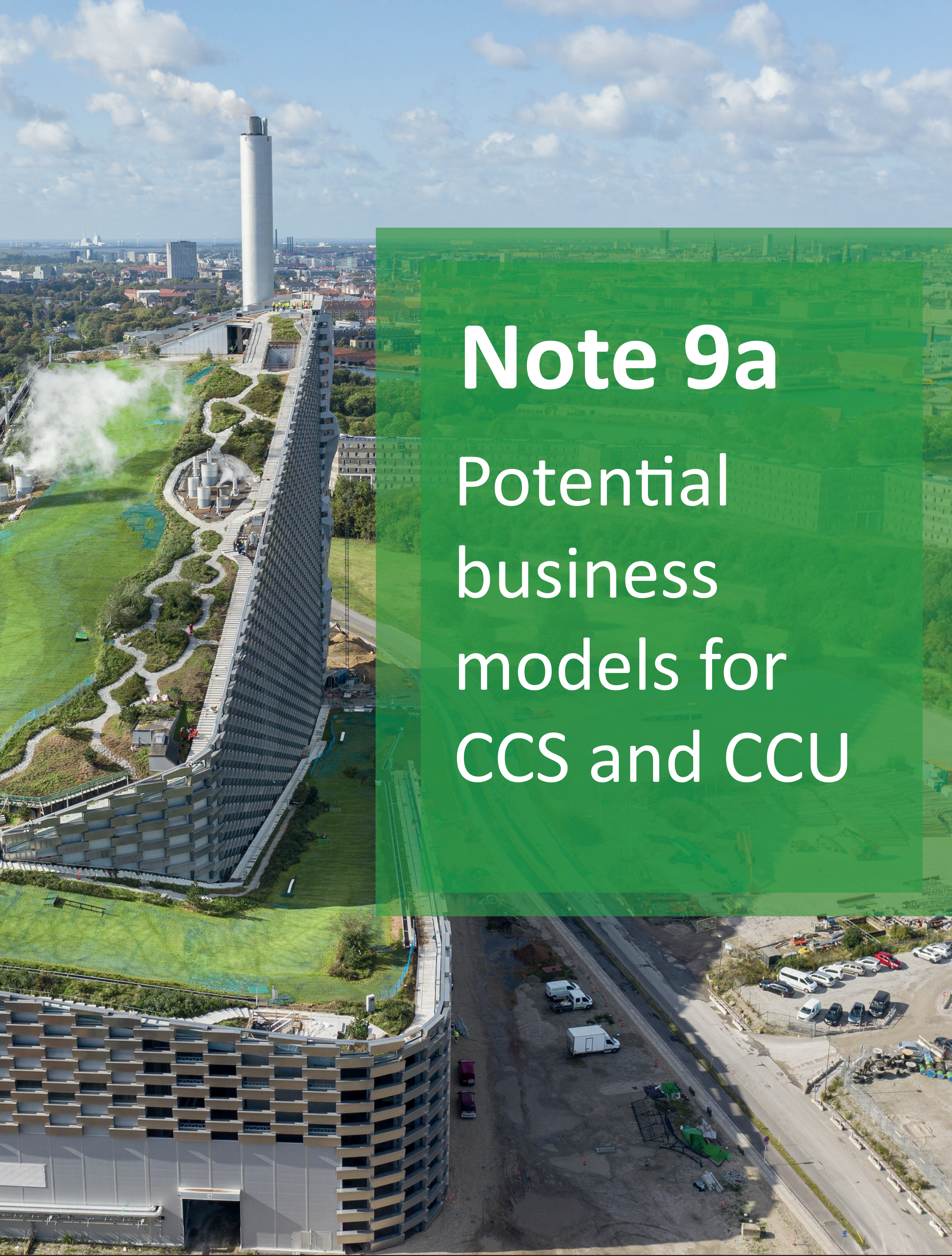
Note 9a

Potential business models for CCS and CCU



CNCA KØBENHAVNS KOMMUNE BELLONA

1.0 Summary

CO_2 capture and Storage (CCS) and CO_2 capture and Utilization (CCU) are two technology pathways that can address emissions from large CO_2 point sources. They have also the potential to draw CO_2 from ambient air. As the name suggests, CCS and CCU share the origin, yet differ in the destination of the CO_2. While CCU technologies seek to reuse the captured CO_2 as a product in itself or a feedstock for new products, CCS' sole aim is to prevent CO_2 from (re-)entering atmosphere by storing it deeply underground. It should be noted, therefore, that the climate benefit for many CCU technologies is limited or counterproductive.

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

CCS and CCU share much of the infrastructure and its associated costs; the capture, transport and intermediate storage. The paths diverge as CO_2 is either transported further and stored in deep underground formations or used in a variety of different processes. From a cost perspective, both pathways hence must deal with comparatively high capture costs of CO_2, ranging from just 20 Euros per tonne of CO_2 to hundreds of Euros depending on the CO_2 source. While initial capital investments into transport infrastructures and storage hubs appear significant, their overall cost per tonne of CO_2 over years of use approaches the ten Euros per tonne range or lower (Zero Emissions Platform, 2011).

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 of. Captured CO_2 can be used to make a range of potential products. As the vast majority of CCU products re-emit the used CO_2 at their end of life, their climate benefit lies primarily in the assumed displacement of fossil carbon 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). This is last step before production of metallic aluminium. The mineral by-product of this is calcium carbonate ($CaCO_3$).

One CCU solution currently attracting 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 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.

For both cases, it appears theoretically possible for cities that own and operate CO_2 capture facilities to sell their CO_2 at production cost to third party developers.

For CCS, the biggest challenge is to fairly and practically recover the total costs associated with disposing CO_2. With no apparent product beyond 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.

Business models for CCU and CCS both rely on favourable policy environments that 'de-risk' initial investment and allow for the transfer of operating costs to the final and associated products and services and those that either purchase or use them.

2.0 Introduction

Costs to implement CCS and CCU can be divided between initial capital expenditures (CAPEX) necessary for new equipment and infrastructures and the operational expenditures (OPEX). The OPEX costs are typically subdivided into energy, labor and other raw material inputs for the capture, transportation, utilisation or storage of CO_2 as the systems are up and running. New process facilities, including those required for climate action, are rarely obtainable for free.

At the same time, for the implementation of CCS and CCU to be considered by an emitter or operator requires mechanisms to receive return on their initial investments (ROI) and recover costs through new revenue streams. For private investors, such investments must typically exceed a minimum threshold RIO. For cities, this threshold can be very low or even zero, and the additional operational costs need not generate a profit. Therefore, in the perspective of cities, it is more appropriate to frame the issue of CAPEX, OPEX and ROI as 'cost recovery'. For the case of CCU, captured CO_2 from a city-owned facility would be sold 'at cost,' or with a modest margin, to a third party. The third party would then have the challenge of turning this purchased CO_2 into a product (or service) that allows them to achieve their threshold ROI.

Since CCS lacks a direct output beyond climate action, its costs will have to be transferred to the new low-carbon product or service. This transfer requires access to a markets for green products that internalise this cost without causing a competitive disadvantage. In the absence of such a market, which likely requires new policy instruments and a discussion around Border Carbon Adjustments, both low carbon goods produced through CCS and CCU products require market intervention to generate demand for these higher-priced, products and services, for example, by purchasing mandates and prescribed procurement.

3.0 CCS priced and monetized as a climate service

We focus in this section first on cost recovery schemes for CCS as a climate service. For emitters, deploying CCS is unlikely to generate any additional incomes. The potential exception to this if biogenic CO2 is captured, and this is financially rewarded in the future as a negative emission. Nevertheless, there is additional cost for producing a low carbon product and for operating the transport and storage infrastructure. These must be covered through policies that address both the operational costs of the system and the initial capital investments (OPEX and CAPEX).

3.1 Operating a CCS business

A transfer of the levelized cost[1] of CCS (LCOCCS) onto the associated final product or service (e.g. raw steel, cement, heat, waste treatment) is possible and conceivable. We illustrate this with the specific example of municipal waste incineration facilities. This is motivated by the fact that these can be the largest point source of CO_2 emissions under the direct management of city government. As a green products market at a macro scale is unlikely to evolve overnight, municipalities can play an important role for first movers also beyond their city limits, through public procurement or regionally limited financial regulations, for example a local taxation system.

Modern waste treatment involves careful sorting of recyclable items before incinerating the residual waste. The incineration process creates significant amounts of heat, which can produce steam to run

[1] Levelized cost of CCS (LCOCCS) is meant here to represent all CAPEX and OPEX for the lifetime of the CCS project, divided by the total net CO2 abatement for the same lifetime. Levelized cost is often used before any tax effects are calculated, such that levelized costs can be compared independent of company-specific tax status.

a steam turbine and electric generator. The final portion of heat can then be used in district heating networks during the heating season. Waste treatment by incineration is often called energy recovery, or Waste-to-Energy (WtE). In some locations, the heat from WtE can also drive evaporative cooling in the summer. These WtE services can be used directly to incentivise greater climate action.

As a first example: one role of waste incinerators is to process unrecyclable waste, such as single-use plastic packaging. Targeting unrecyclable plastic packaging with a surcharge at the packaging production site or the point of sale would provide a double incentive:

1: to reduce production and use of unrecyclable plastic packaging within the city

2: the funds raised would be used to help fund CO_2 capture and storage retrofit to the waste incineration site, thereby closing the loop and preventing CO_2 emissions from the final disposal of these unrecyclable packaging.

The example above would require national coordination. However, cities too can implement their own measures. A second path cost recovery for a WtE CCS project could be to include the service of CO_2 capture and storage in the price for the societal services of WtE plants. In this way, cross-subsidizing of service users by non-users of these services can be avoided, and thereby preserving sound accounting principles and user support.

Consider the following example of a hypothetical WtE facility with the following features.

- (Planned) capture rate 400 000 tons CO_2 /year
- Levelized cost of CCS (LCOCCS) is 100 Euros/tonne all-in
- The WtE serves
  - 280 000 customers (households and businesses) with waste treatment services,
  - 100 000 customers with district heating services,
  - 10 000 customers with electricity services and
  - 10 000 customers with district cooling services.

As a very first approximation,

400000x100/(280000+100000+10000+10000) = 100 Euros/year/customer

Or about 27 eurocents/customer/day. Redistributing these costs between large and small customers in a proportional way is a manageable task. This exemplifies the hypothetical price of a climate service per customer provided by a WtE facility with retrofitted CCS.

To add perspective, one could observe that this LCOCCS-based climate service price is considerably less than the cost of driving on toll roads in and out of cities in Europe, which typically cost 1-10 Euros per day per vehicle. The simplest cost recovery scheme of the LCOCCS for this example is to directly bill all the customers of the WtE waste treatment, district heating and district cooling services.

For industries not under direct municipal management, like cement and steel, public procurement mandates for low-carbon goods can establish a first niche market. Setting a goal of a specified share of construction materials to be low-carbon by a certain date sends a clear signal to industry to invest in new technologies. This will provide certainty that there will be a demand for their product that might otherwise not be competitive anymore. This cost recovery strategy is discussed in more detail in section 4.0.

3.2 Financing the CO_2 Infrastructure for CCS and CCU

Despite the ability for cost recovery of total, levelized costs of a specific CCS project even before a green products market is established, the initial capital investments into CO_2 capture, transport and storage system must be financed. Few if any operators of WtE, cement, steel, petrochemical, etc. facilities can, mobilize this CAPEX. Again, a conducive policy and regulatory framework to absorb some of the risks and financial strains is necessary.

The counterparty risks between the emitter and the transport and storage operators follow basic supply and demand principles: will there be sufficient CO_2 available to make the investment into the transport and storage network worthwhile, and in turn, will I have access to a transport and storage network after investing millions into an expensive capture unit? Providing certainty for the parallel development of both ends of the CCS chain must be a government prerogative.

CCU processes can potentially share the capture and transport infrastructures and therefore costs. However, it can be expected that most CCU processes will be integrated within local clusters and so less long-distance transportation may be needed. However, having such facilities built, even though motivated by CCS, may allow a larger trade of CO_2 between emission centres and utilisation facilities. In certain cases, the utilisation of some of the captured CO_2 can help with making a business case also for the storage of the remaining share of CO_2, e.g. mineralisation in cement.

The CCS system is best centred around CO_2-hubs for industry and intermediate storage. Such a hub could address local emissions but also become a place of transhipment for other CO_2 sources from further afar, also for the purpose of CCU. Particularly, cities in coastal areas or major river routes are strategically well placed to become such hubs. The establishment and coordination of such a CO_2-system can be managed, for example, through a state-owned and/or -funded institution (i.e. a regional CO_2 transport and storage infrastructure development organisation).

Such an organisation would provide guarantees in each part of the CCS value chain and prevent the monopolisation of the transport and storage infrastructure, thereby ensuring reasonable price levels for its use. Such price levels need to be made both commercially viable for the operator and socially and commercially acceptable for the public (in accordance with the polluter pay concept) and the emitting industry.

A CO_2 development organisation could also purchase CO_2 for storage directly from emitters at a price that largely covers added production costs induced by CO_2 capture, e.g. through tendering to avoid windfalls. Its primary role is thereby to absorb initial risks, provide planning certainty, and create the first CO_2-storage market. It can function to varying degrees of government ownership. Infrastructure can, for example, be managed under a regulated asset base system to ensure fair access to emitters or privately operated with governmental oversight.

There are several public funding schemes available to fund organisations or regulatory systems and the infrastructures needed for CCS and CCU. There are support programmes at the EU level, the national level and regional levels. Examples for the latter include the UK and Norway, where Front End Engineering Design (FEED) studies are co-financed. Another example is in the Netherlands, which is about to implement a tender feed-in tariff for the operating costs under the SDE+ system, which is also used for renewables. Generally, financial support is provided in the forms of grants, tax credits, loan guarantees, free but fungible CO_2 emissions allowances, and service cost recovery support. See note 9b for a complete description of these EU funding schemes.

The two most promising EU programs are noted here. The Connecting Europe Facility (CEF) is already accepting proposals for cross-border CO_2 transport infrastructure development through the pre-qualification program Projects of Common Interest (PCI). A new EU funding mechanism with more dedicated focus on CCS and CCU is the Innovation Fund. The EU Emission Trading System (ETS) revenue stream will be earmarked to climate projects and investments at the rate of about 1 billion Euros yearly for ten years. The rate of funding will be up to 60% of CAPEX and OPEX. This can potentially trigger 1-2 full-scale CCS and CCU projects yearly.

4.0 Low-emissions products made using CCS

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, CEEQUAL and other certification programmes.

They operate under the principals that buildings and civil works should be produced as sustainably and with the lowest environmental impact as possible. The measure for this is a consistent account of the life cycles of all embedded components, construction methods used and 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 of sustainability or environmental footprint. These certification systems can then assess the embedded greenhouse gas content of all the used material and components and apply this in overall grading. Municipalities can then specify the necessary grade certificate that reflects use of low-emissions cement, steel, structural wood, etc., produced with a CCS solution. This would allow higher-priced cement, steel, etc. to be procured by building contractors to satisfy specifications for new municipal buildings, civil works and infrastructure.

Cement, steel and petrochemical factories are in general not owned or operated by municipalities. But municipalities are often some of their 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-e products and materials. missions

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, steel, etc. 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 of CCS-cement has been estimated to about 1% more for the total cost of the finished structure (Rootzen and Johnsson, 2016). This despite the current estimates that CCS will effectively double the cost of producing cement. A similar analysis of the costs for steel produced with CCS in the total budget for a typical building yields a comparable result (Rootzen and Johnsson, 2016b).

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 with their high-emissions cement producers. These include raised minimum standards for materials through building codes, guarantees of origin and sector-wide minimum market shares of enhanced products (Holmås, et al., 2019). The common feature of these is that costs for CCS are shared along the value chain of producers and consumers. This is similar to the way the electrical grid is financed. All users share costs of local, incremental expansion and 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.

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 is Norway's 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 Emissions Trading System, 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.

5.0 CCU: Selling captured CO_2 to make other products

The available cost recovery schemes for CCU appear more straightforward, since the endpoint of CCU is a physical product that uses the captured CO_2 to directly or indirectly make other products that can be sold. This possibility to 'valorise' or use the waste product CO_2 is the fundamental reason for the business appeal of CCU versus CCS. However, until now most cases of CCU struggle to be commercial, nor do they deliver large-scale climate benefit.

Captured CO_2 can be used to make a range of potential products. As the vast majority of CCU products re-emit the used CO_2 at their end of life, their climate benefit lies primarily in the assumed displacement of fossil carbon sources.

There are generally three categories of industrial use of CO_2 for CCU. Examples within each category are given here:

1. Replacing current sources of fossil CO_2 as a basic ingredient to existing products, such as
   a. In greenhouses that use CO_2 for accelerating growth rates of vegetables, flowers and other plants
   b. For making carbonated (fizzy) beverages
   c. For producing sodium hydrogen carbonate (baking soda)
   d. For producing ethylene glycol (anti-freeze)
   e. As a buffer gas for fire extinguishers
2. Creating new CO_2-based products or replacing fossil CO_2 feedstocks, such as
   a. To create building blocks through ex-situ mineralisation
   b. For making special metallurgical moulds
   c. As a reactant in chemical processes to refine ores to produce specific elements or metals, which produces a mineralized CO2 by-product that is stable and non-toxic
   d. Making plastics and other carbon-based, non-fuel materials
3. To replace existing fossil energy carriers by
   a. Adding captured CO_2 to hydrogen, produced from renewable electricity, to produce synthetic hydrocarbons that can be refined into standardised fuels and gases

The barrier to realizing CCU for the first category is that captured CO_2 from new facilities would have to compete in product markets that are both small and already well-served by cost-effective, existing CO_2 suppliers. In other words, there is limited room for new entrants to supply CO_2.

However, important exceptions to this exist. For the listed example 1a., the greenhouse industry in The Netherlands has started a transition away from using CO_2 from the flue gas of natural gas boilers, since domestic natural gas supplies are in terminal decline. CO_2 captured from waste incineration is now being developed at two sites to test this solution. More may follow if they confirm their positive expectations.

Small market size also is an issue for some options in category two. For example, mineralisation suffers from a bulking problem. In other words, one tonne of CO_2 results in multiple tonnes of rock. With millions of tonnes of CO_2 available, the use of mineralisation is therefore limited by the practical task of transporting the rock masses to a permanent depot. In addition, these routes in category two are based on technologies still under development. Nevertheless, options a-c in category two can have large potential for using captured CO_2 and permanently storing it as a stabile mineral. If the captured CO_2 used for this is biogenic or taken directly from the atmosphere, these technologies could even lead to a negative emissions CCU application. It is important to note that for option d. in category two (e.g. plastics), environmental effects through pollution and end-of life incineration worsen the ecological footprint of the CCU route. If such costs are internalised, this could equally inhibit a positive business case under an increasingly stringent environmental regulation.

Synthetic hydrocarbons benefit from the ability to use existing infrastructures and engines and a have potentially the largest market for industrial captured CO_2. However, they suffer from tremendous energy requirements and will primarily displace the fossil carbon from existing sources. Furthermore, cleaner competing alternatives exist in most applications of synthetic fuels, e.g. fully electrified road or short-sea transport that is powered directly by renewable energy. Synthetic hydrocarbons have received much attention across CCU technologies. Therefore, their sustainability issues, role as a climate technology and commerciality will be discussed in more detail below.

5.4 Captured CO2 used as a raw material for synthetic hydrocarbons

Because example 3b (CCU to produce synthetic fuels) is currently attracting wide attention, and is potentially the largest CCU market for captured CO2, it is given more in-depth discussion here. CCU fuels and gases (short: synthetic fuels) represent a potentially large market for captured CO_2. They could replace conventional fossil fuels used in transport and natural gas in heating and power generation and are seen as a possible means to match the shortcomings of electrification in transport (particularly in aviation) and renewable electricity generation (due to delayed grid expansions and storage challenges).

The business appeal for potential fuel producers derives from a perceived lower CAPEX through the ability to reuse existing infrastructures, engines and power plants, and access to a potentially profitable market. For emitters, it is naturally the expectation to be able to sell the CO_2 by- and waste product of their production line at scale to be turned into marketable energy carriers.

The role of cities in developing CCU-based synthetic fuel production facilities and challenges related to this are discussed here. While it is true that synthetic fuels can leverage existing infrastructure and engines for fossil fuels, there is still a significant need for investment in new facilities in addition to the CO_2 capture and transport facilities. For the cases where a city owns the point source of the CO_2, e.g. WtE plant, district heating, power production or a biogas plant, it is assumed that the city will drive the CO_2 capture project and take responsibility for project financing and cost recovery. It is unclear, however, if the same city will take a role in project financing of the rest of the facilities required to produce synthetic fuels. This is illustrated here for the case of producing syncrude directly from CO_2 (i.e. not using biogas and not the methanol path to synthetic fuels). The main new, additional process systems required are:

1. Electrolyser to produce hydrogen for reacting with CO_2
2. Syngas production unit. This converts the CO_2 to CO which is the reactant required with hydrogen for the feed to production of synthetic hydrocarbons
3. Hydrocarbon synthesis unit. The most likely technology for this is the Fischer-Tropsch process. This technology has been used to produce synthetic fuels based on methane[3] and at a plant that uses coal as feedstock[4].
4. Additional renewable energy to run system

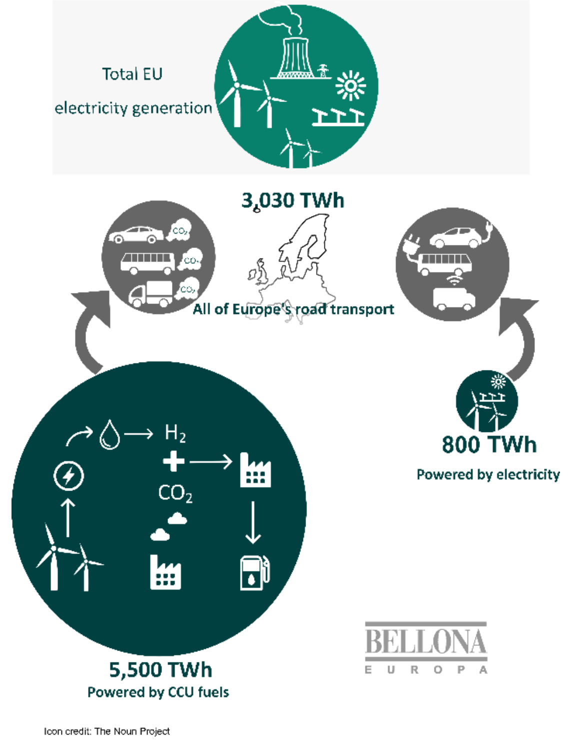


Figure 1: Creating 100% of EU car transport fuels via e-fuels would have unfeasibly large electricity demand, using more than all current EU electricity generation. In contrast, total conversion to electro-mobility for European car traffic would add just ~24% to current electricity demand and provide flexible grid services[2].

Note that capturing of CO_2 from flue gases is the most expensive part of the CCS value chain, but only the second most expensive in the CCU process. This is due to the fact that manufacturing synthetic fuels requires large amounts of hydrogen that must be produced through electrolysis[5]. Hence, these synthetic fuels are often referred to as 'electrofuels/ -gas' or simply 'e-fuels/-gas', as electricity is in fact their primary ingredient.

The challenge for cities that aim to sell their captured CO2 to an e-fuels project is to recruit qualified specialists in designing, building and operating these e-fuel production facilities. There is still a wide

[2] Total net electricity generation in the EU-28 was 3,030 terawatt hours (TWh) in 2014, (Eurostat 2016). Energy use in road transport in 2014 was 289.8 (Mtoe) = 3,370 TWh, (European Union, 2016). Excluding heavy-duty vehicles (HDVs) (-30% = 2660 TWh) for direct comparison with Eurelectric 100% EV electricity requirement estimates (Muncrief, 2015). At 60% P_2X conversion efficiency, 3,940 TWh of electricity would be required for 100% P_2X EU car fleet. 100% electrified fleet will add 802 TWh or a 24.3% increase in total electricity demand. (Eurelectric 2015).

[3] E.g. Oryx GTL, SASOL, Qatar, 34 thousand barrels syncrude per day; Pearl Factory, Shell Qatar, 140 thousand barrels syncrude per day.

[4] E.g. SASOL, South Africa, 160 thousand barrels syncrude per day.

[5] Using hydrogen that was produced from natural gas through Steam Methane Reforming, which takes the CO2 from the gas, only to be replaced by CO2 from industrial sources would result in merely a huge waste of energy with no benefit whatsoever.

range of CAPEX for these four systems, particularly for system 1 and 3 (Table 1, Proost, 2019 and Mortensen, et al., 2019). Furthermore, the electricity costs of running the electrolysis operations depend on future electricity prices, which must be assumed to be subject to dynamic market forces. The large uncertainty in this key cost will be a challenge regarding risk management of investment decisions on this scale.

Table 1. Ranges of CAPEX for two of the four main systems for e-fuel production facility

System type	Low estimate	High estimate	reference
Alkaline electrolysers for hydrogen production	400 €/MW	750 €/MW	Proost (2019)
Fischer-Tropsch syncrude production and refining systems	35000 USD/barrel/day plant capacity (Oryx GTL, South Africa, 2006)	86000 USD/barrel/day plant capacity (Oltin yo'l GTL, Uzbekistan, 2020)	Mortensen et al. (2019)

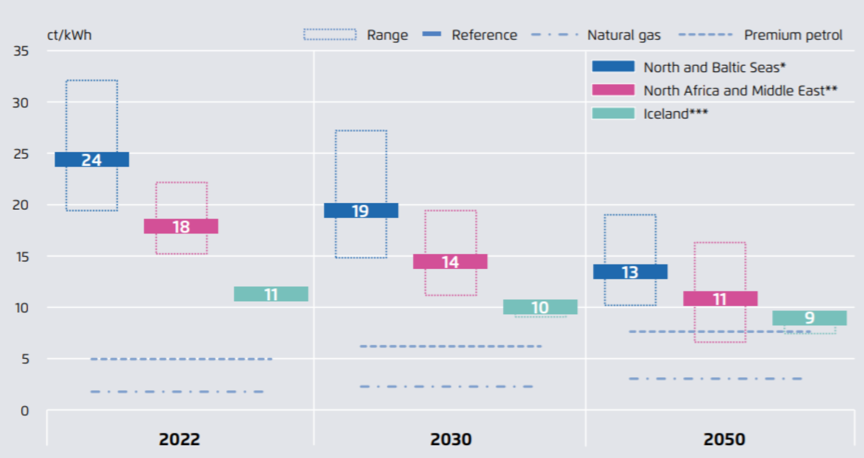
For a hypothetical new-build e-fuels plant with a capacity of 10 thousand barrels per day of crude oil equivalent synthetic hydrocarbons, the CAPEX for the Fischer-Tropsch synthesis unit alone is 350-860 million USD. Electrolysers, syngas production units and new renewable energy production facilities come in addition to this. If a city is striving to monetize its captured CO_2 by using it in a new synthetic fuel production facility, it will most likely need an independent third party to organize financing, constructing, owning and operating this. An attractive strategy might be to align commercial interests with several cities aiming to sell their captured CO_2, to encourage the e-fuel production project developer to stretch for economies of scale. Doing this while achieving compliance with rules regulating market competition, fair trade and subsidies, will be a major challenge.

For an e-fuels plant to deliver a reasonable climate benefit, it needs to be powered by 100% physical renewable electricity. Even if this is the case, the use of CO_2 from industrial sources will merely be emitted as a fuel or gas elsewhere, and at best result in a 50% emission reduction – by replacing fossil energy sources. In other words, CCU-based e-fuels and gas do not result in direct reductions of CO_2 emissions, but do so indirectly, and only if it displaces (not supplements) existing fossil fuel use. For a Paris-compliant footprint, i.e. carbon neutral fuel, CO_2 from biomass or from the atmosphere would have to be used instead of industry CO_2, for example through Direct Air Capture – with a parallel capture and storage of the industry emissions.

Renewable electricity is key ingredient and the prime driver of the operating cost of an e-fuels production facility (Mortensen, et al., 2019). The appeal of industrial captured CO_2 is therefore the comparatively lower cost compared to CO_2 from direct air capture due to higher CO_2 concentration in the industrial flue gases.

However, most European grids are not an appropriate source of electricity for electrolysis as their electricity generation remains highly CO_2 intensive.[6] The synthetic fuel would under these circumstances produce more CO_2 than using an equivalent amount of conventional fuel produced from crude oil. Only additional, dedicated renewable energy generation that is physically linked to electrolysis can therefore be used until increased renewable share has reduced grid emissions sufficiently.[7] With the needed additional renewable electricity comes, however, also an opportunity cost as this electricity will be unavailable to be used to reduce emissions elsewhere. Using solely excess electricity is commercially unfeasible, technically unlikely and would be hugely subsidy-dependent[8].

Cost of synthetic methane and liquid fuels in cent$_{2017}$ per kilowatt hour final product (without network charges and distribution cost)



Note: Prices of natural gas and premium petrol are based on average values from scenarios by the World Bank and the IEA. Other cost reductions for PtG / PtL may result from advancements in PV, from battery storage that increases full load hours, and from especially large electrolysis facilities. Cost increases may result from higher cost of capital due to higher country risks.

* Offshore wind power
** PV and PV / wind systems
*** Geothermal / hydropower (total potential limited to 50 terawatt hours)

Note: 10 cents per kilowatt hour is equivalent to around 90 cents per liter of liquid fuel.

Own calculations based on Frontier Economics (2018), with weighted average cost of capital of 6% (values rounded).

Overall, costs for renewable electricity-based synthetic fuels differ depending on regional potentials and demand. The European North- and Baltic-Sea regions are generally disadvantaged in this respect.[9]

At the same time, the future need for e-fuels in many segments is questionable. Growth in electrified transport, driven by improving cost curves of batteries, is anticipated to completely disrupt internal combustion engine road transport. 100% electric transport is commercially available for a growing range of types of vehicles and vessels. Because the electrolysis process is at best about 60% efficient, and a full charge-discharge cycle of a battery can approach 85-90% efficiency, battery-electric transport uses significantly less electric power than e-fuels, measured in comparable terms of transport service (Serdoner and Whiriskey, 2017).

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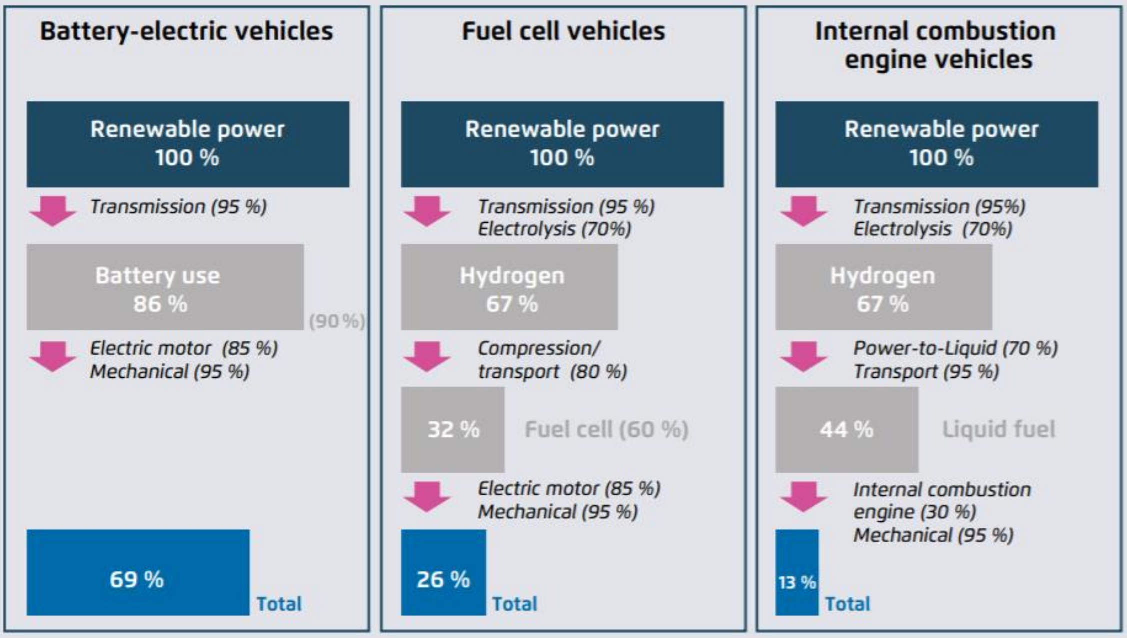
[6] https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis
[7] https://www.sciencedirect.com/science/article/pii/S1361920916307933#f0020
[8] https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynCost-Studie_WEB.pdf
[9] https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynCost-Studie_WEB.pdf

As long distance shipping is considering using a different hydrogen-based fuel (ammonia), the e-fuel project development has turned to the market for aviation fuels. The reason is that the potential for electrifying long-distance commercial air flight with current battery technology is limited. The high energy density of liquid fuels is crucial to long-distance flying, and all aviation turbines and engines are designed to operate using standardized, liquid hydrocarbon jet fuel. So far, however, there are few incentives or mandates to use low-emission fuels.

Based on the above outline commercial requirements, only regions with significant excess, and therefore cheap, renewable electricity generation could reasonably and commercially envisage a CCU



Note: Individual efficiencies are indicated in parentheses. Multiplied together, the individual efficiencies yield the overall cumulative efficiencies in the boxes.

Authors' illustration, based on acatech et al. (2017a), Figure 5

e-fuel production in the near and distant future. Most places with an industry base do not fulfil these criteria. This reduces the opportunity for industrial CO_2 to be used for e-fuels, which indeed from a climate perspective is generally best stored underground through CCS. Under current cost trends and climate requirements for aviation fuels to be considered "low carbon", new long-term subsidy schemes is needed to see any major production taking off in Europe.

To conclude on the business case for CCU-based e-fuel projects, the following criteria should be the basis for realizing a project with good climate benefits and with viable commerciality.

1. The e-fuels plant must have long-term, reliable access to low-priced renewable electricity.
2. The e-fuels plant should pay the true cost of the captured CO2 to avoid cross-subsidies and breach of market competition rules.
3. The product mix of the e-fuels plant must aim for the market/sector with the most difficult de-carbonizing situation. This is currently the aviation fuels market.
4. The captured CO2 must be biogenic or from direct air capture.
5. The e-fuel product should displace fossil fuel use, and there must be a credible verification case to back this up.

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Quote (page 3):

'Electrofuels only have a very small carbon footprint when zero-carbon renewable electricity is used for their production and CO_2 captured from the air. If these criteria are met, electrofuels have an average carbon intensity of 5 gCO2e/MJ (compared to 89 gCO2e/MJ for kerosene). Even with a low carbon intensity of the electricity grid at 25 gCO2e/MJ (equivalent to 90 g CO_2e/kWh) the greenhouse gas (GHG) intensity of these fuels would be a mere 20-47% better than fossil fuels. To put this into context, Germany has a grid of 410 g CO_2/kWh, while Sweden has a grid of 20 g CO_2e/kWh. Produced with the current EU electricity mix (300 g CO_2/kWh), electrofuels' greenhouse gas intensity would be three times higher than the fossil fuel comparator, at 307 g CO_2e/MJ.'

'EU funding of EUR 5.9 million for Alumina Project'. Tuesday, June 11, 2019 09:54 CET

https://news.cision.com/nordic-mining-asa/r/eu-funding-of-eur-5-9-million-for-alumina-project,c2837748

'EU's Horizon 2020 program has granted EUR 5.9 million in funding for continued development of the patented alumina technology owned by Nordic Mining and Institute for Energy Technology (IFE). The technology is currently patented in Norway, USA, Russia, Denmark and Greenland, and approved by the EPO (European

Patent Office) with pending validation in additional European countries and pending in Canada.'

'Mitigating Emissions from Aluminum'.
http://climate.columbia.edu/files/2012/04/GNCS-Aluminum-Factsheet.pdf

'The production of new aluminum results in around 1% of global annual greenhouse gas (GHG) emissions. Mining, refining, smelting and casting primary aluminum releases about 0.4 billion tons (Gt) of carbon dioxide equivalent (CO_2e) emissions per year.'

Towards a greener mineral and metal industry thanks to the AlSiCal project.
https://ife.no/en/towards-a-greener-mineral-and-metal-industry-thanks-to-the-alsicroject/al-p

'Last week the AlSiCal project officially kicked off. The project aims at developing an innovative technology to reduce the environmental impact of producing alumina, silica and calcium carbonate.'

On the Cover: Amager Bakke (Photo: Amager Resource Center/Ehrhorn/Hummerston)