion management at high boiler temperatures is not practical for solid biomass. Chemical looping combustion (CLC) is a promising, emerging technology that can operate at higher temperatures for solid biomass. Efforts are made in advancing the CLC technology, which is still in the pre-commercial development phase[6]. Technological advances within bio-CLC could allow for cost-efficient CO_2 capture[7], or – if the technology should prove less applicable at the plant – traditional post-combustion CO_2 capture plants could be designed to fit the power plant from the start.

Capture of CO2 from energy production in combined heat and power plants that burn biomass is an effective climate mitigation measure. In addition to replacing fossil fuels and reducing emissions, biomass use in a CHP plant with CCS results in carbon-negative products. Bio-CCS projects in the cities could provide a model of using both biomass and geological storage of CO_2 cost-effectively to its highest emissions mitigation potential (Serdoner 2018: 8).

3.0 The role of CCS in reducing emissions

One way of reducing direct CO_2 emissions is by cleaning flue gas (the exhaust) before you release it through a chimney. It is a step-wise process that results in a liquid CO_2, which is perfect for injection wells in e.g. the North Sea in Europe. The CO_2 can thus be permanently stored using the same physical concepts that applies to gas and oil fields. The method is called carbon capture and storage (CCS) and has the potential to reduce emissions by tens – up to hundreds of million tons every year.

To ensure that cities' ambitions of carbon neutrality are fulfilled, capturing CO_2 emissions from large point sources for subsequent permanent storage in deep geological formations (CCS) constitutes an essential part of the solution. CCS complements limitations of feasibility, scale, costs and time associated with other climate action tools. While CCS is sometimes considered an expensive end-of-pipe solution, it in fact is the cheapest option for deep decarbonisation for several industrial sectors at current commodity prices (de Pee et al. 2019).

Furthermore, there are 21 operating, full-scale CCS projects globally that demonstrate its technical maturity. Existing plants can in many cases retrofit carbon capture modules, allowing the owners to continue using their established core process facilities. This limits the necessary capital expenditures for industry.

CCS is a three-step process of capturing CO_2 at a point source, transporting the compressed CO_2 to a storage facility, and then injecting the CO_2 into deep underground storage locations where the CO_2 binds with pre-existing minerals and gradually mineralises again.

Transport and storage infrastructure could be developed as an open network accessible for third parties in order to reduce costs and optimize use. Through providing optionality in climate choices (CCS on industry plant, hydrogen from natural gas with CCS, Bioenergy with CCS and other options), establishing such an infrastructure can drive competition for effective low cost climate solutions in industry. Several companies are actively driving process innovation that improve the resource efficiency and thereby commerciality of carbon capture.

3.1 Capturing CO_2

Established capture technologies for industry sites include pre-, post-, and oxyfuel combustion. Generally, in industries where the CO_2 is more concentrated it is easier and cheaper to isolate and store it, depending also on the CO_2 purity in the flue gas stream.

3.2 Transporting CO_2

Following its capture, CO_2 is liquefied and transported via truck, train, barge, ship and/or pipeline. Many industrial hubs are close to major transport waterways, ships and river barges which are an efficient way of transporting CO_2 from the emissions source to offshore storage sites (IEAGHG 2012). From a CO_2 hub, pipelines are the most scalable option to link up with storage sites. Just as gas transporting ships, existing offshore natural gas pipelines can be re-used to transport CO_2, and potentially onshore pipelines if conditions are met (Brownsort et al. 2016).

3.3 Storage CO_2

Deep underground CO_2 storage takes place in porous and permeable rock layers at a depth of 1000 metres and deeper. Under EU law, these storage locations have to be covered by a thick, impermeable cap rock that seal the storage site and prevent the CO_2 from expanding upwards rather than sideways (Directive 2009/31/EC). CO_2 eventually binds with the surrounding salty water molecules and minerals, to remain trapped between impermeable layers of rock for thousands of years. The potential for CO_2 storage is greatest in offshore saline aquifers and depleted oil and gas fields. Storing CO_2 offshore is only marginally more expensive than onshore (when transport costs are excluded) and benefits from greater storage site availability, pre-existing infrastructures and potentially greater public acceptance.

[6] The project "Enabling negative CO2 emissions in the Nordic energy system through the use of Chemical-Looping Combustion of biomass (bio-CLC)" is made possible by support from Nordic Energy Research

[7] Chemical-Looping Combustion (CLC) enables low-cost capture of CO2 by creating an oxygen-free atmosphere in the combustion process by circulating an oxygen carrier between two chambers (reduction/oxidation). Because of this, CLC is expected to have at least 50 per cent lower energy penalty and cost than any other CO2 capture technology (Negative CO2 2018).

3.4 CCU: Carbon capture and usage

While CCS is acknowledged to provide maximum emissions reductions benefits, it is hindered by challenges to recover its costs and for some cases affordable access to geological storage. The next best option where it is not possible to realize a CCS project can in isolated cases be Carbon Capture and Usage (CCU). This can under special circumstances be realizable under commercial conditions and still provide some emission reductions benefits. These conditions are described here.

Because many CCU applications aim to convert CO_2 into a product, there are two central requirements to achieve climate benefits.

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 low-emissions electricity.

If these conditions are not met, the CCU application is at high risk of producing more CO_2 than if fossil fuels were used in the first place. When in doubt, only a proper life-cycle analysis can determine the overall climate benefit effect of the CCU project. In this case, there is an additional parameter of interest, namely, to what degree the CCU product displaces existing use of fossil fuels. If the analysis shows that it is a high degree, and the life-cycle analysis gives positive indications, then a CCU project might be partially justified from its emissions reductions potential. The remaining need for justification would be its commercial viability, in which there is realistic accounting for product prices, market competition, costs of new installations, new operational costs, new materials and additional energy inputs. In other words, a fit-for-purpose business case analysis is needed as is the general requirement for all major capital expenditure (CAPEX) projects.
These limitations mean that CCU will in many cases directly compete with much more efficient direct electrification of transport, heating and industrial processes.

Most CCU products re-emit the CO_2 into the atmosphere (Bruhn et. al. 2016) within weeks or months after production. This is a significant make-or-break factor in climate change mitigation, the point of which is to keep the CO_2 away from the atmosphere (Kerr 2007).The overall relative climate benefit potentials for the main classes and examples of CCS and CCU projects are illustrated below (Bellona 2018: 23).

4.0 Cities as forerunners

More than 70 per cent of Europeans live in large and small cities and the proportion is expected to rise to 80 per cent by 2050. However, cities face increasing challenges related to the environment, transport and social issues. In order to meet these challenges a multitude of solutions

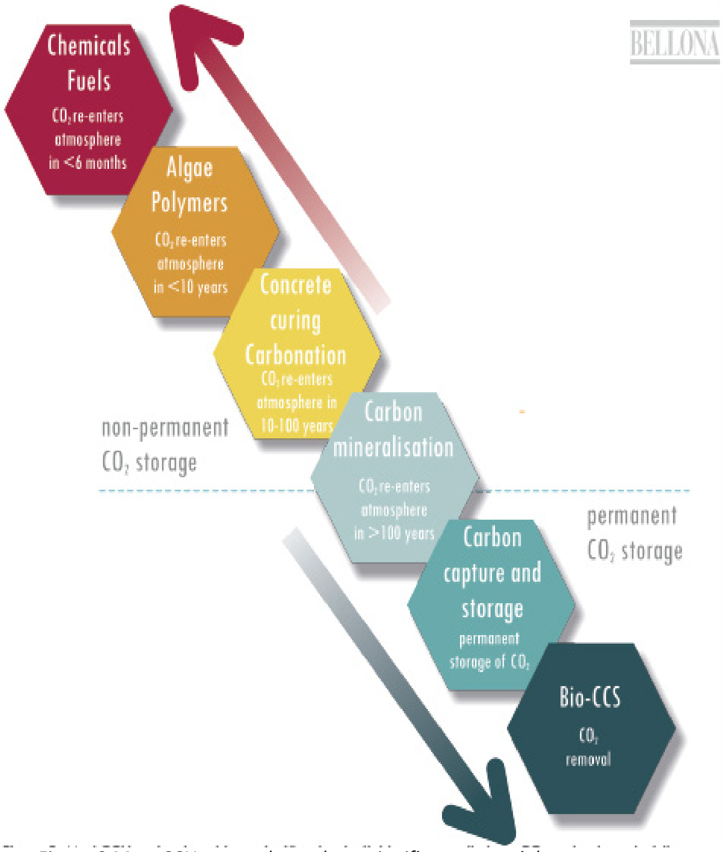

Figure 3 Most CCU routes do not have significant potential to permanently keep CO2 molecules out of the atmosphere

order to meet these challenges a multitude of solutions
must be implemented – CCS is only one such solution. But the point here is the mix of solutions – recognizing that there is no single silver bullet, and as concluded by the long term mitigation strategies, most of which include large-scale implementation of CCS.

Cities can often introduce comprehensive climate measures in a flexible and fast way. Copenhagen, Amsterdam, Helsinki, Oslo, Stockholm and other major cities can push ahead when it comes to curbing direct CO_2 emissions in the city – from e.g. waste-to-energy (WtE) incineration plants and municipal vehicles. But cities can also curb emissions by requesting and requiring low-emission materials in public procurements – like cement produced at a plant equipped with CO_2-capture.

All European cities must operate within a comprehensive European legislative framework. The advantages of this is that processes and means of cooperation developed in one city can easily be transferred to another European city. In addition, the internal EU market operating under a harmonized regulation of GHG emissions can contribute to climate friendly business models being implemented and spread more quickly. The legislative framework the cities operate under is covered in Note 7 and 8. Economic and cost-recovery models and sources of financing and funding are treated in detail in Note 9a and 9b.

4.1 Curbing direct emissions within the city

Some cities directly own large direct CO2 emission sources, such as WtE plants and CHP plants. In these situations, cities can apply existing democratic and evaluation processes and regulations to procure solutions for retrofitting CCS or CCU on their own facilities. In some cases, cities can initiate processes for investing in new-build facilities that integrate CCS or CCU from the start. But even if a city does not own facilities suitable for CCS or CCU, it still has potential and opportunity to support efficientapplication of CCS or CCU, for example through creating a local or regional market for low-carbon building materials.

Table 1 The table gives an overview of five cities' climate goals, their potential for reducing direct and indirect emissions using CCS technology, and measures taken within CCS deployment.

	Amsterdam	**Copenhagen**	**Helsinki**	**Oslo**	**Stockholm**
Indirect measures taken	From 2019 to 2025 the city will put 150 mill € into a Climate Fund				
CCS ambitions	Amsterdam owns the Port of Amsterdam, one of the partners in the ATHOS PCI infrastructure project.	One of the city's waste-to-energy plants, Amager Resource Centre, looks at options for retrofitting a CO_2 capture unit.		Full-scale capture facility at the Klemetsrud plant by 2020. Both fossil and biogenic CO_2 will be captured. The FEED study has been completed for this. Fortum Oslo Varme is awaiting a government and parliament decision by the end of 2020 to fund this project.	Pilot testing plant for CO2 capture for a CHP plant started operating in December 2019.

Direct CO_2 emissions relevant for CCS	AEB Amsterdam waste incineration plant. Nearby steel production site in Ijmuiden (TATA Steel 2019)	Electricity and heat production are the biggest sources of CO_2 emissions and represent 80 per cent of the planned reductions by 2025. The city is working to replace fossil fuel with wind, sustainable biomass, geothermal energy and solar. There is opportunity for bio-CCS. Retrofitting existing natural gas plants, or plants co-firing coal and sustainable biomass with CO_2 capture units may also be considered.	90 per cent of Helsinki`s heat demand (and cooling) is covered by CHP plants. The plants are largely based on coal and natural gas. Helen's power plants are fully owned by the city. It has an excellent opportunity to implement CO_2 capture from the start as a new biomass-based plant will be replacing the Hanasaari plant in 2024.	Oslo has two waste-to-energy plants, Klemetsrud and Haraldrud. The Haraldrud plant is fully owned and Klemetsrud 50 per cent owned by the municipality of Oslo. The Klemetsrud plant is the city's largest emission point source.	Almost 50 per cent of the measures Stockholm plans to take by 2020 are within district heating – CCS can play a significant role. Stockholm`s waste incineration produces approximately 700 000 tCO_2/y (SEPA 2019). These emissions could be captured and linked to the CCS full chain project in Norway. A pilot CO2 capture plant started operating at Värtan starting in December 2019.
Ambitions	55 per cent emission reduction in 2030 and 95 per cent in 2050 (compared to 1990)	Carbon-neutral by 2025 (compared to 2005)	Carbon neutral by 2035	Reduce direct emissions by 50 per cent[8] in 2020 and 95 per cent in 2030 (compared to 1990)	Zero emission and fossil free city by 2040.

References

City of Amsterdam. 2018. ''Policy: Urban development'' Available: https://www.amsterdam.nl/en/policy/urban-development/

Arasto, A., K. Onarheim, E. Tsupari and J. Karki. 2014. "Bio-CCS: Feasibility comparison of large scale carbon-negative solutions". *Energy Procedia* 63, pp. 6756-6769 Available: https://doi.org/10.1016/j.egypro.2014.11.711

Bellona. 2018. "An industry`s guide to climate action". Report. Available: https://network.bellona.org/content/uploads/sites/3/2018/11/Industry-Report-final.pdf

Bruhn T., Naims H. and Olfe-Kräutlein B. 2016. "Separating the debate on CO_2 utilisation from carbon capture and storage", *Environmental Science & Policy*, pp. 38-43

Chatziaras, N., C. S. Psomopoulos and N. J. Themelis. 2016. "Use of waste derived fuels in cement industry: a review", *Management of Environmental Quality: An International Journal* 27, 2, pp. 178-193, Available: http://dx.doi.org/10.1108/MEQ-01-2015-0012

City of Copenhagen. 2012. "The CPH 2025 Climate Plan – A green, smart and carbon neutral city". Available: https://kk.sites.itera.dk/apps/kk_pub2/pdf/983_jkP0ekKMyD.pdf

Dutch Government. 2019. ''Klimaatakkoord hoofdstuk Industrie'' Available: https://www.klimaatakkoord.nl/industrie/documenten/publicaties/2019/06/28/kliimaatakkoord-hoofdstuk-industrie

Energimyndigheten. 2016. "Energy balance", "Total energy supply by energy commodity from 1970, TWh", "Total coal consumption from 1983" and "Input of energy in heat production"

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

European Commission. 2017. "The role of waste-to-energy in the circular economy". COM 24. Available: http://ec.europa.eu/environment/waste/waste-to-energy.pdf

Finnveden, G., T. Ekvall, Y. Arushanyan, M. Bisaillon, G. Henriksson, U. G. Östling, M. L. Söderman, J. Sahlin, Å. Stenmarck, J. Sundberg, J. Sundqvist, Å. Svenfelt, P. Söderholm, A. Björklund, O. Eriksson, T. Forsfält and M. Guath. 2013. Policy instruments towards a sustainable waste management. Sustainability 5, 3, pp. 841-881 Available: doi:10.3390/su5030841

GlobesNewswire. 2018. "Helsinki Energy Company Helen to Go Climate Neutral". Published September 11, 2018. Available: https://www.globenewswire.com/news-release/2018/09/11/1569316/0/en/Helsinki-Energy-Company-Helen-to-Go-Climate-Neutral.html

International Panel for Climate Change (IPCC). 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, R.K. Pachauri and L.A. Meyer (eds.) Geneva: IPCC, pp. 151

Information. 2019. ''Fabrikken bag denne cement står for to procent af Danmarks samlede CO_2-udslip. Nu vil den reducere med op til 70 procent'' Available: https://www.information.dk/indland/2019/07/fabrikken-bag-cement-staar-to-procent-danmarks-samlede-co2-udslip-reducere-70-procent

International Panel for Climate Change (IPCC). 2014. "Summary for Policymakers". In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA Available: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_summary-for-policymakers.pdf

Johnsson, F., R. Skagestad, N. H. Eldrup and J. Kjarstad. 2017. Linking the Effect of Reservoir Injectivity and CO2 Transport Logistics in the Nordic Region, *Energy Procedia* 114, pp. 6860-6869 Available: https://doi.org/10.1016/j.egypro.2017.03.1824

Kerr A. R. 2007. "How Urgent is Climate Change", *Science*, pp. 1230-1231

Kouria, S., E. Tsuparia, J. Kärki, S. Teir, R. Sormunen, T. Arponen and M. Tuomaala. 2017. "The Potential for CCUS in Selected Industrial Sectors – Summary of Concept Evaluations in Finland", *Energy Procedia* 114: pp. 6418-6431

Lackner, K. S. 2003. "A guide to CO_2 sequestration", *Science* Vol. 300, No. 5626, pp. 1677-1678

Negative CO_2. 2018. «Bio-CLC». Available at: https://www.nordicenergy.org/flagship/negative-co2/about-negative-co2/

Norwegian Environment Agency. 2018. "Utslippsstatistikk for Oslo" Available: https://www.miljodirektoratet.no/greenhousegas/api/excel/?areaId=41

City of Oslo. 2016. "Best Practices in The City of Oslo: Carbon Capture of Non-recyclable Waste". Modified 2018. Available: https://www.oslo.kommune.no/politics-and-administration/green-oslo/best-practices/carbon-capture/#toc-1 Accessed: 29.07.2019

Oslo Municipality. 2017. "7 Waste production and management" in *Application Form for the European Green Capital Award 2019*. Available: https://ec.europa.eu/environment/europeangreencapital/wp-content/uploads/2017/06/Indicator_7_Waste_Production_and_Management.pdf

Oslo Municipallity. 2019. ''Carbon Capture and Storage at Klemetsrud'' Available: https://www.oslo.kommune.no/politics-and-administration/green-oslo/best-practices/carbon-capture/

Pour, N., P. Webley and P. J.Cook. 2017. A Sustainability Framework for Bioenergy with Carbon Capture and Storage (BECCS) Technologies. Energy Procedia 114, pp. 6044-6056 Available: https://www.sciencedirect.com/science/article/pii/S1876610217319434

Port of Amsterdam, Tata Steel, EBN and Gasunie. 2018. “Noordzeekanaalgebied”. Available: https://www.portofamsterdam.com/sites/poa/files/nzkg_vliegwiel_voor_een_duurzame_toekomst_0.pdf

Schueler, V., S. Fuss, J. C. Steckel, U. Weddige and T. Beringer. 2016. “Productivity ranges of sustainable biomass potentials from non-agricultural land”, *Environmental Research Letters* 11, Available: http://iopscience.iop.org/article/10.1088/1748-9326/11/7/074026/pdf

Serdoner, A., Whiriskey, K., Tjetland, G., Rydén, M. and Lyngfelt A. 2018. “From mitigation to negative emissions: The case for bio-CCS in the Nordics”, Available: https://network.bellona.org/content/uploads/sites/2/2018/06/From-Mitigation-to-Negative-Emissions_The-Case-for-Bio-CCS-in-the-Nordics.pdf?__utma=123600408.956540728.1540632498.1560944560.1564569321.9&__utmb=123600408.1.10.1564569321&__utmc=123600408&__utmx=-&__utmz=123600408.1564569321.9.2.utmcsr=google|utmccn=(organic)|utmcmd=organic|utmctr=(notper cent20provided)&__utmv=-&__utmk=160308157

Stangeland, A. 2007. “Scenarios for Global CO_2 Emissions”, Available: https://bellona.org/assets/sites/3/2015/06/fil_Bellona_Paper_-_Scenarios_for_global_CO2_emissions-29May071.pdf

Statistikdatabas (official Swedish statistics), Available: http://pxexternal.energimyndigheten.se/pxweb/en/per centC3per cent85rligper cent20energibalans/?rxid=df0189df-236d-4691-8708-102c07dce4f5

Statistics Finland. 2016. "Total energy consumption by energy source", "Carbon dioxide emissions by fuels", “Fuel consumption in electricity and power production” and “Consumption of hard coal, 1970-2018” (official Finnish statistics), Available: http://pxhopea2.stat.fi/sahkoiset_julkaisut/energia2017/html/engl0000.htm

City of Stockholm. 2016. ‘’The Stockholm Environment Programme 2016-2019’’ Available: http://www.stockholm.se/PageFiles/130332/the-stockholm-environment-programme-2016-2019.pdf

Swedish Environmental Protection Agency (SEPA). 2019. ‘’Swedish Pollutant Release and Transfer Register’’ Available: http://utslappisiffror.naturvardsverket.se/en/Search/Plant-page/?pid=3567

Teir, S., J. Hetland, E. Lindeberg, A. Torvanger, K. Buhr, T. Koljonen, J. Gode, K. Onarheim, A. Tjernshaugen, A. Arasto, M. Liljeberg, A. Lehtilä, L. Kujanpää and M. Nieminen (2010). Potential for carbon capture and storage (CCS) in the Nordic region. *VTT Research Notes 2556*

Arnout de Pee , Dickon Pinner , Occo Roelofsen , Ken Somers , Eveline Speelman, and Maaike Witteveen. (2019) ‘Decarbonization of industrial sectors: The next frontier’. McKinsey Article, March 12, 2019. https://www.mckinsey.com/business-functions/sustainability/our-insights/how-industry-can-move-toward-a-low-carbon-future

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