Danish Energy Agency

Appendix 1: Techno-economic assessment of CCS technologies

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1. Introduction

With the agreement on "a strengthened framework for CCS in Denmark"[1] of 20 September 2023, a majority of the Danish Parliament decided to establish the "CCS Fund". The total budget of the CCS Fund is approximately 28,3 billion DKK (2024-prices) which is scheduled for deployment from 2029 to 2044.

The purpose of the CCS Fund is to achieve CO_2 emission reductions and/or negative emissions by permanently and geologically storing fossil and/or biogenic and/or atmospheric CO_2.

The CCS Fund constitutes State aid for climate and environmental protection and is prepared following the Guidelines on State aid for climate, environmental protection and energy 2022 ("CEEAG"). According to CEEAG, the notifying authority must, among other things, show the incentive effect and the necessity of the aid through quantifications of the net extra costs of the reference projects in the counterfactual scenario, i.e. the situation without aid. This appendix outlines the costs of the reference projects, prepared following the principles in CEEAG point 52.

The structure of the appendix is as follows: Section 2 outlines the methodology and general assumptions, and section 3 breaks down the cost of CO_2 capture and storage for each of the reference projects. Section 4 contains a separate cost breakdown for direct air capture and storage.

2. Method and general assumptions

The techno-economic assessment is conducted as a discounted cash-flow analysis, calculating the expected net present value (NPV) of a series of capture projects. NPV expresses the difference between a project's revenues and costs over its expected lifespan. Thus, the method provides a reasonable estimate for the required level of state aid needed to support the value chain.

The calculations of the NPV of carbon capture at various point sources are based on data from the Danish Energy Agency's (DEA) technology catalogue[2]. In addition to these technical and economic data, some general assumptions are needed to calculate the cost of a carbon capture project. The cost of capturing CO_2 is sector-specific and therefore multiple scenarios are assessed with capture projects in different industries. The analysis is based on a reference plant in each industry of a

[1] In Danish: "Aftale om styrkede rammevilkår for CCS i Danmark". The agreement can be accessed here (in Danish)
[2] https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-carbon-capture-transport-and

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given size with a certain amount of yearly full load hours. The sectors assessed are cement, waste incineration, biomass combined heat and power (CHP) and biogas upgrading. These sectors are chosen based on what is expected to be relevant for the CCS subsidy scheme.

Costs include capital expenditure (CAPEX) associated with commissioning carbon capture (including liquefaction and interim CO_2 storage terminals where applicable) and operational expenditure (OPEX), including transportation and storage of CO_2.

As stated above in section 1 of this appendix, the Danish Parliament has allocated funds to the CCS scheme for the period 2029-2044. The analysis is therefore conducted for the period 2029-2044. Any possible value of the capture facility after 2044 is not included in the calculations. The owner of a non-depreciated facility may continue to capture CO_2 after 2044 if the owner can obtain a revenue sufficient to cover variable costs from either the ETS, a market for CCS-credits, or a market for carbon to CCU.

The cost estimation is based on technology data on amine based carbon capture projects. Other technologies could be relevant, but for this analysis amine based capture technology was chosen based on availability of data and it being the most likely technology used in upcoming projects in Denmark.

Sector specific assumptions

The amount of CO_2 captured and the number of full load hours is sector-specific and illustrates the expected scale and number of full load hours of a representative carbon capture plant in each specific sector. These do not reflect any specific emitters in Denmark and should only be used as a frame of reference for the cost of carbon capture in various industries.

Sector specific assumptions for capture amount and full load hours

Sector/industry	Annual capture (ton CO2)	Full load hours	Transport assumption*	Transport distance (km)*	Transport assumption**	Transport distance (km)**
Cement	900.000	8500	Pipeline and ship	600	Pipeline	100
Waste to energy	500.000	8000	Truck and ship	600	Truck	100
Biomass CHP scenario 1	500.000	7000	Truck and ship	600	Truck	100
Biomass CHP scenario 2	500.000	4500	Truck and ship	600	Truck	100
Biogas upgrading plant	50.000	8500	Truck and ship	600	Truck	100
Refinery	250.000	8500	Truck and ship	600	Truck	100

* Offshore CO_2 storage scenario

** Onshore CO_2 storage scenario

Currently, no backbone CO_2 pipeline infrastructure is available in Denmark. Therefore, investments in pipeline transportation is assumed to be made on a project basis, i.e. in a pipeline from the specific point source to the contracted storage provider. CCS projects therefore need to be of a certain size to justify the infrastructure investment of building a CO_2 pipeline. The selection of different transport assumptions are therefore based on the annual quantity of captured CO_2 of the reference projects.

The exact scale at which pipelines are economically viable is uncertain, but based on the DEA's technology catalogue, road transportation (by trucks) is – by a small margin – the cheapest option when the quantity to be transported amounts to 500.000 tons. However, if a network of CO_2 pipeline infrastructure becomes available in the future, it may become viable for projects with a lower annual quantity of captured CO_2 to connect to this infrastructure.

Both offshore and onshore storage providers based in Denmark have been granted exploration licenses. Currently, no CO_2 storage licenses have been granted. Cost assumptions regarding CO_2 storage are therefore highly uncertain. However, the DEA expects offshore storage to be significantly more expensive. Consequently, results for both options, onshore and offshore storage, is shown in the calculations, cf. section 3 *Cost of capture, transport and storage*.

The relative low number of full load hours for Biomass CHP scenario 2 compared to scenario 1 implies a higher capacity of the capture facility and hence higher investment costs.

CO_2 capture rate
The CO_2 capture rate is the percentage amount of CO_2 in the flue gas that is collected. It is assumed that the capture rate is 90%. This means that a plant emitting 1.000.000 tons of CO_2 yearly can capture 900.000 tons.

Energy inputs and outputs
Assumptions for energy inputs and outputs are sector specific. The capture process needs both heat and electricity. For a cement plant, it is assumed that the heat needed to run the capture process comes from a natural gas boiler. For waste to energy and biomass CHP, it is assumed that steam is utilized that otherwise would have been used to create electricity and heat for district heating. Waste to energy and biomass CHP sell the waste heat from the capture process as district heating. The revenue from selling waste heat from the capture process is included in table 2. Lastly, for biogas upgrading plants, it is assumed that no additional energy is

needed as the CO_2 capture is already being done as part of the biogas upgrading activities.

In addition to the energy consumption for the capture process, post-processing to make the CO_2 ready for transport also uses electricity. The amount depends on whether the CO_2 is liquefied and transported as a liquid in trucks or compressed and transported in pipes.

Construction time

The expected construction time for a CCS project is 2.5 years, based on data from the technology catalogue. It is assumed for biogas upgrading, where the capture facilities are already present, that the time to construct post-processing facilities is 1.5 years in the technology catalogue. The construction time is assumed to be the time between the final investment decision and the start of operations.

Price of CO_2 in EU ETS

The price of a CO_2 allowance in the EU emissions trading system is based on the Danish Ministry of Finance[3] forecast used in various DEA forecasts.

Price of CO_2 based on Danish tax rules

On 24 June 2022, a majority of the Danish Parliament entered the Green Tax Reform Agreement for Industry, etc., entailing the introduction of a new CO_2 tax regime, incentivizing fossil carbon emission reduction activities in, amongst others, the industry and utility sectors.

In February and May 2024, the Danish Ministry of Taxation introduced legislative proposals in the Danish Parliament to implement the agreement. These legislative proposals includes a new tax ("emission tax") of DKK 375 per ton of emitted fossil CO_2e by companies covered by the ETS with the caveat that the tax level for ETS-covered mineralogical processes will be set at DKK 125 per ton of emitted CO_2e. The tax base is proposed to be the CO2e emissions for which ETS allowances must be surrendered under Directive 2003/87/EC

The proposals also include an adjustment to the existing CO_2 tax. This entails, inter alia, that fossil CO_{2e} emissions associated with production of district heating by companies covered by the ETS will now be taxed at 375 DKK per ton of CO_2.
The tax base for the CO_2 tax is the CO_2e emissions associated with use of energy products, covered by the Energy Taxation Directive.

The legislative proposals, if approved by the Danish Parliament and the EU Commission, is expected to enter into force by 1 January 2025.

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[3] https://fm.dk/media/27370/noegletalskatalog_november-2023.pdf

Table 1: Sector specific CO_2 and emission tax levels

Sector/industry	Emission tax level pr. ton of CO_2e emissions (DKK)	CO_2 tax level pr. ton of CO_2e emissions (DKK)
Cement	125	0
Waste to energy	375	375
Refinery	375	0
Biomass CHP scenario 1	0	0
Biomass CHP scenario 2	0	0
Biogas upgrading plant	0	0

Internal rate of return

The average (real, pre-tax) cost of capital applied to discount the cash flows to the present, i.e. the WACC, is assumed to be 7%.[4]

Assumptions on emissions from waste-to-energy

The fossil share of fuels is on average approximately 20 percent in waste to energy production.

Decommissioning

Costs associated with decommissioning of the project is not included in the calculation. This is because the subsidy schemes duration of 15 years is less that the expected lifetime of a capture project in the technology catalogue. The expected lifetime is 25 years. The project could therefore continue at the end of the subsidy scheme if economical.

Voluntary carbon credits

The DEA assesses the voluntary carbon market (VCM) to be highly immature[5]. Further, the DEA finds it unlikely that the VCM will mature markedly until the EU carbon removal certification framework is fully developed.

While the DEA cannot rule out that some biogenic CO_2 emitters may generate an

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[4] See Steffen (2020): “Estimating the cost of capital for the renewable energy projects “, https://www.sciencedirect.com/science/article/pii/S0140988320301237 and PWC (2020): “Værdiansættelse af virksomheder”, https://www.pwc.dk/da/publikationer/2020/vaerdiansaettelse-af-virk-pub.pdf . Based on a survey study Steffen finds a real cost of capital after tax of 8.3 % for off-shore wind for OECD. PWC finds a nominal cost of capital (pre tax) in the range of 7-10 %. Estimates varies greatly across studies and the assumption of 7 % is within this range. Relative low cost of capital implies lower costs per unit captured.

[5] This assessment is, inter alia, based on data from cdr.fyi, which is a repository for global purchases, deliveries, and verifications of voluntary carbon credits traded on the voluntary carbon market.

income from the sale of certified negative emissions, no income from the sale of certificates has been included in the counterfactual scenario. The DEA is unable to reliably gauge how the future demand for carbon credits based on bioenergy-CCS (BECCS) and DACCS[6] will develop. Moreover, only a few carbon credit agreements based on BECCS and DACCS have so far been made globally. Consequently, the DEA is unable to reliably determine the value of such potential BECCS or DACCS-generated carbon credits. Nevertheless, even assuming a high carbon credit value, the DEA believes that this potential income is far from enough to incentivize CCS.

3. Cost of capture, transport and storage

The tables found below provide an overview of the costs and revenues of CO_2 capture and storage for each of the reference projects. Table 4 shows the estimated NPV and hence the level of state aid needed for each reference project to capture, transport and store one ton of CO_2.

Offshore-based storage of CO_2 is assumed to cost DKK 335. This includes shipping cost from a harbor to the offshore storage site (500 km, including round trip). Transport to the harbor is assumed to be 100 km, including round trip.

Onshore-based storage of CO_2 is assumed to cost DKK 175. This is the cost of permanent storage, i.e. the cost of injecting CO_2 into the subsoil. Transport to the onshore storage is assumed to be 100 km, including round trip.

The transport costs are therefore the same in both scenarios, as the shipping costs are contained in the offshore storage price.

Table 2. Technical costs in CCS-value chain, DKK. pr. ton captured CO_2

Sector/industry	Investment (capture)	Operations (capture)	Transport	Onshore storage	Offshore storage	Total onshore	Total offshore
Waste to energy	740	200	160	180	340	1280	1440
Biogas	260	120	200	180	340	760	920
Biomass (Scenario 1)	800	220	160	180	340	1360	1520
Biomass (Scenario 2)	1020	260	160	180	340	1620	1780
Cement	420	120	160	180	340	880	1040
Refinery	880	240	160	180	340	1460	1620

Note: The calculated costs are deducted revenue from sale of waste heat for the sectors Waste to energy and Biomass. The value is approximately 50-100 DKK per ton CO_2. The table is based on standardized points sources for the individual sectors and do not reflect any specific point source.

[6] "Direct air capture with storage"

Table 3. Savings on emission tax, CO_2 tax and EU ETS, DKK. pr. ton captured CO2

Sector/industry	EU ETS	CO2-tax	Emission-tax	Total
Waste to energy	220	80	80	380
Biogas	0		0	0
Biomass (Scenario 1)	0		0	0
Biomass (Scenario 2)	0		0	0
Cement	580		80	660
Refinery	880		340	1220

Table 4. Estimated Level of aid needed for projects, DKK. pr. ton captured CO2

Sector/industry	Total costs[1]	Total saving	Net Present Value (NPV)[1]
Waste to energy	1280 - 1440	-380	900-1060
Biogas	760 - 920		760 - 920
Biomass (Scenario 1)	1360 – 1520		1360 – 1520
Biomass (Scenario 2)	1620 – 1780		1620 – 1780
Cement	880 - 1040	-660	220 - 380
Refinery	1460 - 1620	-1220	240 - 400

[1]Reflects onshore based storage for the lower number and offshore for the higher. As seen in table 2.

4. Cost of Direct air capture

The cost of direct air capture (DAC) has not been modeled in detail. Instead for cost estimation and avoided emissions analysis the work by the National Energy Technology Laboratory (NETL) [7][8] is used as a reference. NETL is part of the US Department of Energy. Two different technologies for DAC were modelled by NETL, solvent based DAC and sorbent based DAC.

The basis for the cost estimation is neither first of a kind plants nor nth- of a kind plants but somewhere in between. The cost estimation is therefore a guess at where the price could be somewhere in the future. The plants modelled are at a significantly larger scale than what has been built today.

Several different configurations of the two types of DAC is analyzed. For the solvent based DAC the cheapest configuration is estimated to cost 292.5 US

[7] https://www.netl.doe.gov/energy-analysis/details?id=36385f18-3eaa-4f96-9983-6e2b607f6987
[8]https://www.netl.doe.gov/energy-analysis/details?id=d5860604-fbc7-44bb-a756-76db47d8b85a

dollars to remove a ton of CO_2 from the atmosphere. For the sorbent based DAC the cost is 430.4 US dollars. The cost is stated at a net removed basis.

In the table below costs in DKK can be seen based on a conversion rate of 1 dollar to 6.9 DKK.

Table 5. DAC cost estimation on a net removed basis

DAC type	Solvent based	Sorbent based
Cost (DKK)	2018	2970

It is important to note that this is not the expectation of current prices for DAC, but the best estimation at what a future price of DAC could be.