Feasability Study of Capturing CO_2 from the Klemetsrud CHP Waste-to-Energy Plant in Oslo

– Carbon Capture and Storage in Norway and Europe –

Johnny Stuen

1. Result

- Carbon capture from 3 different industrial sites and storage in the North Sea basin can be done and ready for operation in 2022 – at a cost from 12,4 bill NOK (approximately 1,35 bill Euro). If only one capture site is chosen, the cost will be 7,5 bill NOK.
- Carbon capture from waste incineration (energy recovery) works well and it is possible to integrate a carbon capture plant in the existing energy recovery plant at Klemetsrud (hereinafter *KEA*). Similarly, carbon capture can be integrated in other existing plants for energy recovery, with a potential capture of more than 60 to 70 million tons of CO_2 in the EU alone (CEWEP Energy Report 3, status 2007-2010).

- Energy recovery is an internationally growing industry that is subject to increasingly stringent regulatory and environmental requirements. There is more reason to expect broad adaptation to proven carbon capture capabilities here than in many other industries.
- Carbon capture from energy recovery provides future opportunities for sales of CO_2 emission permits from the biological portion of captured CO_2.
- Carbon capture from waste incineration in Oslo will build local expertise and have great competence- and regulatory transfer value.
- Establishment of carbon capture at KEA has broad political support in Oslo.
- A full-scale plant can be built and started up within 31.12.2020, given an investment decision no later than Q1 2018, secondarily built and started up within 12.31.2021 provided an investment decision no later than Q4 2018. The Norwegian government has given a timeline for an investment decision Q2 2019, this will realize the complete chain within 2022.
- A full-scale capture can be built for approximately 220 million Euro, and with estimated operating expenses of 16 million Euro pr year. These numbers have a +-40 percent error margin.
- Carbon capture at KEA is a safe choice; there is no risk that the business closes down or moves. KEA has extensive experience with the establishment and operation of advanced processing facilities, including the handling of chemicals and control of emissions.
- Approximately 315,000 tons of CO_2 can be removed per year with a full-scale facility at KEA (90 percent catch of 350,000 tons of CO_2). Of this, a substantial proportion is carbon negative (about 60 percent have biological origin). It has already been initiated efforts to increase capacity to 375,000 tons of waste annually, which increases the potential capture rate by approximately 20,000 tons.
- Carbon capture has no negative impact on the heating supplied from KEA. District heating delivery to Hafslund Varme is maintained, and may be increased with establishment of a full-scale capture plant at Klemetsrud. There is potential to take out additional heat to the district-heating network with extra heat pumps.
- Conducted test with the mobile test unit, based on amine process, shows good and stable treatment results by approximately 90 percent catch.
- The electricity consumption of the capture process is covered through self-generated electricity.
- Transport of CO_2 to the port can be solved in several ways. From the time startup is projected it can be done with green road transport. Use of climate neutral road transport can contribute to technology development of heavy transport with battery and/or hydrogen power in an open market. In the longer term transport through a pipeline from Klemetsrud down to the harbor will also be feasible.

- Increased demand for energy for district heating and -cooling is expected over time to trigger the need for enhanced combustion capacity at KEA. A full-scale plant can meet the need for carbon capture also from such extended combustion capacity and could increase their catch with approximately another 90 to 150,000 tons of CO_2 annually.
- There is potential for capturing additional about 150,000 tons of CO_2 per year from the established combustion plants at Haraldrud (bio and waste).

2. Introduction

The municipality of Oslo by Energigjennvinningsetaten (EGE) was in December 2015 awarded funding from Gassnova (a state owned company that coordinates the Norwegian CCS-work) to conduct a feasibility study. The purpose of the feasibility study was to demonstrate at least one workable solution for carbon capture from energy recovery for waste, with technical descriptions, cost estimates, project plan and plan and budget for the next phase.

Through the feasibility study EGE wanted to examine opportunities, challenges, risks and costs by integrating carbon capture in an existing energy recovery. The feasibility study includes capture, transport to port, storage at port and loading of liquid CO_2 to vessels in Oslo harbor.

KEA currently has permission to accept and process 320,000 tons of waste per year and has a technical capacity to process approximately 350,000 tons of waste per year. The feasibility study has been based on the plant's current technical capacity. KEA annually produces approximately 0.8 TWh of energy, out of which about 170 GWh is electricity and approximately 630 GWh is heat for district heating. The plant is implementing increased capacity, and the goal is that the plant in 2018 will produce more than 1.15 TWh of energy in the form of electricity and heat.

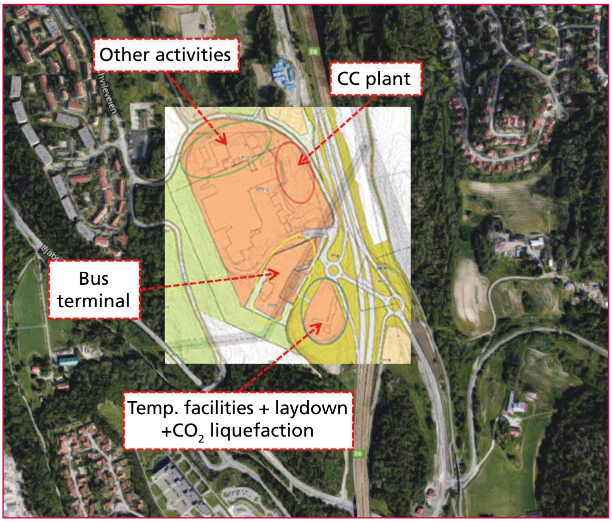

Figure 1:

Combined aerial and equipment overview on Klemetsrud

All the heat is delivered to Hafslund Varme, and approximately equals 40 percent of Hafslund's annual heating (1.6 TWh in 2015). Hafslund Varme has aim to increase district heating deliveries in excess of 2 TWh, but if the framework conditions improve, the potential for district heating in Oslo is close to 3 TWh. Increased demand for district heating and -cooling could provide a basis for the establishment of a new line 4 at KEA, with additional combustion capacity of 90 to 150,000 tons of waste annually. The total future carbon capture potential of KEA with 90 percent capture rate can reach up to 450,000 tons of CO_2 annually.

3. Technical solution

The feasibility study has focused on two different capture technologies and several different storage and transport options. The feasibility study was divided into four different parts, where two capture technology providers (Captureprovider1, Captureprovider2) developed independent capture concepts while a third company (Multiconsult) was responsible for developing the transport and storage concepts. The fourth study, the overall feasibility study was drafted by Citec. Citec has been responsible for quality control, consolidation and summary of the study, confirmations and assessment and concept development of integration between the capture plant and KEA. Citec has also analyzed and ensured that the individual studies are comparable and that the relevant interfaces with existing plants is maintained in a so much as possible appropriate and efficient manner.

A condition for establishing a CO_2 capture facility at KEA, is that CO_2 capture from flue gases takes place with the least possible impact on existing energy production and supply. KEA currently has an annual technical capacity to incinerate up to 350,000 tons of waste, and by 90 percent capture rate this corresponds to a catch of about 315,000 tons of CO_2 per year. It will also in 2016 and 2017 be invested in an increase of the technical capacity to approximately 375,000 tons per year. Efforts are underway to deliver a new application for environmental permit equivalent to this new capacity. It is expected that a permit will be issued in the first half of 2017. The expected upgraded combustion capacity of 25,000 tons are considered to be within the feasibility study definition margins, and it is not made any further reviews beyond this.

3.1. Capture technologies

Two different capture technologies have been considered. Both are based on absorption technology, but using different solvents. Captureprovider1 based the report on using their proprietary amine, while captureprovider2 based on the use of conventional available ammonia. Use of absorption for separating CO_2 is a known technology, based primarily on the use of amines as solvent. Both technologies have conducted successful test programs at the Technology Center Mongstad (TCM) and has satisfactory reference lists.

Since both technologies are based on the same basic principles (absorption, desorption), the integration with energy recovery is relatively equal. Both technologies are based on using heat pumps and steam turbine to recover and return adequate heating/electricity,

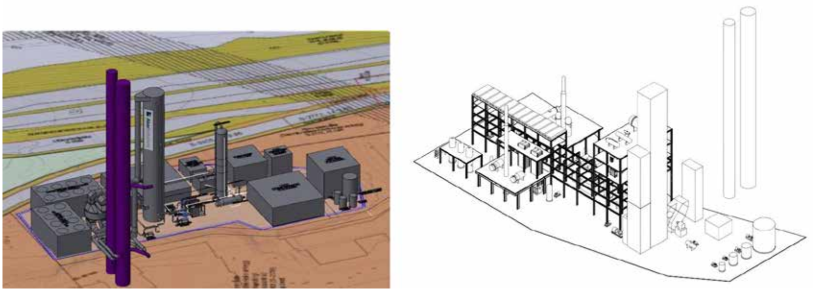

Figure 2: Sketch of amine plant (left) and ammonia plant (right) at Klemetsrud

so energy recovery maintains an unchanged heat energy balance. Both technologies, however, will result in a bit lower electricity production for sale from the plant.

By normalizing the independent premise parameters (such as the efficiency of heat pumps) affecting heat- and electricity production, the simulations show that by maintaining the existing heat production and 90 percent capture the following effect is obtained:

- Captureprovider1: 13.7 MW_e electricity consumption, while electricity for sale falls from 19.8 to 18.4 MW_e,
- Captureprovider2: 12.6 MW_e electricity consumption, while electricity for sale falls from 19.8 to 16.4 MW_e.

In both cases, the power consumption is within the framework of normal electricity produced at KEA. There is no need for investments in grid reinforcement for electricity relating to the public network.

An important finding in the feasibility study is that we manage to integrate the capture facility with existing facilities using heat pumps and a new steam turbine, thereby keeping district heating production unchanged at around 85 MWt_h in the winter period. The technologies are relatively equal in energy efficiency.

3.2. Transport and interim

CO_2 can be transported in the gas phase, liquid phase or supercritical phase (gas, but with physical properties as liquid). Several different options were considered for CO_2 transport and intermediate storage before transferring to vessels in Oslo harbor. Transport via pipeline with different routes (over land and along the seabed), trucks and trains were assessed against each other. The feasibility study included assessments of what will be distorted state on the gas for transport, and the most appropriate placement of facilities for liquefaction of gas to liquid phase. There are several possible sites for loading CO_2 at Oslo harbor, depending on the transport solution from the plant to the harbor.

Pipeline transport is a common alternative to transport large quantities of CO_2, and USA has long experience with this. For pipeline transport gas phase is considered as the most favorable option. A combination of land and seabed pipeline to Ormsund Quay is launched as recommended route for a possible pipeline. A pipeline solution will involve a cooling plant for the transfer of CO_2 in liquid form to the vessel that must be placed in the harbor and demands larger port areas. Establishing a pipeline will eventually be able to provide joint implementation and interaction with other important society structures, such as district heating, electricity, fiber etc. If one in other contexts needs a pipeline between Klemetsrud and port, such a collocation/cost sharing contribution to other desirable environmental projects are economically feasible.

For transport by truck (or train) CO_2 must be floating, which means that the cooling plant must be placed on Klemetsrud. There must also be a smaller cooling system for receiving return gas from the vessel during loading. A placement of the cooling plant at Klemetsrud enables further increased district heating. Trucking from Klemetsrud and down to the port of Oslo will to some extent increase the traffic load in Oslo. Basically, it is estimated a need for 30 trucks per day. The traffic load at rush hour can be minimized through proper sizing of intermediate storage and good logistics management. Conventional fossil-based trailers will result in increased greenhouse gas emissions, and is not a desirable solution. By adopting trailers that use biofuels, CO_2 emissions will be climate neutral (use of biofuels, however, will still result in local emissions of NO_x and dust).

From the plant's expected lifetime and time to realization, there is a high probability that it will be developed commercially available technologies for electric or hydrogen based propulsion. Eco trucking is therefore a real alternative to pipeline transport with the use of biofuels in a transitional phase.

Rail transport from Klemetsrud to a shared storage in Grenland is not considered realistic because of the number of logistics operations between Klemetsrud and Grenland.

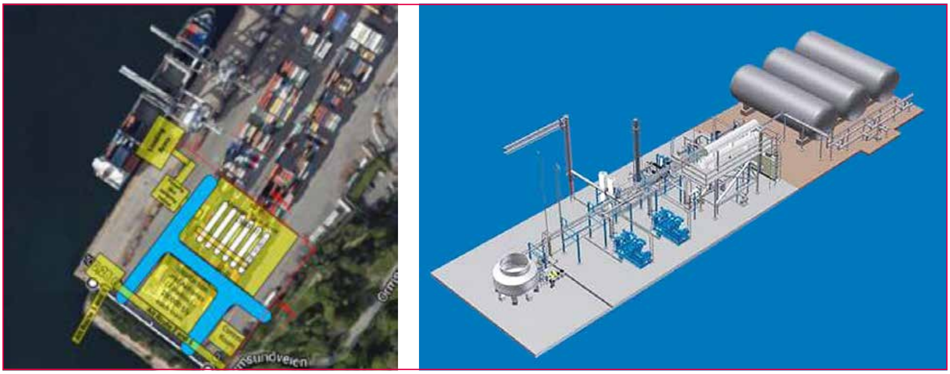

Figure 3: View of possible location at Ormsund Quay with intermediate (left) and typical small-scale CO_2 storage facility (right)

3.3. Health, safety and environment (HSE)

The feasibility study assumed that the carboncapture plant should remain within existing emission permits and that new emissions should be minimized. The primary safety risks are considered to be related to:

- CO_2 (emissions or accident),
- Ammonia (emission or accident),
- Amin (emissions or accident),
- Fire or explosion,
- Exposure to harmful substances,
- Noise.

These risks are generally considered to be manageable, and in areas where KEA already have considerable experience. KEA is already ISO-certified for environment and quality, and is subject to Emergency regulations mm. Measures to reduce risks are further described in the feasibility study.

4. Financial considerations

The cost-estimates for capture, transport and temporary storage has ± 40 percent accuracy, defined by the maturity of development. As a part of the study it was expected to present one complete basic concept. Based on the results obtained in the study EGE has decided to use ammonia-capture technology and transport by truck as a basis for the design of the basic cost estimating. It is emphasized that this is not a final technology choice, and it is recommended that the next phase investigates other possibilities further before final decisions are made. Results from the feasibility study provides the following cost breakdown for the selected basic concept:

Table 1: Total assembled cost breakdown CAPEX; capture technology and trailer transport with loading at Oslo harbor

CAPEX – capture and trailer transport with loading at Oslo harbor	**sum** mEUR
Capture plant EPC incl. suppliers unforeseen expenses (22 %)	133
Transport by truck incl. suppliers unforeseen expenses (20 %)	43
Total capture plant EPC and transport/intermediate	176
Owner's cost (estimated at 20 % of capture plant EPC, transport and loading)	35
Owner's unforeseen expenses (20 %)	7
Total owner's cost	42
Total cost capture plant EPC, transportation/storage and owner's cost	218
CAPEX – Total sum	**218**

Table 2: Total assembled cost for OPEX; capture technology and trailer transport with loading at Oslo harbor

OPEX – capture and trailer transport with loading at Oslo harbor	**sum** mEUR
Capture plant including suppliers unforeseen expenses (20 %)	11
Transport by truck incl suppliers unforeseen expenses (20 %)	5
OPEX – Total sum	**16**

In the cost estimates there are not placed additional reserves for cost overruns on top of contractor recommended sum for incidentals. This project reserve, which is normally not controlled by the project must be considered beyond the turnkey contract in a later phase.

5. Regulatory compliance

A carbon capture at Klemetsrud is likely to involve an exemption from the existing zoning, but there is a possibility for a new regulation. It should probably be drawn up an impact assessment in accordance with applicable law. It is also assumed new building permits, implementation of risk- and vulnerability analysis as well as adjustments of existing emission permits.

For the pipeline option a new zoning and environmental impact assessment is required. Offshore option would also involve maritime authorities. Transport by truck will simplify authority process compared with pipeline option.

6. Risk elements and project opportunities

Table 3: Key risk elements

Risks	**Possible measures**
The crowd possible resistance to carbon capture plant at Klemetsrud occasion. (NIMBY) Fear of large emissions of CO_2, amino compounds, ammonia and other harmful emissions.	System design according to the relevant safety standards, monitoring and detection systems Good and frequent information and communication with the public and stakeholders.
Emissions of CO_2, amino compounds , ammonia and other harmful emissions.	System design according to the relevant safety standards, monitoring and detection systems.
Available area of Klemetsrud is not compatible with the space requirements for carbon capture with refrigeration for trailer transport.	Area Studies, detailed design. Placing parts of capture in other areas, where possible and appropriate. Careful planning of manufacturing logistics and available laydown area. Consider the use of space for the bus terminal.
Cost overruns for owner and delays.	Careful preparation and monitoring of contracts with subcontractors. Dividing scope of work in several separate EPC contracts. Good change control. Quality Verification of technical documentation and design basis for contracts. Freezing concept.

The feasibility study considers the following four elements of risk as the most important, based on carbon capture technology and trailer transport with loading at Oslo harbor:

The following three project opportunities are rated as the most promising:

1. Demonstrate that integration of a carbon capture facility to an existing energy recovery plant without loss of thermal energy, using heat pumps and air coolers.
2. Capture of biological CO_2 and the global impact of this and future sales of CO_2 emission permits.
3. Finding a market for the waste products from the capture plant, thereby avoiding landfilling or treatment cost for these products.

7. New considerations, learning and dissemination potential

The global market for waste is enormous and steadily rising. According to the World Bank, and if one looks isolated on municipal solid waste and do not include industrial waste, this waste is increasing in a rate faster than urbanization rate. 10 years ago 2.9 billion urban citizens generated about 0.64 kg of waste per person per day (0.68 billion tons per year). At present it is estimated that 3 billion urban citizens generates 1.2 kg per person per day (1.3 billion tons per year). By 2025 the World Bank assess that the numbers will increase to 4.3 billion urban citizens, generating about 1.42 kg per person per year (2.2 billion tons per year).

If one examines the CO_2 emissions from existing waste facilities in Europe, it is stated that the waste has 228 point sources that emit 61.2 million tons of CO_2 per year (The European Pollutant Release and Transfer Register, 2013). It is believed that this is only the fossil proportion as the actual discharge is approximately 60 percent higher; ie 97.9 million tons of CO_2. Waste facilities are among the most important point sources of emissions after power generation in Europe, and about the size of cement production (133 million tons of CO_2).

Many areas of the world have landfills as a primary treatment solution for waste, which is not a sustainable solution. EU ban on landfilling of biodegradable waste, and the transition from waste disposal to energy recovery from residual waste means that carbon capture from waste will have a huge global transfer value. Carbon capture from waste incineration may influence climate impacts for the whole waste industry, providing even more CO_2-negative waste management and contribute significantly to cut global greenhouse gas emissions.

Waste is an industry that traditionally is heavily regulated, and often with great public interests, which can provide greater and faster penetration of demands for CO_2 capture. This can then be pursued by the individual governments, as local initiatives to achieve the objectives of a global climate and environmental agreements. Waste is also traditionally locally processed, and will in the future largely continue like this. This leads to the inability to move waste to countries with no requirement for CO_2 capture and avoiding therefore the risk of carbon leakage.

Oslo has adopted ambitious climate targets, with 50 percent reduction of greenhouse gas emissions by 2020 and a 95 percent reduction by 2030. An important prerequisite for achieving the city's climate goal is the establishment of a plant for carbon capture at Klemetsrud plant. KEA accounts for a significant proportion of the city's CO_2 emissions, and emit more than 300,000 tons of CO_2 per year. 60 percent of these emissions come from biological material. From a global point of view the removal of biological CO_2 is very important, since it in reality removes CO_2 from the atmosphere with the corresponding amount, and the source of the biological CO_2 will eventually grow back and again removing the corresponding amount of CO_2 (photosynthesis). The environmental accounting gets even better with increased sorting and recycling before energy recovery. That increases the bio proportion of waste incinerated, making carbon capture potential from energy recovery even more important in a global perspective.

One ton of waste produces about one ton of CO_2 during combustion. This shows that the potential is very large by establishing incineration with carbon capture, particularly if it is assumed that 60 percent of the waste has biological origin and is carbon neutral. Oslo wishes to contribute to the establishment of a concept for carbon capture from waste-based energy recovery, which is used for energy recovery in the world. It will be an important goal to spread the learning of a carbon capture plant at Klemetsrud. EGE and KEA has a long history of accepting visits and attend conferences, and see this as a key part of its social responsibility.

As part of the next phase and the eventual realization one should develop strategies and plans to disseminate knowledge and expertise, so that one is able to influence public opinion and decision-makers in other countries and sectors for the development of future carbon capture projects. KEA wants to involve NGOs to develop frameworks and concepts for carbon capture and fossil free transportation.

KEA see it as a natural part to utilize the skills of Gassnova and TCM to utilize their skills and receive technical assistance.

Besides the direct climate advantages, the establishment of a full-scale plant at KEA helps secure market advantages for receiving waste. It is often defined environmental criteria for tenders for the treatment of residual waste, and an energy recovery with carbon capture is expected to get good results in these tenders.

Oslo also has significant emission from the Haraldrud plants (waste incineration and pellet combustion), and there is potential for capturing additional about 150,000 tons of CO_2 annually from these facilities in addition to KEA.

8. Plan for the next phase

KEA will take over the project from the next phase, due to strategic discussions. The strategy presented in the feasibility study involves a FEED phase with a prior concept phase. Conceptual phase is planned over three months and subsequent FEED phase will lead to agreement on further phases where there will be one to three parallel FEED for the capture facility. Inviting more technology providers into the FEED-phase will provide several technology providers the opportunity to offer their best solution, while they are in competition. FEED phase will include milestones. Whenever there is an adequate decision -and tender to conclude a binding agreement for the establishment and operation, KEA can choose to continue with only one supplier.

KEA considers that there is a possible risk factor by a lack of transparency in the capture actors' processes, given the competition between them. To ensure a common good project implementation it is important that it is done reassessments when there is an adequate decision -and tender, then possibly go into a binding agreement for the establishment and operation with one supplier. The effect of any lack of transparency can also be muted with requirements for uptime, performance and operation as part of the contract.

KEA will develop functional specifications for FEED and realization. Angling on functional requirements must be designed so that the owner has the opportunity to influence technical solutions. Basically the FEED study for capture is going to be technology neutral, assuming sufficient number of providers.

The FEED phase can be split into five different types of contracts:

- Contract 1-3: FEED Carbon capture (2 to 3 suppliers),
- Contract 4: FEED Transport (1 to 2 suppliers),
- Contract 5: Engineering for EPC offers under KEA framework agreements,
- Earthworks Klemetsrud,
- Caching and unloading Oslo harbor,
- Transportation (truck),
- Integration with energy recovery systems, interfaces, and technical assistance,
- Government Involvement and applications.

Establishment of a full-scale carbon capture will be of great strategic importance to suppliers, as it will be one of the larger Norwegian onshore industrial projects in a few years. A full scale plant can be built and started up within 31.12.2020, given an investment decision no later than Q1 2018. Based on information about the presumed timeline for the entire value chain, capture, transport, storage, however, the plant can be built and started up within 31.12.2021 granted an investment decision no later than Q4 2018. The decision is assumed based on completed FEED study, and that the supply agreement for both the establishment and operation of a 3-year period is entered through the FEED study. To reach this time it must be expected to start work on regulation, environmental impact assessment and other regulatory approvals as soon as possible. Because of pre-study duration it is not necessary that the physical work starts parallel to regulation and impact assessment, all licenses are expected to be in place by decision project startup.

To ensure a good transition to the operational phase it is intended, as far as possible, a turnkey which includes operational phase the first three years (BOT; Build, Operate and Transfer). At the same time it will be established a good system for change orders, given that the project will be characterized by ongoing development and learning. This implies contract and an agreement for operation. It would be natural with two contracts that govern the various phases; both can be negotiated in the FEED phase.

An agreement for the operation should include:

- Guaranteed cost for the production phase
- *Performance based contracting*, ie a mechanism that drives operational cost down over time (stair model)
- Option for further operation, plus an option for only service.

The Norwegian Oil- and Energydepartment has in the complete study drawn the conclusion that a complete chain for carbon capture and storage in the North Sea can be operational in 2022.

9. Conclusion

EGE considers that the feasibility study demonstrates that carbon capture at the Klemetsrud plant, transport and loading of CO_2 for vessels in Oslo harbor, is technically and economically feasible. The feasibility study also shows that the implementation of the capture plant will be done without adversely affecting KEA, which remains and will fully maintain its primary function with energy recovery from waste and heat supply to the district heating network. The plant gets a higher specific consumption of produced electricity. Establishing CCS provides potential for future revenues from waste treatment and helping to lay the groundwork for increased future incineration capacity.

EGEs basic concept for the feasibility study are based on a ammonia process as carbon capture technology and the transport of CO_2 on trucks to intermediate storage at Oslo harbor.

Capture Technology:

- Both technologies have advantages and disadvantages. EGE will, due to both technical and commercial reasons not recommend doing a final choice at this time. Both capture technologies emerge as feasible and can be integrated with energy recovery. The assessments in the feasibility study indicate that carbon capture based on the ammonia process currently emerges at cost terms more favorable, but it is still too early to draw a final conclusion.

Transport and interim:

- EGE considers it necessary to make further efforts in the next phase to finally determine transport concept. The various risks must be assessed further, and investment and operating costs must be quality assured further before making a choice. The assessments in the feasibility study indicate that transportation by lorry currently appears most promising. Loading will depend on the development of Oslo harbor, there are several potential sites.

Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.dnb.de abrufbar

Karl J. Thomé-Kozmiensky, Michael Beckmann (Hrsg.):

Energie aus Abfall, Band 14

ISBN 978-3-944310-32-9 TK Verlag Karl Thomé-Kozmiensky

Verlag: TK Verlag Karl Thomé-Kozmiensky • Neuruppin 2017
Redaktion und Lektorat: Dr.-Ing. Stephanie Thiel, Elisabeth Thomé-Kozmiensky, M.Sc.
Erfassung und Layout: Sandra Peters, Anne Kuhlo, Janin Burbott-Seidel, Claudia Naumann-Deppe, Ginette Teske, Gabi Spiegel, Cordula Müller
Druck: Universal Medien GmbH, München