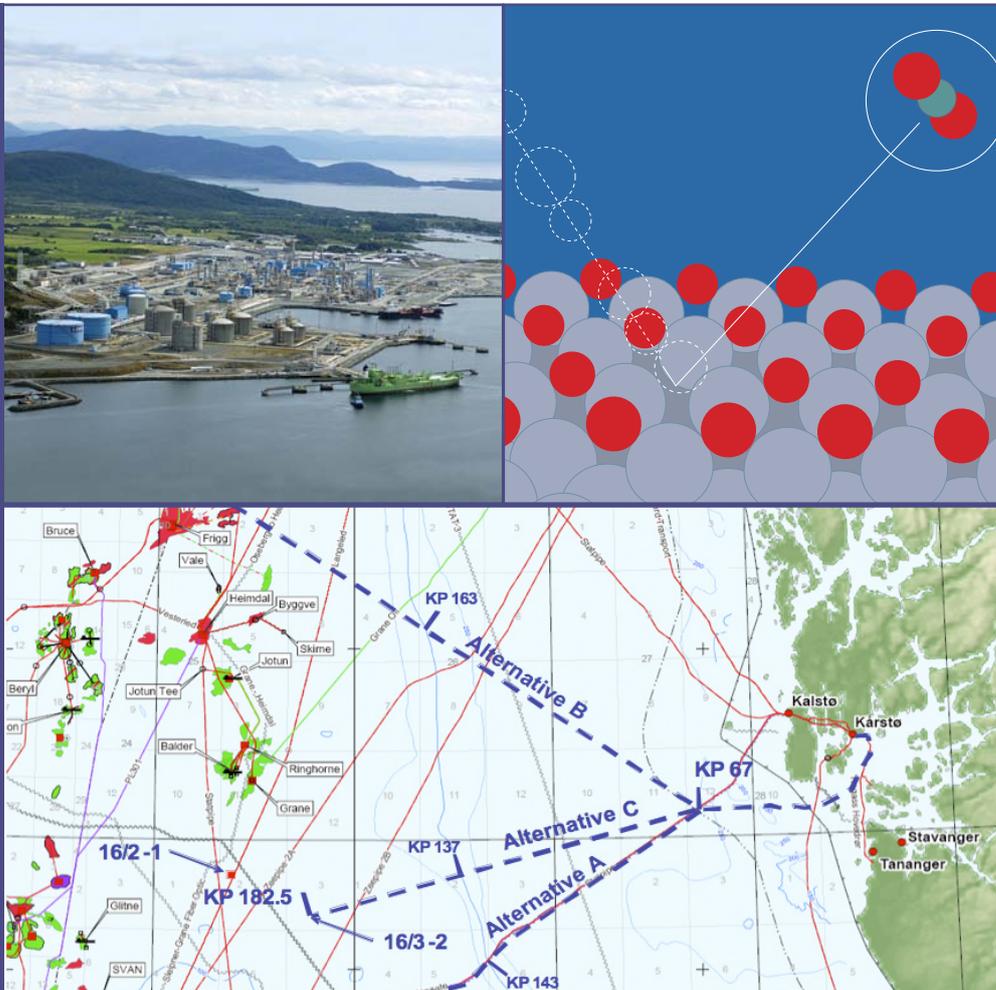


# Carbon Capture and Storage at Kårstø

*Pål Tore Svendsen (Ed.)*

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# **Carbon Capture and Storage at Kårstø**

## Report no. 3

# Carbon Capture and Storage at Kårstø

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**Summary:** The report describes technical, economic and scheduling aspects of a CO<sub>2</sub> capture and storage facility at Kårstø. Such a plant located at Kårstø would be around ten times as large as the biggest equivalent plant currently in existence. NVE regards it as likely that a full-scale plant would provide technical performance as described. The costs of the planning phase are estimated to be approximately NOK 330 million, investment in the capture plant around NOK 3.46 billion, and the costs of transportation and storage are estimated at NOK 1.56 billion. Based on the assumption of 8000 hours of operation, annual operating costs are estimated to be about NOK 370 million, leading to a cost of CO<sub>2</sub> abatement of about NOK 700 per tonne of CO<sub>2</sub> captured in the course of 8000 hours of operation. An ambitious but responsible schedule would see operation under way at the turn of the year 2011/2012. The project is exposed to a significant degree of risk in terms of performance, costs and time. The utilisation factor for the gas-fired power plant, energy costs, the fact that the plant would probably be the first of its size in the world, and commercial interfaces with the parties involved at Kårstø are all significant uncertainties.

**Keywords:** Gas-fired power, electricity, CO<sub>2</sub>, natural gas, climate change, amines, CO<sub>2</sub> pipeline, CO<sub>2</sub> storage, CO<sub>2</sub> capture.

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# Preface

This report represents the response of the Norwegian Water Resources and Energy Directorate (NVE) to the task assigned to it by the Ministry of Petroleum and Energy (OED); to carry out preparatory work related to the establishment of a project for the capture and storage of CO<sub>2</sub> from Naturkraft's gas-fired power plant at Kårstø. This has been a challenging task for NVE, particularly since our role has largely consisted of acting as a demanding and impatient plant owner vis-à-vis industry and other authorities.

The report discusses the challenges identified by NVE as being central to the next stages of the task of constructing a CO<sub>2</sub> capture plant at Kårstø and its associated storage solution. Working on this project, we have experienced a wider range of challenges than it has been possible to describe in this report. NVE therefore wishes to point out the importance of allocating the time and resources required to hand over the work that we have done to those who will carry on the project. NVE wishes to contribute to good handover and to the constructive continuation of the project.

In the course of our work, we have collaborated with a number of consultants and institutions. Olav Falk-Pedersen (Grenland Group) and Sverre Lund (Lucon) have worked closely with NVE and have done very good and important work. NVE has also enjoyed significant benefits from input and discussions with representatives of Gassco, Gassnova, Naturkraft, Norsk Hydro, OED, the Norwegian Petroleum Directorate (NPD), Petoro and Statoil.

During the course of its work, NVE has employed the engineering company M.W. Kellogg Ltd. (UK) in the preparation, implementation and evaluation of studies with the vendors of technology. M.W. Kellogg have also planned the necessary tie-ins at Kårstø and helped to evaluate alternative designs. Studies have also been carried out by Det Norske Veritas (DNV), GassTek, NILU and Norconsult.

NVE wishes to thank everyone who has contributed to the fulfilment of this project.

Oslo, May 2007



Agnar Aas  
Director



Pål Tore Svendsen  
Project Manager

# Executive Summary

This report describes technical, economic and scheduling aspects of a capture and storage facility for CO<sub>2</sub> from Naturkraft's gas-fired power plant at Kårstø. The facility will produce up to one million tonnes of CO<sub>2</sub> a year, and will include the capture plant, a CO<sub>2</sub> pipeline and CO<sub>2</sub> storage under the seabed.

The project was carried out by NVE between March and December 2006. It has provided insight into current technologies, investment and operating costs, a schedule for implementation and an overview of the risks and uncertainties involved in the project. The aim of these efforts has been to provide the central authorities with a good basis for future decision-making that will enable a capture plant at Kårstø to be built as soon as possible.

**Available technology:** A number of smaller plants for the absorption of CO<sub>2</sub> from flue-gases already exist. This project has carried out comprehensive studies of relevant technologies with four technology vendors. The studies have revealed a high degree of similarity between these vendors with respect to process, design and costs.

A capture facility for the gas-fired power plant will be ten times as large as the largest existing plant for separation of CO<sub>2</sub> from gas turbine exhaust gas in Bellingham, Massachusetts, USA. NVE believes that it is technically feasible to design, construct and operate a full-scale plant with an acceptable capture rate and consumption of amines and energy. However, the significant scale-up raises the degree of uncertainty regarding performance, consumption and completion of construction and commissioning in comparison with the situation if such a plant had been built several times previously. In the fields of pipeline transport and CO<sub>2</sub> storage facilities, it is planned to employ available technology with relatively predictable technological solutions and costs.

**Cost estimates:** On the basis of technology studies, evaluations of potential deliveries and agreements with adjacent industry, studies of transportation solutions and current markets for materials, equipment and personnel, NVE have estimated investment and operating costs.

Total costs during the planning phase are estimated at around NOK 330 million, investment in the capture plant around NOK 3.46 billion, while the costs of transportation and storage is estimated at about NOK 1.56 billion (based on Sleipner as a solution for CO<sub>2</sub> storage). These figures add up to a total of about NOK 5 billion, with an uncertainty of ± 40%. This is a normal level of uncertainty at the stage reached by this project.

The estimate of investment costs is higher than previously published estimates for CO<sub>2</sub> capture plants. This is largely due to the fact that prices have been obtained in a market in which the level of activity is high, and because Kårstø is a demanding construction site where safety standards and requirements for coordination with other activities are high. Investment costs are also affected by a mark-up for contingency, which reflects the stage reached by the project, as well as the requirement for high capture plant regularity.

On the basis of 8000 hours of operation and assumptions regarding energy costs, annual operating costs are estimated at around NOK 370 million, i.e. a cost of around NOK 700 per tonne of CO<sub>2</sub> captured. Around half of the cost is related to operating costs, and the

other half to investment costs. The cost of CO<sub>2</sub> abatement is very sensitive to the annual operating hours of the power plant, with an abatement cost of more than NOK 2000 per tonne of CO<sub>2</sub> for 2000 hours of operation a year. The cost of abatement is also sensitive to changes in energy prices and investment costs.

**Implementation plan:** All the important choices of concept must be made and a number of factors investigated during the planning phase, before investment decisions are made and contracts signed. It is during this phase that the most important project decisions are taken and the foundations are laid for the choice of optimal solutions.

This phase involves the establishment of a project organisation, the taking of basic strategic decisions, the preparation and implementation of negotiations with nearby industry, initial planning, technology qualification, preparation of calls for tender, obtaining the necessary permits from the relevant authorities and summarising the results of these efforts as a basis for investment. An investment decision can be made during the autumn of 2008 at the earliest.

The construction phase involves the following activities: detailed design, purchase of equipment, module fabrication, installation, connection and commissioning. Activities must be adapted to and coordinated with other activities, CO<sub>2</sub> pipelines must be laid and the storage facility offshore must be established. The ordering, manufacture and installation of CO<sub>2</sub> compressors appear to be critical path elements in the construction phase of the project, as delivery times have been estimated at up to two years.

On the basis of the above considerations, an ambitious but responsible schedule suggests start-up at the turn of the year 2011/2012. An ambition to run the course more rapidly will involve risks of making unfortunate choices and incurring major extra costs. Start-up in 2009 is not regarded as feasible.

**Uncertainty and risk:** The project faces a significant degree of risk in terms of technical performance, costs and annual operating hours. The hours of operation of the gas-fired power plant will be determined by Naturkraft on the basis of power prices, gas prices and the cost of CO<sub>2</sub> quotas. The high investment cost of the capture plant mean that a low number of full load hours will significantly increase abatement costs per tonne of CO<sub>2</sub>. The energy costs of the capture plant (including compression) are high, and will depend on the market price of electricity. The plant will probably be the first of its size in the world, an aspect that in itself brings considerable challenges and risks. The project has a commercial interface with a number of industrial parties at Kårstø, and is dependent on suitable agreements being signed with these if construction and operation are to be cost-efficient.

Concepts for transport and storage have yet to be selected, and these also involve uncertainty as far as the costs and implementation of these parts of the project are concerned.

Rapid mobilisation of the project organisation, as well as a high level of competence on the part of the plant owner who will carry on the project, are extremely important. These aspects are potentially capable of leading to significant delays with respect to the suggested schedule. Revenues from sales of CO<sub>2</sub> quotas and of CO<sub>2</sub> for enhanced oil recovery (EOR) are potential upsides for the project. The number of full load hours and

energy costs are regarded as the most important risk factors as far as final capture costs are concerned.

Uncertainty with respect to rapid progress appears to be most closely linked to the mobilisation of a new project organisation, sufficiently rapid choice of concepts, efficient access at Kårstø as a construction site, the clarification of commercial and technical interfaces, sub-project coordination, the CO<sub>2</sub> regulation regime and unanticipated environmental and safety requirements.

**New challenges:** Since NVE was given the task of making preparations for a full-scale CO<sub>2</sub> capture plant at Kårstø, a number of new circumstances of relevance for the project have emerged. These include Gassco's studies of CO<sub>2</sub> value chains, the development of the Statoil/Shell project at Tjeldbergodden and Haltenbanken, the contract between the government and Statoil regarding Energiverk Mongstad and a range of different plans for thermal power plants with CO<sub>2</sub> abatement in Norway. Apart from evaluating potential coordination with other projects, no attempts have been made to deal with any new challenges emerging from these projects. If the schedule for Kårstø is followed, it will be possible to exploit experience gained from Mongstad to only a slight extent as far as learning and quality assurance of the Kårstø project are concerned. The project has been kept within the conditions of the mandate, and any modifications to the plans on the basis of new considerations will have to be made in later stages of the project.

**CO<sub>2</sub> capture:** Naturkraft's gas-fired power plant at Kårstø will come into operation in 2007, and the flue gas from the power plant is the capture plant's source of CO<sub>2</sub>. Because the capture plant will have to be retrofitted, only "post-combustion" absorption processes will be suitable for CO<sub>2</sub> capture at this site. The plants that have been supplied for similar flue gas compositions are usually based on amines as the absorption medium, and amines are regarded as the most suitable also for this site. A disadvantage of amine-based capture plants is the high energy consumption of the capture plant. The technology also produces a certain level of emissions of amines and other chemicals to the atmosphere.

In the capture plant, the flue gases from the power plant, which contain about 4% CO<sub>2</sub>, are cooled and passed through an absorption column, where exhaust gas is in direct contact with a mixture of water and amines. The CO<sub>2</sub> molecules bind to the amines and the mixture is transferred to another column where it is heated by steam and the CO<sub>2</sub> is released from the amines. The CO<sub>2</sub> free amine solution is returned to the absorption column, while the CO<sub>2</sub> is transferred to the compression unit where it is compressed and pumped to the final supply pressure. Separating CO<sub>2</sub> from the amines and recycling these requires large amounts of heat in the form of steam. The process also requires energy for compression and pumping of cooling water. The capture rate of CO<sub>2</sub> from the flue gases is around 85%.

**Technology:** Existing plants for absorption of CO<sub>2</sub> from flue gases are small plants for CO<sub>2</sub> production for the food and chemical sectors. The largest existing plant for capture of CO<sub>2</sub> from a gas turbine power plant has a capacity of about 100 000 tonnes CO<sub>2</sub> per year. In gas turbine power plants using gas turbines, combustion takes place with a high rate of excess air. This offers challenges in terms of large volumes of flue gases with low concentration of CO<sub>2</sub> and a high concentration of oxygen. The main challenge will be to minimise the investment costs and total energy consumption of the process. Optimising such plants also involves a number of technical challenges.

**Interfaces:** The establishment of an optimal CO<sub>2</sub> capture plant at Kårstø will mean arriving at good solutions in collaboration with external parties. This concerns such areas as site location, steam supply, seawater for cooling, flue-gas reception, electric power supply, control systems and operation and freshwater. Important players here will include Naturkraft, Gassco and Statoil, and agreements will have to be signed regarding technical solutions and commercial conditions. The technical studies and cost estimates involved making a number of assumptions regarding these deliveries, but binding agreements have not yet been signed. The final choices made in this area will affect the design and cost level of the facility.

**Transport and storage:** The project has investigated and identified solutions for CO<sub>2</sub> transport and storage, but the final choice of concept have not been made. Safe, long-term storage is the baseline target solution, but the possibility of using CO<sub>2</sub> for enhanced oil recovery (EOR) has also been discussed.

In collaboration with the Norwegian Petroleum Directorate (NPD), five potential CO<sub>2</sub> storage sites have been evaluated: Heimdal, Karmsundet, Coastal (Kystnært) Utsira, Nordøst Frigg and Sleipner. The simple solution appears to be Sleipner. Here CO<sub>2</sub> is already being stored safely in the Utsira formation and it would probably be possible to utilise the existing injection well. The transportation distance is around 250 km. The platform would have to be modified in advance of receiving the CO<sub>2</sub>, and agreements with the Sleipner license and Statoil as operator would be needed. Coastal Utsira, using a subsea template is a possible alternative, and this should be the subject of further study.

CO<sub>2</sub> can be transported either by pipeline or by ship. Since the transport distances are moderate and in order to reduce the need for interim storage and expensive reheating and recompression on the field, it is recommended that transportation from Kårstø should be by pipeline. If sufficient water is removed from the CO<sub>2</sub> gas, pipeline materials and pipelaying methods already known from the offshore sector can be employed. On the basis of an indicative volume of 160 tonnes per hour, a 10 inch o.d. pipe should be sufficient. If it proves to be desirable to prepare for subsequent increases in transport volume and for use in EOR, the pipe diameter could be increased and other reservoirs considered.

**Health, safety and environment:** The environmental challenges of the capture plant particularly concern emissions to the atmosphere of amines, additives and reaction products, as well as ammonia, NO<sub>x</sub> and steam. The facility will also produce water-soluble salts that will need to be treated. Siting within the Kårstø area presents safety challenges with respect to adjacent plants, and strict safety requirements will have to be observed. CO<sub>2</sub> can only be stored below the seabed in accordance with international agreements.

Implementation of the project will require emission permits in accordance with the Pollution Act, treatment according to the Climate Quota Act, permits from the Petroleum Safety Authority (PSA), and possibly building permits, impact assessments and treatment in accordance with the Petroleum Act.

# 1 Introduction

## 1.1 Background, mandate and objectives

Under the terms of a letter dated 07.03.2006 from the Ministry of Petroleum and Energy (OED), the Norwegian Water Resources and Energy Directorate (NVE) has carried out a study concerning the establishment of capture and storage of CO<sub>2</sub> from Naturkraft's gas-fired power plant at Kårstø. The study forms a central part of the government's effort to implement CO<sub>2</sub> capture and value chains for utilising and storing CO<sub>2</sub> in suitable production reservoirs. The ambition of the government, as described in the Soria Moria declaration, has been that a CO<sub>2</sub> capture plant should start operation at Kårstø in 2009. The individual sub-projects that make up the government's efforts are the following:

Sub-project 1: Preliminary negotiations between commercial parties in a CO<sub>2</sub> chain.

Sub-project 2: Planning and design of a CO<sub>2</sub> capture plant at Kårstø.

Sub-project 3: Legal and organisational aspects of state involvement in a CO<sub>2</sub> chain.

NVE's participation is related to Sub-project 2. The physical facilities studied by NVE can be divided in their own turn into three sub-projects, namely **capture, transport and storage** of CO<sub>2</sub>. The objectives of NVE's efforts are summarised in Table 1.

**Table 1** NVE's objectives

Result measure	Effect measure
Establish cost estimates that cover the investment and operating costs of capture, transport and storage	Establish as good a basis as possible for the future work of implementing the project
Obtain knowledge of relevant technologies, survey capture efficiency, supplier guarantees, etc.	Provide the project sponsor with the best possible basis for evaluations and decision-making
Provide an overview of emissions to water and the atmosphere	Make it possible to start the operation of a capture plant at Kårstø in the course of 2009 or as early as possible
Provide an overview of risks and uncertainties	
Propose a realistic schedule	
Have a final report ready by the 4th quarter of 2006	

## 1.2 Project framework

**Mandate.** NVE's mandate is limited to capture of CO<sub>2</sub> from Naturkraft's gas-fired power plant at Kårstø. This power plant will be in operation before the construction of a capture plant for CO<sub>2</sub> can be started, a factor that limits the potential choice of CO<sub>2</sub> capture technology. Only capture of CO<sub>2</sub> from the power plant's flue-gases ("post-combustion" capture) is possible. The potential for integration of the power plant and the capture plant

is also limited, since the former was designed without taking the capture plant into consideration.

**Kårstø as a construction site.** Theoretically, around 155 tonnes of CO<sub>2</sub> per hour from the Naturkraft plant's flue-gases will be available for capture when the power plant is running at full capacity. Other sources of CO<sub>2</sub> are also to be found at Kårstø, but capture from these sources has not been taken into consideration. The CO<sub>2</sub> capture plant will have to be built as close as possible to Naturkraft's power plant in order to minimise investment and operating costs. This means that the CO<sub>2</sub> capture plant will be established within the same safety regime as the gas-processing facility at Kårstø.

Kårstø is an expensive location at which to establish a processing plant. Its location close to the gas-processing facility involves a number of requirements with regard to the planning, construction and operation of a CO<sub>2</sub> capture plant. This means that performance of the construction project will have to be coordinated with other ongoing activities at Kårstø, and requires that the project is given sufficient priority to ensure that it can be implemented within the limits of a responsible level of activity for the gas-processing facility as a whole. Given the quantities of natural gas that is processed every day at Kårstø, there will also be special requirements designed to prevent the possibility of accidents that could create a risk of explosion, to the design of power and control systems, to ensure safety against the risk of thermal radiation from process flares, contingency planning, access to the gas-processing facility, etc. The gas-processing facility is also subject to strict requirements regarding permitted noise levels and emissions of NO<sub>x</sub> and other components.

**Storage.** If CO<sub>2</sub> capture is to be of benefit to the climate, solutions are also needed for long-term storage of the CO<sub>2</sub> once the capture plant has come into operation. NVE has therefore studied and evaluated potential CO<sub>2</sub> storage solutions, where one of the criteria has been that the storage solution must be capable of being ready at the same time as the CO<sub>2</sub> capture plant. Any storage location will also require a transport solution, and this has also been studied and evaluated.

**Use of CO<sub>2</sub>.** In practice, the alternative to simple storage of CO<sub>2</sub> from power plants and other major sources is to use the gas for enhanced oil recovery (EOR). Separated CO<sub>2</sub> can also be used as an input in various types of industry, but a common feature of such industrial uses is that the quantities involved are minor in comparison with emissions of CO<sub>2</sub> by large gas-fired power plants and industrial complexes. It was not part of NVE's task to study the potential of CO<sub>2</sub> for EOR, but since such potential is expected to be an important factor in making the final selection of a solution for transport and storage, relevant characteristics of CO<sub>2</sub> for use in EOR have been studied as an aspect of the storage solutions.

**Rapid realisation.** The ambition of the government has been to have the facility in operation in the course of 2009. NVE has adopted this as a guideline insofar as it will require a rapid but responsible implementation of this measure. NVE has not regarded 2009 as an absolute requirement, but has attempted to establish schedules for planning and implementation that would lead to responsible realisation as soon as possible.

**Studies.** An important part of NVE's efforts has been the studies that have been carried out in cooperation with technology vendors. Since only a few such vendors are potential

builders of a CO<sub>2</sub> capture plant, good contact with those that do exist is very important. NVE believes that good contact has been established between the project and the technology vendors, contact that has been characterised by a high degree of interest in the project and mutual understanding and respect. The technology vendors have chosen to use very capable engineers in their studies, resources with a high alternative value in a “hot” market for engineering services. They have also demonstrated a general interest in what is happening in Norway.

**Guarantees and distribution of risk.** Since the CO<sub>2</sub> capture plant involves the use of technology on a new scale, it has been important for NVE to assess the potential for risk-sharing between the technology vendors and the developer. This has included an evaluation of various potential forms of cooperation between the parties involved, and what sort of contracted risks the technology vendors would be willing to assume.

**Annual hours of operation.** The capture plant will only be able to capture CO<sub>2</sub> when the gas-fired power plant is in operation. Naturkraft itself will determine when it wishes to generate electricity, and will decide on the pattern of operation. This means that the ability of the capture plant, the transport solution and the storage solution to follow changes in the production pattern of the power plant, including start-up and shutdown, will be important criteria. NVE has set as a requirement that the capture plant should be designed for a high degree of regularity, adapted to the power plant’s pattern of electricity generation.

### 1.3 Working process

Figure 1 illustrates the process adopted by NVE in the efforts involved in the production of this report.

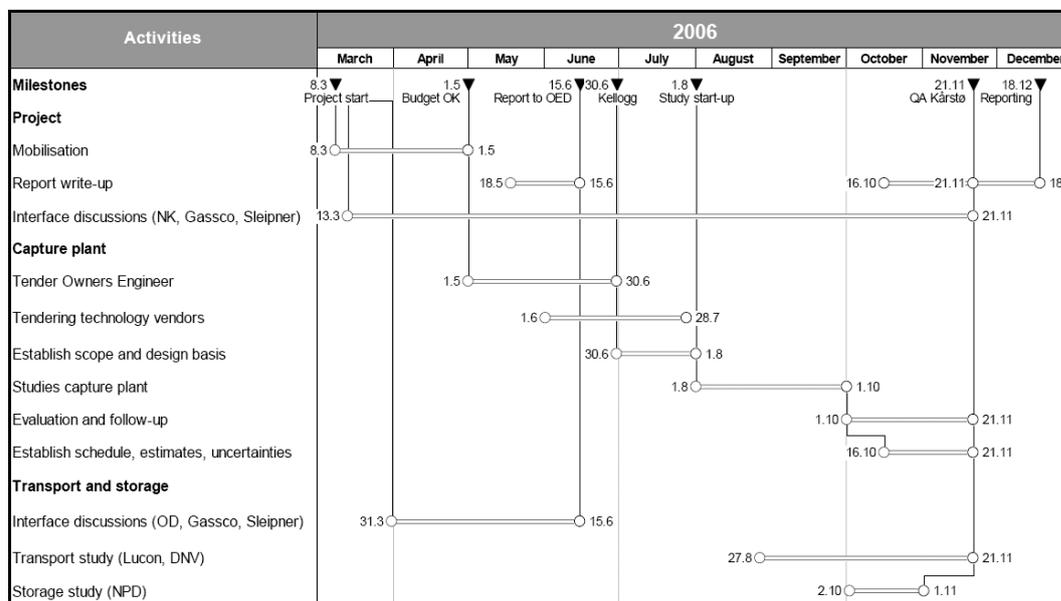


Figure 1 NVE project schedule

The assignment was received on 08.03.2006, while personnel mobilisation and clarification of the framework and financial aspects of the project were finalised by 01.05.2006. In the course of this period, contacts were initiated with most of the parties with whom NVE regarded it as appropriate to cooperate; these included Gassco, Statoil (in several roles), Naturkraft, Gassnova and the Norwegian Petroleum Directorate (NPD).

The project has advertised two public calls for tender throughout the European Economic Area (EEA), one of them to engage an owner's engineer and the other to identify and evaluate potential technology vendors. The owner's engineer contract was awarded to M.W. Kellogg Ltd. (UK), in competition with five other bidders.

Four studies were allocated to technology vendors who were evaluated as qualified for this purpose:

- Aker Kværner Engineering and Technology (AKET) [1]
- Fluor Inc. (California, USA) [2]
- HTC Purenergy (Regina, Canada) and Bechtel Inc. (USA) in a joint venture [3]
- Mitsubishi Heavy Industries (Japan) [4].

A further two companies submitted documentation, but these were not found to be qualified to perform the work in accordance with NVE's criteria.

The task of identifying suitable technologies for the transport and storage of CO<sub>2</sub> was carried out before the summer in close collaboration with NPD (storage) [6] and sub-project 1 (Gassco) [15]. Coordination between the different processes involved in the task of evaluating CO<sub>2</sub> capture and storage was established. NVE submitted a preliminary report to OED on 15.06.2006.

On 01.07.2006 M.W. Kellogg commenced its work for NVE, and the scope of work for the technology studies was drawn up in close collaboration with NVE in the course of July. At the end of July the process of qualifying the technology vendors had been completed, and these were awarded contracts and given the scope of work on 01.08.2006, with a requirement to deliver a draft report by 01.10.2006.

In a parallel process, NVE engaged Sverre Lund (Lucon) to continue work on CO<sub>2</sub> transportation solutions, while NPD was requested to continue its efforts to identify and evaluate potential storage locations for CO<sub>2</sub>. Det Norske Veritas (DNV) carried out a design study [9] as part of the transport study in October, based on the storage solutions that had been identified. Lucon [5] and NPD [7] submitted their reports December 2006.

In October, a great deal of time was put into studying, commenting and improving the studies carried out by the technology vendors. At the same time, the commercial conditions that NVE has used as a basis for its evaluations, particularly with regard to agreements with adjacent companies (interfaces) were determined.

In November, efforts were concentrated on the individual deliveries to the project, and on drawing up the final report. A number of quality assurance activities were also performed, both internally and with the participation of organisations outside NVE; these activities included a one-day seminar with Statoil at Kårstø on November 21. The results of the transportation study and the evaluations of storage solutions were coordinated.

Most of the efforts of the project in December were put into the revision and quality assurance of the report and its supporting documentation.

## 1.4 Coordination with other projects

Several projects are currently at various stages of evaluating CO<sub>2</sub> capture and storage in Norway. Most of the plans for gas-fired power plants that NVE is or has been dealing with – around ten such – involve an evaluation of CO<sub>2</sub> capture. There is also a considerable level of activity in research, studies and technology development in this area. These parallel activities and projects involve both possibilities and challenges for each individual project. In particular, the projects will face a struggle over limited resources (technology vendors, consultants, equipment). At the same time, there may be some benefits in coordinating certain activities between the individual projects.

In the following paragraphs NVE wishes to briefly discuss the relationship of the Kårstø project to the projects at Mongstad and Tjeldbergodden/Haltenbanken, and the K-Lab demonstration plant at Kårstø.

### 1.4.1 Technology qualification and development

Given that CO<sub>2</sub> capture on this scale has not been attempted previously, and because such capture will involve major investment and operating costs, activities such as technology qualification and technology development are important, as concerning both the implementation of projects and in the course of public debate.

In this report, the **technology qualification** concept is used of activities that are carried out to assure the quality of the solutions that potential vendors could envisage using as a basis for a plant and commercial contracts with acceptable risk today. Technology qualification is carried out in order to improve the insight of the plant owner into the plant that is going to be built, to reduce risk and to improve control of the remaining risk factors. Qualification may involve small-scale testing of technology, and is performed for the most part during the planning phase.

**Technology development** is used by NVE as a term for activities that is carried out in order to demonstrate and improve solutions that are believed to be available today. Technology development thus involves efforts to improve technology and reduce costs, emissions and risks relative to current levels. Technology development may involve the establishment of **demonstration** and/or **test plants**.

The purpose of a **demonstration plant** is to show that a given technology is capable of functioning on a scale that is larger than is in existence at the present. To build a full-scale capture plant at Kårstø using current technology on a scale that is ten times as large as anything built to date involves in itself major challenges and risks, and will help to bring the technology for amine absorption from gas turbine power plants a good bit further, even if the costs involved are high.

On the other hand, ambitions to develop new technological solutions are not included in the Kårstø project. New technological solutions might involve new absorbents, new process equipment or new ways of integrating the power plant and the capture plant. NVE does not regard the proposed facility as a **test plant**. Such a facility is currently being

built at K-Lab at Kårstø, and a contract has been signed by Statoil and the government to build a test facility with the capacity to capture 100 000 tonnes per year at Mongstad, to commence operation in 2010.

#### **1.4.2 Mongstad**

On 12.10.2006, a contract was signed by the Norwegian state and Statoil, regarding the development of a power plant and CO<sub>2</sub> capture plant at Mongstad, in two phases:

- Stage 1: Establishment of a power plant and a CO<sub>2</sub> test plant with the capacity to capture at least 100 000 tonnes of CO<sub>2</sub> per year, in the course of 2010
- Stage 2: Investment decision regarding full-scale CO<sub>2</sub> capture at Mongstad in 2012, with the goal of start-up taking place in the course of 2014.

This schedule indicates that the ambitions for Mongstad regarding *technology development* are higher than for the capture plant at Kårstø. Furthermore, thorough qualification of the technology that is proposed for use in the full-scale plant is also desired. The Kårstø and Mongstad projects ought to be able to learn a great deal from each other. The final schedules for the two projects will determine whether the Mongstad project will be able to make most use of the Kårstø project, or vice versa. Assuming that the schedule for Kårstø described in this report is followed, it will be possible to make only limited use of the experience gained in Mongstad Stage 1 as part of the learning and quality assurance in the Kårstø project. One possible exception might be to use Mongstad for the training of operating personnel. To benefit from potential technological innovations at Mongstad, the Kårstø project would have to be significantly postponed.

#### **1.4.3 Halten CO<sub>2</sub> (Tjeldbergodden – Draugen)**

Statoil and Shell are carrying out a value-chain project for CO<sub>2</sub>, based on using CO<sub>2</sub> from a gas-fired power plant at Tjeldbergodden for EOR in the Draugen field (and subsequently, Heidrun). This project has progressed about as far as the Kårstø project, a situation that has the potential to lead to competition between these projects for resources and capacity. Such competition might involve competent manpower, purchases of critical items of equipment and the attention of potential vendors of technology. There may also be synergies to be derived from collaboration on particular activities. Among other things, both projects have identified a need for long-term testing of absorbents, a process that could be performed in collaboration on a cost-sharing basis. Similarly, there may be gains to be made from coordinating other aspects of technology qualification, communication with vendors, scheduling, etc.

#### **1.4.4 K-Lab**

Via Gassnova and in collaboration with Statoil, the Norwegian state has plans to upgrade a demonstration CO<sub>2</sub> capture plant at K-Lab at Kårstø. This facility can be used to test chemicals and for other aspects of technology qualification and development. Aker Kværner's Just Catch™ project has plans to test absorbents at this plant. The facility will also be suitable for use on the Kårstø, Mongstad and Tjeldbergodden projects. It may turn out that demand for test capacity is much greater than this facility can satisfy, unless the various test programmes are coordinated. The facility may be the only large-scale test plant for CO<sub>2</sub> capture from power plant flue gases (with a high content of O<sub>2</sub> and a low

CO<sub>2</sub> content) in the world at the planned start-up, three years before the Mongstad test facility is planned to open.

## 2 The power plant and the capture plant

### 2.1 The gas-fired power plant

The flue gases from Naturkraft's gas-fired power plant will be the CO<sub>2</sub> source of the capture plant. The power plant will supply about 420 MW net electric power, and will release up to 2 MSm<sup>3</sup> an hour of flue gases into the atmosphere. The plant is what is known as a combined cycle plant, which uses a gas turbine and also utilises the exhaust heat from this unit to produce electricity via a steam turbine. Alternatively, the steam can be sold to external users, a step which will reduce the amount of electricity generated. The temperature of the flue gases from the power plant will be around 90°C. The general layout of the power plant is illustrated in Figure 2.



Figure 2 Naturkraft's gas-fired power plant at Kårstø (source: Naturkraft)

Gas turbines burn natural gas with a high rate of excess air in order to control combustion temperatures and cool the internal materials of the turbine. The volume of the flue gases from such power plants is therefore large, and the exhaust pipe will have a diameter of about eight metres. The principal components of the flue-gases will typically be (vol. %) nitrogen 75%, oxygen 12%, steam 8%, CO<sub>2</sub> 4%.

The power plant will be equipped with an efficient NO<sub>x</sub> removal system that will remove virtually all of the NO<sub>x</sub> (the remaining emissions are expected to be about 5 ppm NH<sub>3</sub> and around 2 ppm NO<sub>x</sub>). Emissions of SO<sub>x</sub>, VOC and particulate matter will also be very low.

## 2.2 CO<sub>2</sub> capture facilities

### 2.2.1 Chemical absorption

CO<sub>2</sub> can be captured from a gas-fired power plant by a chemical absorption plant (post-combustion), by decarbonising natural gas before combustion (precombustion decarbonisation) or after combustion with pure oxygen (Oxyfuel). Because the Kårstø power plant is already under construction using a conventional gas turbine, only a chemical absorption system can be implemented to capture CO<sub>2</sub> from Naturkraft's power plant. Most facilities that have been supplied to date for absorption of CO<sub>2</sub> from gas mixtures at low pressure are amine-based, and amines are also regarded as the most suitable group of absorbents for this project. It is possible to retrofit a capture system of this sort to an existing gas-fired power plant. The principal disadvantage associated with the use of amine systems is the high cost of energy, consumption of amines and other utilities. Amine systems also involve limited emissions of amines and other substances to the atmosphere.

Monoethanolamine (MEA) is most often used to absorb CO<sub>2</sub> at low pressure, and it is still the amine that is expected to be used by several vendors. The MEA process offers a number of challenges, which include corrosion, high energy consumption and a high rate of degradation of the amine itself.

Since the end of the 1980s, progress has been made in the development of new absorption chemicals, additives and processes aimed at obtaining better and more cost-efficient capture of CO<sub>2</sub> from flue-gases. The principal objectives of these developments have been to reduce:

- Energy consumption
- Amine circulation rate<sup>1</sup>
- Size of process components
- Amine consumption
- Corrosion

Mitsubishi Heavy Industries (MHI) was a pioneer with its KS-1 process, which involves the use of other amines than MEA. The KS-1 process reduces steam consumption, circulation rates and the consumption of chemicals in comparison with MEA-based processes.

### 2.2.2 The absorption plant

When the gas-fired power plant is in full production, the capture facility will typically be able to produce around 131 tonnes of CO<sub>2</sub> an hour. This is equivalent to about 1.05 million tonnes a year if the facility is in operation for 8000 hours. These figures mean that about 0.2 million tonnes of CO<sub>2</sub> would be released by the power plant instead of around 1.25 million tonnes without CO<sub>2</sub> capture, if it was in operation for 8000 hours.

The design proposed by the different vendors will be very similar, using the same main components. The process is illustrated in Figure 3.

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<sup>1</sup> The flow rate of the chemicals (mass per unit time) that are circulating at any given time between the absorber and desorber, and which require energy for heating and cooling.

The exhaust gas from the power plant is the source of CO<sub>2</sub>. The exhaust gas is cooled before it reaches the capture process itself in order to optimise the process. The flue-gas cooler is the largest consumer of cooling water in the process, typically using 50% of the cooling water (around 10 000 m<sup>3</sup>/hour).

The flue-gas will meet some physical resistance within the capture plant on its way to the atmosphere, and this will result in a certain pressure drop in the exhaust gas. In order to ensure that the power plant's gas turbine does not suffer a loss of power because of the capture facility, a blower will be located in the flue-gas duct, either before the cooling unit or between it and the actual capture plant.

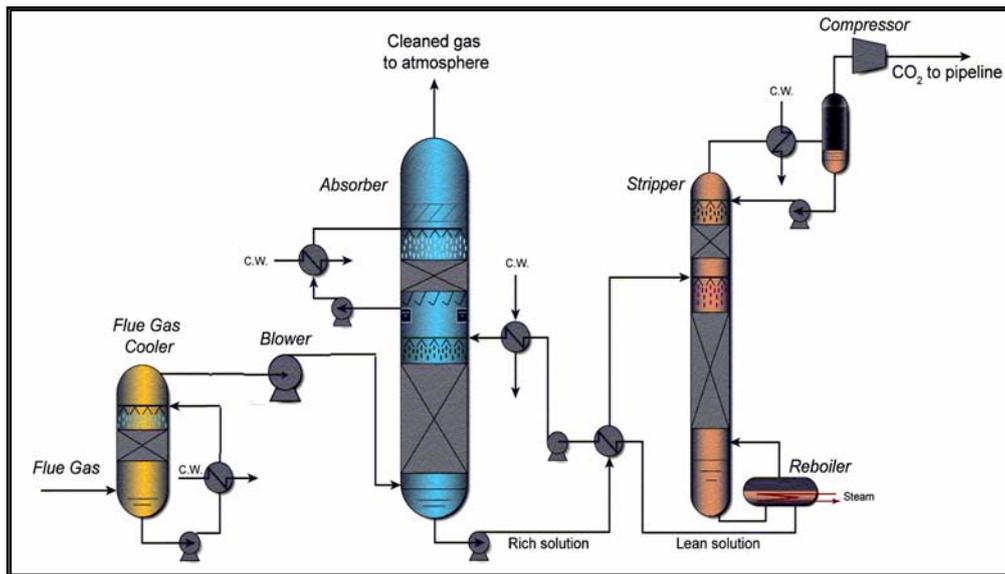


Figure 3 Typical amine process (Source: SINTEF)

From the blower, the gases are brought to the bottom of an absorption tower, which is filled with a packing material that offers a large surface that the absorption solvent follows on its way down through the tower. The solvent is an amine or a mixture of amines dissolved in water, which absorb the CO<sub>2</sub> in the flue-gas as it flows upwards through the tower. The CO<sub>2</sub> removal efficiency for flue-gases from gas-turbine exhaust will typically be 85%.

After the CO<sub>2</sub> has been captured by the amine, it has to be released by heating the solvent. The desorption of CO<sub>2</sub> takes place in the desorption tower, also known as a stripper. This is done by allowing the amine containing the CO<sub>2</sub> to flow down the packing material that fills the tower, while steam and CO<sub>2</sub> flow upwards. The steam has two functions: 1) it transfers the necessary heat to the amine, and 2) it draws the released CO<sub>2</sub> out of the tower. The mixture of steam and CO<sub>2</sub> that exits the top of the stripper is cooled down, and most of the steam is condensed while the CO<sub>2</sub> remains in a gaseous phase. The water is pumped back to the stripper while the CO<sub>2</sub> is directed to the dehydration and compression stages and on to transportation. The amine flows from the bottom of the stripper to the reboiler, where the steam used in the desorption process is generated. The heat for the reboiler is steam generated by heat from an external source. This reboiler is the largest consumer of heat in the CO<sub>2</sub> separation process. A flow of virtually CO<sub>2</sub>-free amine

solution leaves the boiler and is led back to the absorber, where it once again absorbs CO<sub>2</sub>.

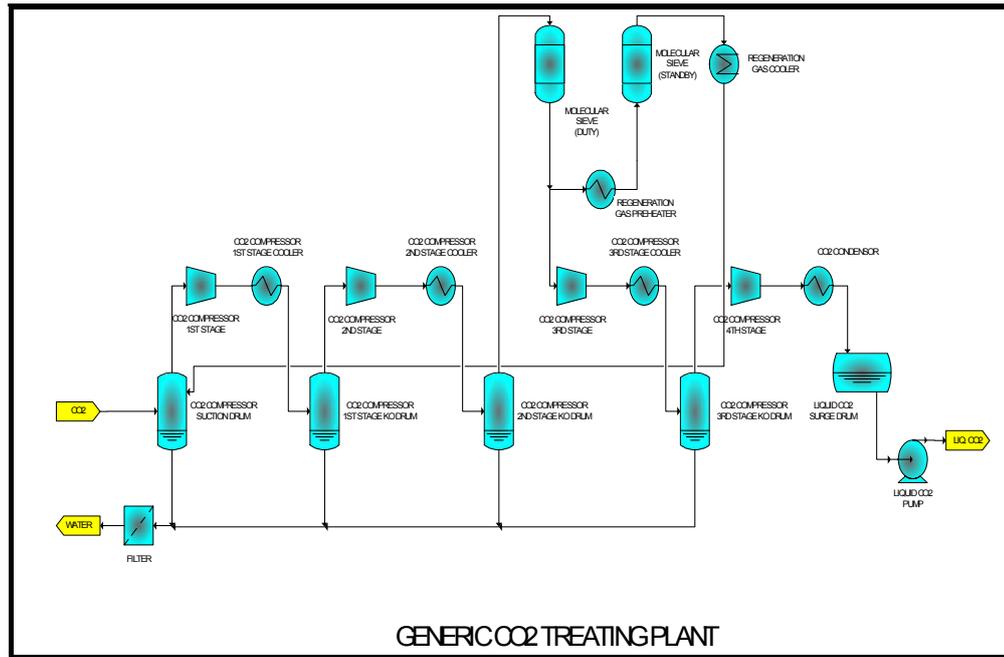
In the absorption tower, the reaction between CO<sub>2</sub> and amine produces heat, with the result that a certain amount of amine and water will evaporate during the absorption process and be carried upwards through the tower along with the flue-gases. The gas is saturated with steam and amines and typically contains 125 ppm amines, an unacceptably high emission rate in both economic and environmental terms. As well as losing a lot of amines, the water losses will also be large. In order to minimise water losses and emissions of amines, a water-wash process is integrated at the top of the absorption tower. Cold water with a low concentration of amines washes the flue-gases, dissolving the amines while the water balance is maintained by the steam being condensed by the cold water.

When the solvent comes into contact with the flue-gases, the amines will also react with other components in the flue-gas, such as O<sub>2</sub> and NO<sub>x</sub>. How much of these are absorbed will vary from one amine to another, and will also depend on the design of the absorption tower. These reactions form heat-stable salts that will not be released from the amine solution by the stripping process. Since the amine mixture is circulated between the absorber and the desorber, the amount of heat-stable salts in the solvent will gradually rise. After a certain period of time, the concentration of these salts will be so high that the CO<sub>2</sub> absorption rate will be reduced. This is handled by the use of a reclaiming unit. A side stream of the circulated solvent is heated so that the water and amines evaporate and are led back to the process. When the water and amines have been boiled off, what remains at the bottom of the reclaiming unit is a viscous liquid that must be treated as hazardous waste. The waste will contain some amines and water, but will consist mostly of heat-stable salts.

### **2.2.3 Dehydration and compression**

After the CO<sub>2</sub> has been separated from the flue-gas in the capture plant, it must be dried and compressed. This is done in a multistage process of compression, cooling and water separation. Pressure, temperature and water content all need to be adapted to the method of transportation (pipeline or vessel) and pressure requirement at the storage site. A typical compression and dehydration process for pipeline transportation is illustrated schematically in Figure 4.

CO<sub>2</sub> from the capture plant arrives at the dehydration and compression stage at about room temperature and at a little above atmospheric pressure. Apart from the CO<sub>2</sub>, the gas contains some steam and small fractions of impurities (nitrogen, oxygen, and traces of amines and other substances).



**Figure 4** Flow diagram for CO<sub>2</sub> compression and dehydration (Source: M.W. Kellogg)

When CO<sub>2</sub> is being transported by pipeline, compression requirements are determined by the supply pressure at the delivery site and the pressure drop through the transportation pipeline. The pressure in the pipeline should always be high enough to ensure that the CO<sub>2</sub> is in a supercritical state, i.e. above 50 – 70 bars, depending on the temperature. Where a simple storage solution is involved, the offshore supply pressure is 70 – 100 bars while the pressure requirement for EOR may be higher. In order to meet pressure requirements of this order, the pressure of the CO<sub>2</sub> may be anything from 150 bars to 300 bars or higher as it leaves the capture plant, depending on the type of transportation and the storage pressure involved.

The combination of water and CO<sub>2</sub> in a pipeline creates corrosive conditions, requiring the water content to be kept low and monitored continuously in order to avoid corrosion and hydrate formation.

## 2.3 Studies with technology vendors

There already exist a number of facilities for absorbing CO<sub>2</sub> from exhaust gas. Most of these are relatively small units that typically produce CO<sub>2</sub> for the food industry (up to 100 000 tonnes a year), while five larger units are utilised by the chemical industry.

What is special about flue-gases from gas turbine power plants, compared with gases from coal-fired power plants or CO<sub>2</sub> capture from other gas flows, is that combustion in gas turbines takes place in the presence of a large excess of air. This presents three challenges; first, that the total gas volume will be high, secondly, that the concentration of CO<sub>2</sub> will be correspondingly low and thirdly, that there will be a high concentration of oxygen in the flue-gases. NVE is aware of only one plant that has captured CO<sub>2</sub> from flue-gases from a gas turbine power plant on a commercial scale for several years. This plant, in Bellingham, Massachusetts, captures only 10% of the quantity of CO<sub>2</sub> that is

envisaged at Kårstø (100 000 tonnes). The technology vendors have made significant technological advances since the Bellingham plant was built, but these improvements have not been adopted in units of equivalent or greater capacity.

As mentioned above, NVE has carried out studies of technology with four vendors, and these are described and evaluated below. The studies show a high degree of similarity in terms of the processes involved, design and costs. There are only minor differences in the vendors' estimates of the investments costs of these plants; a consequence of relatively similar processes and the widespread use of commercially available equipment. The variable operating costs, which are largely a matter of energy consumption, are also similar. Due to confidentiality agreements between NVE and the vendors, the following evaluations are made at an aggregated level.

### **2.3.1 Aker Kværner (AKET)**

AKET is a supplier with know-how of the design and construction of major process facilities, including gas processing plants. AKET runs a technology development programme, supported by Gassnova and 12 industrial partners, aimed at developing its technology and know-how for the supply of CO<sub>2</sub> capture plants. AKET has applied for several patents related to its Just Catch™ process. AKET does not have its own absorbent, but wishes to cooperate with existing absorbent vendors. The company has already built a CO<sub>2</sub> capture pilot plant at Kårstø; K-Lab.

The study performed by AKET is comprehensive. Since AKET does not have an amine process, it has based its design on a standard absorbent (30% MEA by weight, dissolved in water) and commercially available simulation software. In connection with optimisation of the heat consumption AKET has proposed a heat integration solution. NVE has not been given full insight into this heat integration system. AKET has also studied improvements that could be achieved by using an absorbent that is assumed to be available in the future. These assumptions and internal calculations make it difficult to evaluate the company's Just Catch™ process against those of other vendors. On the basis of the study performed, the AKET process appears to be less mature than those of MHI and Fluor.

### **2.3.2 Fluor**

Fluor has its own Econamine FG Plus (EFG+) process for CO<sub>2</sub> capture. In the course of the past 20 years the company has delivered 24 plants based on its process/License. Fluor's plant in Bellingham, Massachusetts has an annual capacity of 100 000 tonnes of CO<sub>2</sub> from gas turbine flue-gas, which is very similar to the flue-gas produced by Naturkraft's power plant. In the 14 years during which this facility has been in operation, Fluor has developed a wide range of know-how about its own process and potential optimisations. Fluor's study shows that the company understands the capture process very well, that it has a great deal of experience from EPC projects and that they have performed a number of studies related to CO<sub>2</sub> capture.

Fluor's process is based on the use of their existing absorbent and known process components, with two exceptions; a unit that is used as part of the heat integration process and a new amine reclamation process.

### **2.3.3 HTC Pureenergy/Bechtel**

HTC/Bechtel submitted a comprehensive study. HTC Pureenergy has made a large number of developments in the field of amine absorption, and has ambitions to develop this process further. Bechtel performed the planning and made the cost estimates for the technical study. On the basis of their study, the HTC process would appear to be less mature than those of MHI or Fluor.

### **2.3.4 Mitsubishi Heavy Industries (MHI)**

MHI has delivered four CO<sub>2</sub> capture plants, two of them pilot systems. They also have a number of plants currently under construction, although none of their plants will capture CO<sub>2</sub> from gas turbine power plants. Like Fluor, MHI has know-how about designing and constructing large process plants. As a major supplier of scrubbing processes for coal-fired power plants (sulphur, particle scrubbing, etc.) the company possesses both technology and know-how that would be useful in the design and building of a large-scale facility for CO<sub>2</sub> capture from a gas turbine power plant.

MHI has submitted a very comprehensive and detailed study. MHI has designed the process on the basis of its KS-1 absorbent, which has a number of advantages in comparison with MEA (see section 2.2.1). One uncertainty associated with this company's process is that KS-1 has never been used in a commercial CO<sub>2</sub> capture plant in which the oxygen content of the flue-gas is as high as in the flues-gases from a gas turbine power plant. The design and cost estimates have been presented very clearly, an aspect that offers confidence in their results.

## **2.4 Choice of technology**

As described above, there are many similarities between potential vendors as regards process design. At the same time, there are a number of technology choices that will have to be made when a plant of this sort is engineered, and each supplier has preferences that are adapted to its technology and its absorbents. The individual choices are also mutually dependent and are often patented, with the result that a potential plant owner is not in a position to choose among the solutions offered by different vendors and bring them together in his plant. Because of the need to protect their innovations, vendors are prepared to supply only a limited amount of information about them, particularly during the early stages of a project such as is represented by the efforts of NVE. In the following paragraphs, some of the relevant technology alternatives for a CO<sub>2</sub> capture plant at Kårstø are described.

### **2.4.1 Connection to the stack**

The connection to the stack can be made in one of two ways. One can decide to treat less than 100% of the flue gases in the capture plant so as to ensure that air is not drawn down through the outlet and into the absorption process. In order to achieve a scrubbing efficiency of 85%, the capture plant is thus designed to separate more than 85% CO<sub>2</sub> from the share of the flue gases that are sent to the capture plant. As an alternative, almost 100% of the flue gases can be introduced into the capture plant.

## 2.4.2 Flue gas cooling

Flue gases can be cooled in several different ways:

1. A cooling unit, in which the flue gases are sprayed with freshwater which evaporates, cooling the flue gas in the process. The freshwater goes through a cycle in which the heated water is condensed by seawater in a heat exchanger before it is pumped back to the flue-gas cooler.
2. Hybrid solutions, in which the cooling unit is located in a separate section at the bottom of the absorption tower, in order to reduce the number of process components.

These solutions have been evaluated and the following conclusions have been drawn:

- The degree of cooling is important for the water balance
- The choice of technology has little influence on total costs.

## 2.4.3 Absorber design

Vendors can choose from among several designs for the absorber itself. They can choose between circular and square towers. The absorption towers can be filled with special randomly oriented rings that distribute the absorbent, or utilise a more structured packing design. All of these possibilities are known and used in other industries, and the vendors have chosen to employ well-known packing materials.

## 2.4.4 Energy consumption

Capturing CO<sub>2</sub> from the flue gases of gas turbine power plants is a very energy-intensive process, and energy costs are a dominant proportion of the operating costs of the plant. Research and development that aims to significantly reduce the costs of CO<sub>2</sub> capture ought therefore to focus on the energy consumption of the process. The capture plant's energy consumption will be influenced by the chemicals used, the design of the process plant and its degree of integration with the power plant. Energy consumption is a combination of electricity consumption and steam consumption. If steam is extracted from the gas power plant, both electricity and steam consumption will mean that the power plant can supply less electricity for sale outside Kårstø.

The desorption part of the capture plant has by far the greatest need for heat. Steam consumption in the capture plant will be about 160 tonnes per hour. When this steam is extracted from the power plant the steam turbine will receive less steam and the electricity generation in the steam turbine will be reduced by about 36 MW.

In the studies that have been carried out, electricity has been used as the source of energy for all rotating equipment (compressors, pumps, etc.). The power consumption of the capture plant itself is 12 – 13 MW. Compression and pumping the CO<sub>2</sub> produced will also require a great deal of energy. The individual vendors have proposed different technical solutions, so that their estimates of power consumption for compression and pumping range from 15 to 17 MW. The total power consumption of the capture plant will thus be between 27 and 30 MW.

Table 2 illustrates the energy requirements of the capture plant with respect to the power plant.

**Table 2** Energy consumption in the capture plant (including compression of CO<sub>2</sub>)

	<b>Net power generation (MW)</b>	<b>Reduced power supplied “ex-Kårstø” (MW)</b>	<b>Total efficiency with CO<sub>2</sub> capture (%)</b>
Power plant without CO <sub>2</sub> capture	420	0	58
Power plant with steam and power extraction	354	66	49

#### **2.4.5 Water wash and water balance**

Water must be used at the top of the absorption tower to absorb emission components from the flue-gases before these are released to the atmosphere. The conventional method consists of cooling the flue gases from the absorption section of the absorber using a water spray from a separate water wash system. A large proportion of the water and the amines in the flue gases will condense and will be led out of the absorber. In order to further reduce amine loss, clean water is introduced into the final polishing stage. If a relatively low temperature is chosen for the exiting flue gases, the process will be a net producer of water, while the loss of amines will be very low. The disadvantage of this method is its high consumption of water. The degree of cooling in the water wash stage and the quantity of clean water used in the polishing stage differ from supplier to supplier. There are uncertainties with respect to Kårstø’s freshwater and seawater supply capacity, and the water wash in the absorption unit and the overall water balance of the plant can potentially be used to adapt to the framework conditions, when these are better known.

#### **2.4.6 Amine reclamation**

The reclamation unit is needed to remove the heat-stable salts from the absorbent. A conventional reclaimer will typically require about 1000 m<sup>3</sup> a year of hazardous waste to be transported away from the plant and deposited as landfill (this applies to plants that utilise MEA as absorbent). There are environmentally acceptable ways of destroying this waste. In Norway, there exist at least two companies that are potentially capable of handling such waste; Norcem and NOAH

An alternative is to integrate an incinerator unit into the process. A unit of this sort will also be capable of incinerating amines, glycol, waste oil, etc present in other liquids. The incinerator unit will be in continuous operation and must be fed with waste amines from a tank. It will produce annual emissions that are low in comparison with those of the power plant and the capture plant.

A new concept for solving some of the environmental problems associated with CO<sub>2</sub> capture plants is based on two of the operational challenges presented by such facilities; the emissions to the atmosphere of the absorber and the treatment of degraded amines

from the reclaimer. The solution involves continuous regeneration/purification of the amines. Virtually uncontaminated amines leave the process along with a liquid flow that should be clean enough to be discharged directly into the Kårstø drainage system. The other environmental advantage is related to emissions of degradation products that are stripped from the absorbent in the absorption tower and are discharged to the atmosphere together with the flue gas. These components are produced at extremely low concentrations, but with continuous stripping of undesirable components from the absorbent, such emissions will be reduced even further.

## 3 Interfaces

In this report, the term “interface” refers to all issues and physical connections whereby the capture plant is dependent on supplies from, or agreements with, external companies. A number of important interfaces will have to be clarified before a capture plant can be built. This applies in particular to the commercial and technical interfaces with Naturkraft and with Gassco, the operator at Kårstø. The most important interfaces are discussed below, including the concepts on which NVE has based its work and the alternatives available.

### 3.1 Parties involved

**Naturkraft**, which is owned equally by Hydro and Statkraft, owns the gas-fired power plant that is currently under construction at Kårstø. NVE has discussed the important interfaces of site, steam, seawater, flue-gases and electric power with Naturkraft, and a joint understanding of the points of departure of the parties involved has been established. Naturkraft has declared that the company is ready for further discussions and negotiations when a framework for the next stages of the project has been established.

**Gassco** is the operator of the Kårstø gas-processing plant, which is owned by **Gassled**. This company is owned by the oil and gas companies that have invested in the gas infrastructure on the Norwegian continental shelf. **Statoil** is Gassco’s technical service provider (TSP) at Kårstø, which means that Statoil possesses much of the engineering resources and detailed knowledge of the operation of the Kårstø plant. NVE has engaged M.W. Kellogg in addition to holding discussions with Gassco and Statoil in the process of clarifying the technical and commercial conditions for the establishment of a CO<sub>2</sub> capture plant at Kårstø. Gassco will provide an arena for coordination between the capture plant and other activities at Kårstø.

### 3.2 Site

The implementation and costs of most of the interfaces between the capture plant and its surroundings will depend on the siting of the capture plant. Since the CO<sub>2</sub> is to be captured from the flue gases of Naturkraft’s gas-fired power plant, the capture plant should be constructed as close to the power plant itself as possible. Transporting flue gases over any distance is a demanding process in terms of the size of the flue-gas ducting, and it would involve a pressure drop that would have to be compensated for by a higher consumption of energy.

The potential sites for a CO<sub>2</sub> capture plant are shown in Figure 5. Naturkraft currently holds the areas marked “Naturkraft” and “Sørlig tomt” on a 25-year long-term lease from Statoil. Sites are also available immediately to the north (“Nordlig tomt”) and east (“Østlig tomt”) of the power plant, both of them owned by Statoil. The siting of the power plant is such that the flue-gas outlet is on the east side.

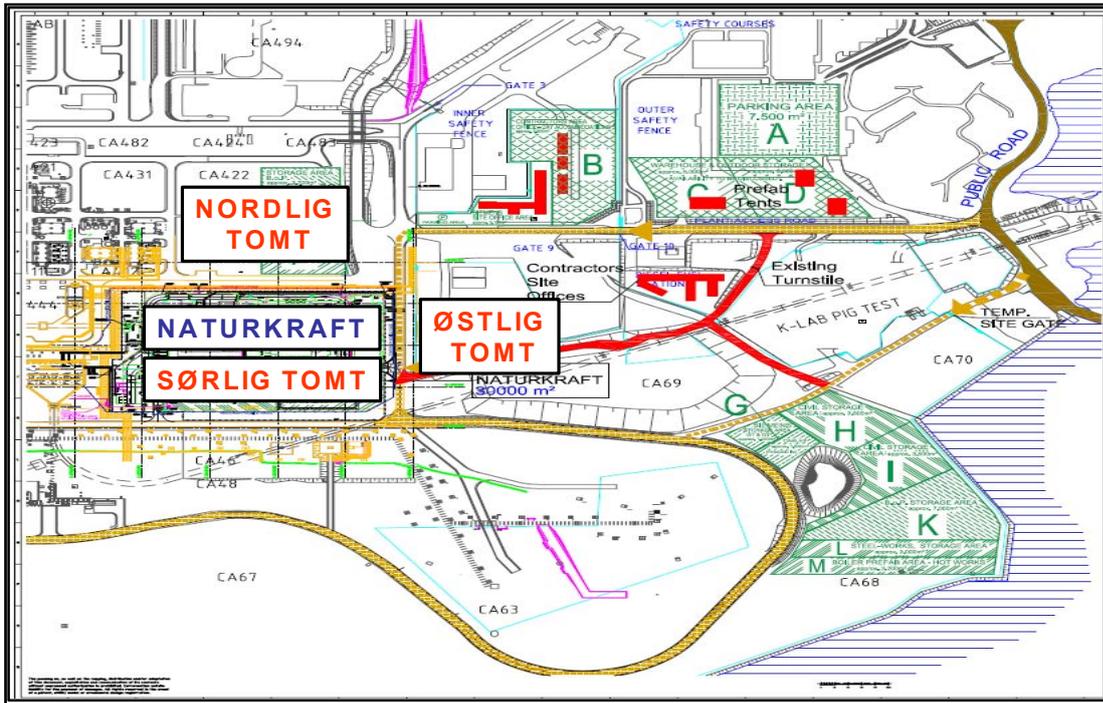


Figure 5 Layout of the Kårstø plant (Source: Naturkraft)

Naturkraft plans to use the southern site (“Sørlig tomt”) for a possible new gas-fired power plant at some point in the future. The company has therefore clearly indicated that it does not wish to see a CO<sub>2</sub> capture plant on this site.

Gassco has plans to develop Kårstø as a gas-processing site. The site north of the power plant site (“Nordlig tomt”) represents one of the last remaining possibilities for the expansion of gas processing at Kårstø, and Gassco is very negative towards the use of this site for a CO<sub>2</sub> capture facility. The same attitude is expected to be expressed by Gassled and Statoil. As TSP, Statoil is positive towards the use of an eastern site for the CO<sub>2</sub> capture plant.

Following discussions with Naturkraft, M.W. Kellogg and Statoil, NVE has taken the eastern site (“Østlig tomt”) as a basis for its studies. A solution based on the eastern site is illustrated in Figure 6. The alternative would appear to be the southern site. The eastern alternative would require somewhat longer piping of flue-gas, cooling water, steam and other capacities than the southern site. The eastern site would also require re-routing of the main module road at Kårstø, and would involve higher site preparation costs. On the other hand, such a localisation could involve less stringent requirements with regard to the work permission system and coordination with other projects, as well as offering more area, both during the construction phase and after the plant has been completed.

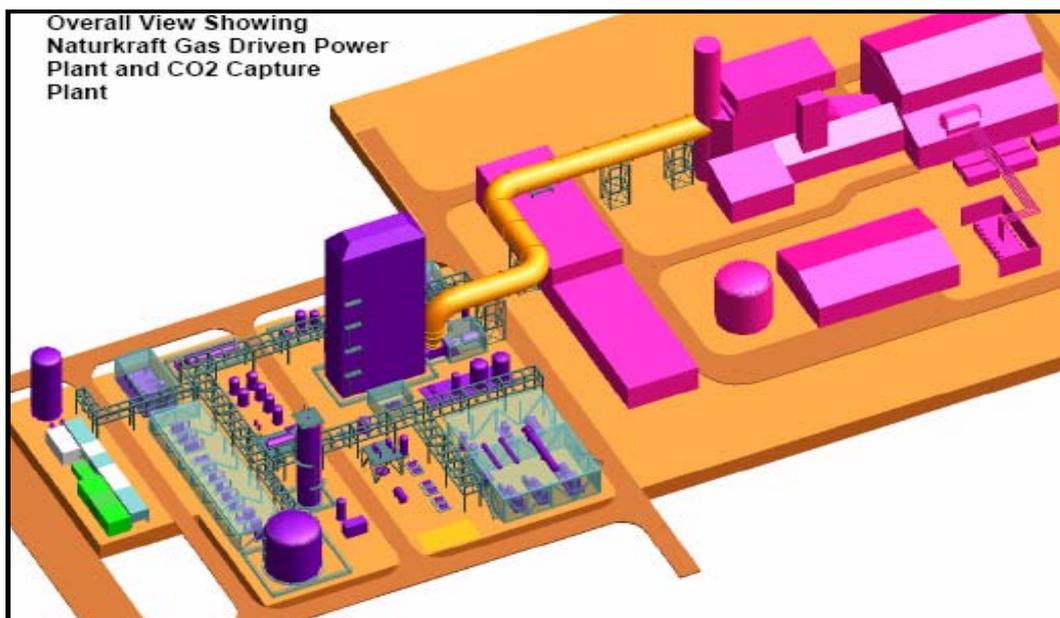


Figure 6 The CO<sub>2</sub> capture plant located on the eastern site (power plant is coloured pink, Source: AKET)

### 3.3 Steam

The CO<sub>2</sub> capture plant will have a high consumption of energy for absorbent regeneration. This energy will be consumed in the form of low-pressure steam, which can either be produced on-site or purchased from external sources. Naturkraft is an obvious potential supplier, which could extract low-pressure steam from the power plant's steam turbine. Other sources of steam can also be envisaged at Kårstø, where Gassco has begun to upgrade its steam supply system. Using externally sourced steam will involve returning steam condensate to its source.

If the capture plant has to produce its own steam from natural gas, using natural gas within the capture plant site will involve strict safety requirements, much higher investment costs, higher NO<sub>x</sub> emissions and larger quantities of CO<sub>2</sub>, which will mean both larger amounts of CO<sub>2</sub> being treated and more CO<sub>2</sub> emissions.

**Naturkraft** confirms that it would be technically possible to meet the needs of the capture plant for steam with low-pressure steam from Naturkraft's system. Transferring steam to the capture plant will involve a loss of power generation for Naturkraft, which will have to be compensated for. A solution along these lines will also demand additional investment in Naturkraft's plant.

**Gassco** does not wish to see its own steam production in connection with the requirements of a CO<sub>2</sub> capture plant, as this would raise the degree of complexity and establish undesirable interdependences between the plants. Gassco has already declined to purchase steam from Naturkraft.

**NVE** believes that purchasing steam from Naturkraft would be the best solution in technical terms for bringing steam to the capture plant, and has employed this assumption in the technical studies. It is quite possible to produce steam in a separate boiler, possibly

as part of the rest of the Kårstø steam-generation system, but this is expected to be significantly more expensive and would produce more emissions locally.

A study of the possibility of establishing a separate steam boiler has been carried out in order to assess the effects of having to produce steam within the plot space of the CO<sub>2</sub> capture plant. A solution along these lines is expected to involve using Naturkraft's flue-gases instead of combustion air in the steam boiler, and returning the flue-gases from the steam boiler to the capture plant (an additional 32 tonnes/h or so of CO<sub>2</sub> to the CO<sub>2</sub> capture plant). A complete study of the dimensions and costs of such a capture plant has not been carried out.

Some of the technology vendors will also need steam at a higher pressure than would be available from Naturkraft, for absorbent reclamation. The pressure required is equivalent to the steam pressure in the low-pressure steam grid at Kårstø, and it is assumed that the steam can be taken from this system. Steam consumption would not be continuous, and would involve small quantities of energy on an annual basis. Statoil TSP reports that such a supply of steam cannot be guaranteed at present.

### 3.4 Seawater

The CO<sub>2</sub> capture plant will have a significant seawater requirement for cooling purposes. At present, there is a seawater basin in the immediate vicinity of Naturkraft's site at Kårstø. Naturkraft estimates the capacity of this facility to be around 110 000 m<sup>3</sup>/hour, of which Gassco and Naturkraft each controls 50%. If the CO<sub>2</sub> capture plant is unable to exploit this existing capacity, a new seawater tunnel will have to be built at a high cost.

**Naturkraft** will use around 28 000 m<sup>3</sup> per hour in its gas-fired power plant. The remaining capacity which is at the disposal of Naturkraft will thus be necessary if a second gas-fired power plant is constructed at Kårstø.

**Gassco** currently fully utilises its share of the capacity of the seawater basin and thus has no spare capacity available for the CO<sub>2</sub> capture plant.

**NVE** has based its technology studies on the use of existing cooling water capacity at Kårstø, but has also studied an alternative, whereby a dedicated seawater tunnel for the capture plant would be constructed.

The CO<sub>2</sub> capture plant's seawater requirements can also be seen in the context of the other interfaces between the CO<sub>2</sub> capture plant and the gas-fired power plant. If the capture plant's need for steam can be met by low-pressure steam from Naturkraft, the amount of steam sent to the power plant's condensers will be correspondingly reduced, which in turn means that the quantity of cooling water sent to the condenser can be reduced. If the steam requirement of the CO<sub>2</sub> capture plant can be met in its entirety by purchasing steam from Naturkraft, a significant quantity of seawater could theoretically be released for other purposes. However, this quantity would not be sufficient to satisfy the total needs of the CO<sub>2</sub> capture plant, and will also require technical modifications of the power plant.

### **3.5 Flue gases**

The gas-fired power plant has been designed with a conventional stack, to which the CO<sub>2</sub> capture plant would be connected via a large flue-gas tunnel. Transporting flue-gases over long distances should be avoided, as this would demand significant amounts of energy to drive the fans needed to counteract pressure drop.

The tie-in to Naturkraft's stack will require a certain degree of clearance of the site and the moving of existing equipment. A considerable amount of foundation work and supporting structure for the flue-gas pipeline would also be required, as well as a damper to control the flow of flue-gases under different operating modes.

### **3.6 Electric power**

The CO<sub>2</sub> capture plant and the plant for dehydration and compression will require considerable quantities of electric power to operate the flue-gas fans, for compression and pumping of CO<sub>2</sub>, pumping of seawater, and for other small pumps. The CO<sub>2</sub> capture plant will not be in ordinary operation when the power plant is not generating electricity. This means that the capture plant can largely be supplied with power from the gas-fired power plant, and that it should be possible to avoid paying distribution costs and consumption taxes. A certain power requirement for turning down the plant and for running pumps to keep the facility warm (in order to avoid long-start-up times and equipment damage) will have to be drawn from the distribution grid.

### **3.7 Control systems and operation**

Operation of the CO<sub>2</sub> capture plant, transport and storage will have to be coordinated with the operation of the gas-fired power plant, and it would be useful to have a joint operations centre and control room for the two plants. Space and costs could be saved by not building a separate control room and organisation for the CO<sub>2</sub> capture plant, and rather installing the necessary equipment in Naturkraft's control room. Such a step would promote good coordination and a higher expected degree of regularity in the two plants. Alternatively, synergies could be obtained by integrating the operation of the plant with Gassco's operation of the gas processing plant, but the potential here is regarded as being less than via integration with Naturkraft. Such coordination would be sensible, and is one of the assumptions adopted in the technology studies. In order to identify the most important gains to be made by coordination, the establishment of a completely separate operating organisation has also been evaluated in terms of costs.

### **3.8 Natural gas**

The CO<sub>2</sub> capture plant will not utilise large volumes of natural gas unless the plant needs to produce its own steam. The plant could potentially use small quantities of natural gas if a system for waste destruction is incorporated, or if natural gas is used for regeneration in the CO<sub>2</sub> dehydration plant.

### **3.9 Raw water (freshwater)**

Depending on the design, the CO<sub>2</sub> capture plant could be either a net producer or net consumer of water. However, it will certainly be dependent on supplies of freshwater at commissioning and start-up and during other situations when it is not in regular operation. The supply of freshwater to the gas-processing plant at Kårstø is strained and there is some uncertainty with regard to whether the existing supply pipeline to the gas-processing plant will have sufficient capacity to supply the CO<sub>2</sub> capture plant with large volumes of water on a continuous basis. The possibilities and costs of establishing a new freshwater supply to Kårstø have not been examined.

### **3.10 Other potential interfaces**

Other connections and auxiliary systems, whose capacity can either be purchased from external sources or be generated within the CO<sub>2</sub> capture plant, include demineralised water (boiler water), instrument air, fire-fighting water, waste services, nitrogen, compressed air, emergency shut-down systems and fire and gas alarm systems.

The CO<sub>2</sub> storage solution will also require an onshore pipeline to the landing site of the submarine pipeline. The necessary valve systems and pig receiver for operation and inspection should preferably be located on the site of the CO<sub>2</sub> capture plant.

Table 3 presents a summary of the interfaces.

**Table 3 Summary of interfaces**

<b>Interface</b>	<b>Baseline alternative</b>	<b>Alternative solutions</b>	<b>Comments</b>
Site	Eastern site	Southern site, northern site	Site rental
Steam/condensate	Extraction from Naturkraft and some extraction from the gas-processing plant for absorbent reclamation	Own steam generation. Increased generation by the gas-processing plant	Condensate returned to the steam source, scrubbing of condensate not included
Seawater	Purchase of capacity from Naturkraft	New seawater tunnel	
Flue-gases	Tie-in to Naturkraft s stack		
Electric power	Operation: from Naturkraft Standby: national grid	Steam-powered operation of pumps, fans and compressors	
Control systems and operation	Coordination with Naturkraft	Independent organisation and control system. Coordination with gas-processing plant	
Natural gas	No consumption of natural gas	Natural gas for steam generation, chemical destruction or CO <sub>2</sub> dehydration	Could involve higher costs due to security concerns (fire/explosion hazard)
Flare	Not required	Required if natural gas is used	Tie-in could involve complete shut-down at Kårstø
Raw water	Virtually zero consumption	Major consumer Major producer	Uncertainty with respect to supply capacity
Demineralised water	Demineralisation plant incorporated	Utilise existing capacity	
CO <sub>2</sub> pipeline	Interface on CO <sub>2</sub> capture plant site		Supply pressure determined by storage solution
Fire-fighting water	Tie-in to existing fire-fighting system	Establish own supply	Establish new ring main around plant site
Instrument air	Own production	Utilise existing capacity	
Compressed air	Own production	Utilise existing capacity	
Nitrogen	Own production	Coordination with gas-processing plant	Nitrogen not available at Kårstø at present
Waste	Largely own treatment processes	Coordination with gas-processing plant	Wide range of waste flows (see section 7.3)
Safety systems	Some integration required		

# 4 Transport and storage

In its efforts to identify a potential solution for the transport and storage of CO<sub>2</sub>, NVE has concentrated its resources on studying a range of alternatives, without making a final choice of concepts. In this chapter, NVE presents a number of alternative concepts, along with their advantages and disadvantages. These concepts need to be worked on in more detail, in both technical and commercial terms, particularly with respect to the offshore production licenses that could be affected, before choices are made. The evaluations were made in close collaboration with the NPD.

## 4.1 Suitable reservoirs

Optimal storage security can be obtained when CO<sub>2</sub> is stored in abandoned oil or gas fields that have demonstrated their ability to hold natural gas for millions of years. Water-filled reservoirs (aquifers) may also be suitable, but in such cases there is a need to ensure that their layer of cap rock has sufficient sealing capacity. Alternatively, the distance from the point of injection to areas where the cap rock sealing capacity is limited should be sufficiently large to ensure that injected CO<sub>2</sub> will not leak out of the reservoir. The Utsira formation in the Sleipner area is one example of an area that would offer safe storage in an aquifer.

In collaboration with the NPD, NVE has evaluated a total of five potential CO<sub>2</sub> storage sites. These sites do not represent a complete survey of all potential storage sites for CO<sub>2</sub> from Kårstø, but are those that have been possible to assess on the basis of the data that NPD currently possesses. There may thus exist potential storage sites that are just as secure and cost-effective. However, an exhaustive survey would be very expensive, while there is no guarantee that it would lead to any better solution.

The following potential storage sites for CO<sub>2</sub> have been evaluated and are illustrated in Figure 7.

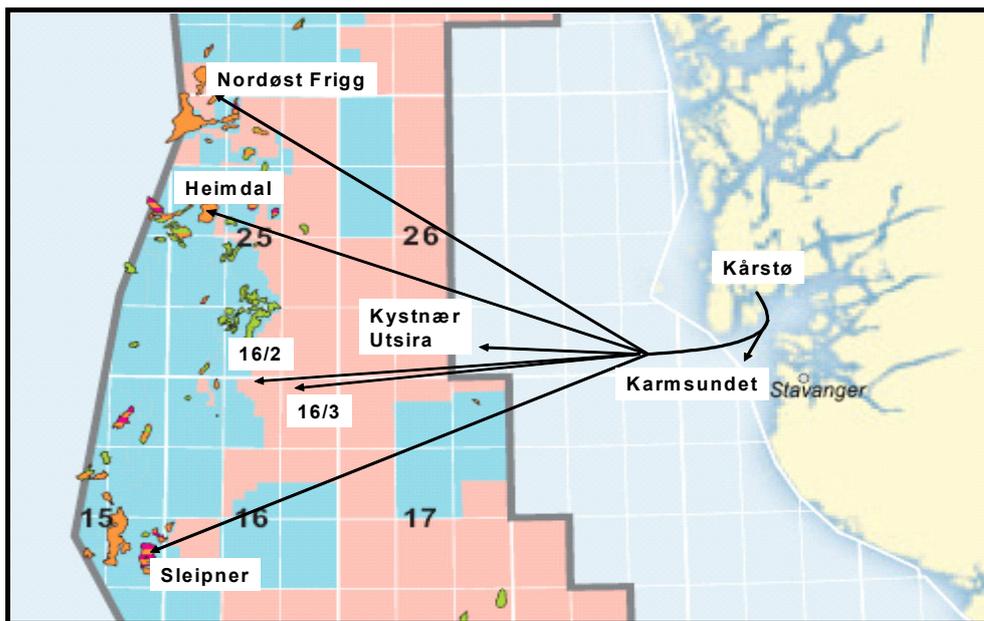


Figure 7 Storage alternatives for CO<sub>2</sub> from Kårstø (Source: NPD)

**Heimdal** is a hub for the processing and distribution of gas, and consists of an integrated drilling, production and accommodation facility on a steel jacket, as well as a new riser platform. Heimdal has held natural gas at high pressure for a long period of time, and is regarded as a secure potential storage site. Heimdal is situated approximately 220 km along a potential pipeline route from Kårstø, and it would probably be possible to convert a production well on the field to a CO<sub>2</sub> injection well. The disadvantages of Heimdal are the considerable costs of modifying and preparing the site for injection, uncertainty regarding the time of removal of the platform, and potential conflicts with current gas production.

**Karmsundet:** In Karmsundet there is a basin of sedimentary rock, which the NPD has evaluated as a potential site for CO<sub>2</sub> storage. It is bounded to the east by a large normal fault that falls to the west, while the geological properties of its western limits are unclear. The basin is partially overlaid by shale, but some parts of the overlying layers are heavily faulted. Uncertainties with regard to sealing and the depth of the structure suggest that it would not be suitable for CO<sub>2</sub> storage.

**Coastal Utsira (Kystnær Utsira):** The NPD has considered the possibility of injection using a subsea template in the Utsira formation, independent of Sleipner and as close to Kårstø as possible. The extent of the Utsira formation with its grid references is shown in Figure 8. Storage in Utsira would involve relatively low transportation costs, but would require comprehensive charting and studies, drilling and intervention from a mobile rig, steering and control cabling from shore and its own monitoring programme.

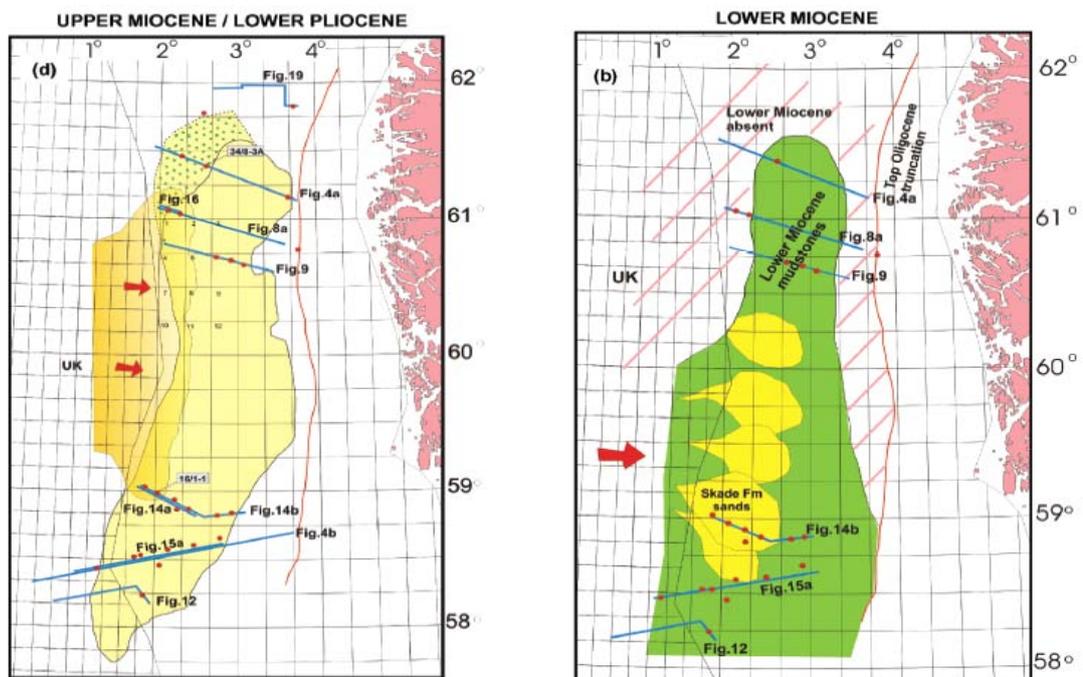
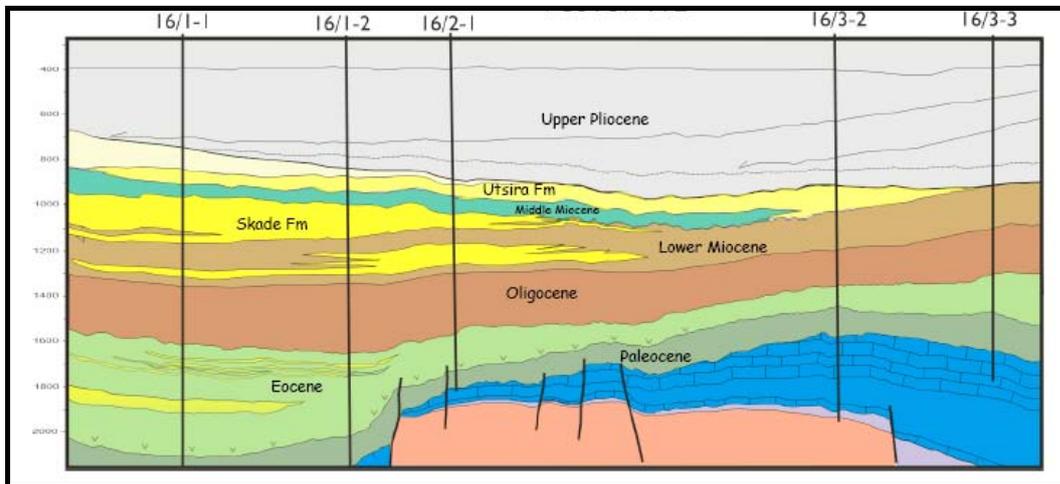


Figure 8 Sketch of the Utsira formation (left) and the Skade formation (in yellow) on the right [17]

Only limited data for the Utsira formation are available. Although most of the wells in this area of the North Sea have been drilled through the Utsira formation, well logging was not always performed. On the basis of the data and surveys of the Utsira formation in the hands of the NPD, the area south of 59° N would be most suitable for CO<sub>2</sub> injection and storage, as far as storage security and distance to Kårstø is concerned.



**Figure 9** Cross-section of the Utsira and Skade formation in blocks 16/1, 16/2 and 16/3 [16]

The area between 59° and 61° N has not been studied in equivalent detail, and further studies are needed to be certain of the potential for CO<sub>2</sub> storage there. In such a case, the Skade formation would probably be more suitable than the Utsira formation in this area. The Skade formation lies beneath the Utsira formation (see Figure 9). It appears to have a good overlay, but better surveys of the characteristics of the reservoir and its extent are required in order to assess its capacity and storage security.

As far as a coastal solution involving Utsira is concerned, block 16/3 is regarded as a sensible area for storage, and this would require a pipeline of at least 180 km. This would provide a guarantee that the formation is tight, so that there would be no need to invest in drilling a well to demonstrate the suitability of this area for storage. Furthermore, at the moment no license has been issued for this block, so that there would be no commercial interface with an offshore operator.

There may be other locations closer to shore in the Utsira formation whose properties would make them satisfactory for long-term CO<sub>2</sub> storage, but in order to be definite about the areas to the west of Kårstø comprehensive studies would have to be carried out in order to determine whether or not such storage would be possible. Adequate seismic data for use in such a study are assumed to exist, but a new well would have to be drilled in order to obtain sufficient data about the extent of the reservoir, its injection characteristics and its sealing. Pre-investment in such a project is estimated to be of the order of NOK 200 - 300 million. The costs, plus the risk that an area closer to land would not be suitable for long-term CO<sub>2</sub> storage, have led the NPD to recommend that a location in block 16/2 or 16/3 should be chosen for the coastal Utsira solution. Coastal Utsira will require

further studies, but the risk that this solution will turn out to be unsuitable is regarded as low.

**Nordøst Frigg** was a satellite field to the Frigg field. The field entered production in December 1983 and production ceased in 1993. All the installations on this field have been removed. The reservoir is connected to the Frigg field via an underlying aqueous zone. The water depth is 100 m and the reservoir pressure at the time of shut-down was 159 bars. The field has been taken over by the state, but some interest in the field was shown in the 2006 licensing round. It is therefore uncertain whether Nordøst Frigg could be a candidate for CO<sub>2</sub> injection and storage. The Nordøst Frigg reservoir is well mapped, but reference data would have to be obtained before CO<sub>2</sub> injection could commence.

**Sleipner** is already storing CO<sub>2</sub> in the Utsira formation, which indicates secure storage from ten years of experience of CO<sub>2</sub> injection and storage. On this field, it would probably be possible to utilise the existing injection well, and the additional costs of monitoring stored CO<sub>2</sub> are expected to be low. The transport distance from Kårstø is about 250 km.

The current high price of oil and gas means that known hydrocarbon deposits are regarded as commercially attractive for continued production, a situation that makes it difficult to use such formations for CO<sub>2</sub> storage. NVE therefore regards the uncertainty surrounding Heimdal and Nordøst Frigg as being so high that these solutions are not recommended for further consideration as storage site for CO<sub>2</sub> from Kårstø. However, these formations are potential CO<sub>2</sub> storage sites in the future.

In view of the above considerations, **Sleipner** appears to be a suitable alternative, if emphasis is put on establishing the lowest possible cost of simple storage and low risk involved in initiating the storage process. This would require the Sleipner license agreeing to accept CO<sub>2</sub> from the date of start-up without demanding unreasonably high compensation. In order to have an alternative to Sleipner, it would be sensible to examine **Coastal Utsira** in more detail before a choice of concept is made. This should include further studies of the potential for storage in Utsira and possibly other formations closer to the coast, with the aim of further reducing transportation costs. It would also be sensible to consider coordinating the process with the transport and storage of CO<sub>2</sub> from other projects, such as Mongstad and Tjeldbergodden.

## 4.2 Transportation pipelines

Transporting CO<sub>2</sub> to suitable offshore formations and reservoirs can be done via pipeline or by ship.

*Ship-based transport* is most relevant for smaller quantities and long distances. CO<sub>2</sub> would be transported to an onshore hub close to the fields, where it would be pressurised and taken on by pipeline to the field for storage or for use in EOR. Ship-based solutions are much more flexible in terms of delivery site than pipelines, but require interim storage facilities, either at dedicated storage sites or by the vessels themselves acting as storage sites during loading and discharging operations.

*Pipeline transportation:* At normal temperature and pressures greater than 70 bar, CO<sub>2</sub> remains in what is known as “supercritical state” (a state similar in many ways to a

liquid), and can be pumped. Pumping is much less energy-intensive than compression for a given pressure increase. In this state, CO<sub>2</sub> exhibits less friction with the pipeline wall, and it can therefore be transported over long distances with a relatively small pressure drop.

For transport from Kårstø to offshore storage sites and possibly later conversion to use for EOR, pipeline transportation is likely to be the method of choice. This is primarily due to the moderate distances involved and the reduced need for heating and recompression on the field, and because it avoids the need for interim storage. Ship transport of CO<sub>2</sub> is therefore not discussed further in this report. In its studies of pipeline transport, NVE has made use of the services of Dr. Sverre Lund (Lucon) [5], and has carried out a design study with DNV [9].

Small pipeline dimensions relative to the quantity of gas transported may result in severe pressure drop and thus to disadvantages associated with high design pressure and very thick pipe-walls. The dimensions of the pipeline must therefore be adapted to transport volume and pressure requirements. A simple storage solution will probably require a relatively low offshore supply pressure. For reasons of pipelaying technology, however, a pipeline capable of withstanding a pressure in excess of 300 bars will probably be chosen, even when not planning to operate the pipeline at such a high pressure. When the choice of concept for transport and storage has been made, the outlet pressure from the CO<sub>2</sub> capture plant (CO<sub>2</sub> pump dimensions) will be adapted to the pressure drop in the pipeline, without this having any particular consequences for the design of the pipeline.

With a capture rate of 85%, the CO<sub>2</sub> capture plant will produce about 131 tonnes per hour when Naturkraft is generating at full capacity. With a safety margin included, a transport capacity of 160 tonnes per hour has been used as the basis for studies of the transportation pipeline.

Water in a mixture with CO<sub>2</sub> is a very aggressive corrosion agent in ordinary carbon steel pipelines, which are well-known and cost-effective for the transport of crude oil, gas and condensate. Removal of the water and monitoring the water content of the CO<sub>2</sub> flow, with shut-down in the case of risk of the water content rising above a given level will be extremely important for the safe operation of the transportation pipeline and the injection well.

On the basis of assessments of the design pressure and the quantity of gas to be transported, NVE has found it appropriate to base the transport solutions on a 10" o.d. pipeline, but consideration could be given to reducing this to 8" o.d.; see section 6.4.2. NVE has assumed standard dimensions for natural gas pipelines in considering transport pipeline dimensions, in order to avoid the expense of customised solutions.



costs. Although some of the routes to the North Sea pass through areas that have not yet been charted in detail, bottom conditions are well known, with a favourable topography that is not expected to offer major surprises.

## 4.3 Flexibility

NVE was requested to investigate a simple storage solution for CO<sub>2</sub> that would have to be available for the start-up of the CO<sub>2</sub> capture plant at Kårstø. Seen in isolation, this leads to emphasis on achieving safe, long-term CO<sub>2</sub> storage at the lowest cost possible.

Consideration should also be given to what can be done to make the storage solution as suitable as possible for subsequent adaptation for EOR. Value chains for CO<sub>2</sub> for EOR will also have to send CO<sub>2</sub> to storage for certain periods of time. Adaptations of this sort will largely consist of investing in future flexibility, and this aspect can be divided into two main categories:

1. **Choice of storage site.** Reservoirs can be chosen on the basis of which of them offers the lowest costs if the pipeline is subsequently extended to supply an EOR application.
2. **Choice of transportation conditions.** One can invest in compression facilities and transportation pipelines that will meet the needs of future EOR applications in terms of supply pressure and volume transported.

### 4.3.1 Choice of reservoir

The transportation pipeline from Kårstø will probably be the first CO<sub>2</sub> transport pipeline in the southern part of the Norwegian continental shelf. If a willingness to pay for the use of CO<sub>2</sub> offshore is demonstrated, it would be a major advantage to be able to use the same transportation pipeline for EOR applications. As efforts to establish value chains for CO<sub>2</sub> and to deal with CO<sub>2</sub> from other sources develop, it will be possible to coordinate project decision-making processes and benefit by coordination of these processes.

### 4.3.2 Transport capacity

The design parameters determined at the time of concept choice and investment decision will be decisive for the future utilisation of the transportation system. If there is reason to believe that CO<sub>2</sub> from Kårstø will later be used for EOR, there may be good reasons for investing in future capacity by oversizing the pipeline and systems for CO<sub>2</sub> compression.

Several offshore fields will require as much as 5 million tonnes of CO<sub>2</sub> a year in order to achieve efficient EOR. This will require CO<sub>2</sub> from several different sources, and Kårstø has the potential to become a CO<sub>2</sub> hub, particularly for Norwegian onshore sources. The greatest degree of flexibility would be obtained if pipelines and the plant at Kårstø could be adapted from the very start to deal with much larger volumes than will emerge from Naturkraft's gas-fired power plant alone. However, doing so will involve significant additional investment costs, without any guarantee that such facilities will ever be required.

The field supply pressure for use in EOR will range from about 70 bars (for example to Volve via Sleipner) to as much as 300 bar or more at the surface. If a high injection

pressure is required, a low design pressure in the compression system and/or transportation pipeline would require expensive pumping of the gas offshore.

# 5 Schedule

## 5.1 The planning phase

A recommended schedule for the planning phase is shown in Figure 13, while the individual activities involved are described in Table 4. The schedule shows that it should be possible to award contracts for the CO<sub>2</sub> capture plant, transportation pipeline and storage solution in December 2008. If this deadline is met, the system could be in operation by the turn of the year 2011/2012.

### 5.1.1 Assumptions

The schedule is based on a number of assumptions that may or may not be met, and is therefore subject to uncertainty. A factor of particular importance during this phase will be the ability to make decisions in time. The planning phase largely consists of making well-founded choices of concepts, and of narrowing the margin of error in order to enable projects to be implemented efficiently and contracts signed.

Figure 12 is intended to illustrate the importance of spending the time needed to do a good job during the project planning phase. This is when the major conceptual and design choices are made, a choice that will have a dominant effect on the final costs and performance. As the project enters the implementation phase there are fewer possibilities of modifying decisions already made, contracts already signed, etc. The consequences of the choices made during the planning phase will largely be felt during the construction phase.

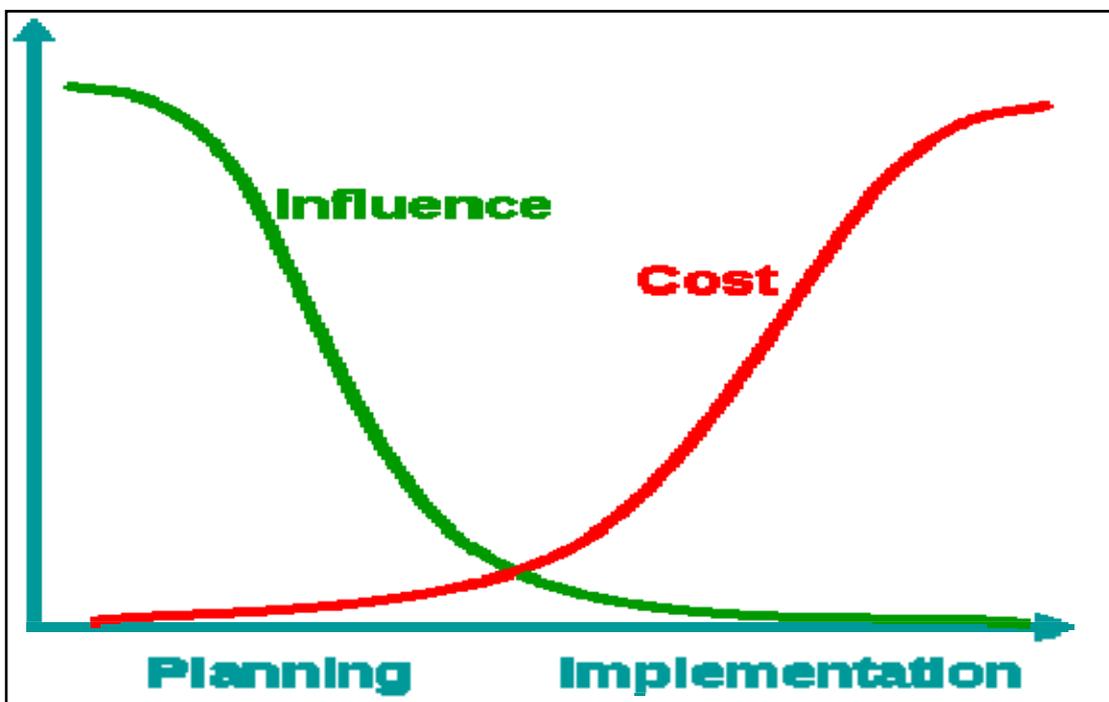


Figure 12 Project phases and their influence of the final result (Source: Lucon)

The schedule illustrated in Figure 13 takes as its point of departure NVE's mandate, as well as several assumptions that NVE has had to make during the course of its work. The most important assumptions are described below.

NVE's mandate specified that NVE should "implement and coordinate part of the preparatory work related to the establishment of a CO<sub>2</sub> capture plant at Kårstø by 2009." A guideline for NVE's efforts has been the aim that the facility should be in operation in the course of 2009; secondarily, as soon as realistically possible.

NVE has assumed that for Engineering, Procurement, Construction (EPC) contracts a call for tenders will be the chosen method of award, in order to obtain the best possible contract conditions in terms of investment costs and distribution of risk, and to satisfy EEA regulations regarding competitive tendering. It is assumed that there will be no guidelines regarding the use of Norwegian vendors of CO<sub>2</sub> capture technology.

NVE has also assumed that there will be no requirement that the project will contribute to technology development or testing of new concepts, beyond what the vendors themselves might wish to use as the basis of an EPC contract with acceptable risk distribution at present. Building a full-scale CO<sub>2</sub> capture plant at Kårstø using current technology on a scale that is ten times as large as anything built so far, involves a major challenge and risk of delays. Technology qualification and activities aimed at reducing risks and increasing knowledge of current technology are regarded as relevant to this project.

It is also assumed that the government will need a good basis for decision-making in order to enable it to make an investment decision. There will be a requirement that the project should be carried out in a controlled way and with an acceptable level of risk. If it is to be realised by the end of 2011, the project director and project staff that are to be mobilised must also regard the schedule described as sensible and capable of being realised.

NVE has not made any assumptions regarding a particular procurement or implementation strategy in its efforts, but has largely left such considerations and choices to the next phase of the project. The schedules have been made as independently as possible of these choices, even though it has been necessary to make certain assumptions. Strategies of this sort should be decided as soon as possible in the next phase of the project.

### **5.1.2 Description**

The schedule has been drawn up on the basis of mobilising a project director and project staff at the turn of the year 2006/2007. This organisation will need some mobilisation time to obtain an adequate understanding of the project and how it should be carried out. An implementation strategy will have to be drawn up before discussions with potential technology vendors and other parties involved can start. Concept studies will have to be continued as a basis for making a number of technical choices before the pre-engineering phase commences. Specifications and tendering documents for the pre-engineering phase will have to be drawn up, so that a call for tenders can be issued to prospective technology vendors. Before the start of pre-planning, thorough discussions should have been held and ideally, the necessary agreements should have been signed with companies

in the vicinity. The pre-engineering phase is estimated to take about eight months. In parallel with this phase, the EPC contract for the construction of the CO<sub>2</sub> capture plant should be drawn up. The pre-engineering phase should end up with a call for tenders for the contract to construct the capture plant. During the evaluation of the EPC contract, a third-party evaluation of the basis of the project should also be performed, in order to substantiate the decision regarding the allocation of funds and the implementation of the project.

Parallel to the planning and design of the CO<sub>2</sub> capture plant, the engineering for transport and storage should also be planned and concept choices made. The task of obtaining permits from the authorities must also be carried out during this phase, in order to prevent this work from ending up on the critical path.

The planning phase should also be utilised to carry out technology qualification, in order to obtain the best possible insight into and knowledge of the relevant technology.

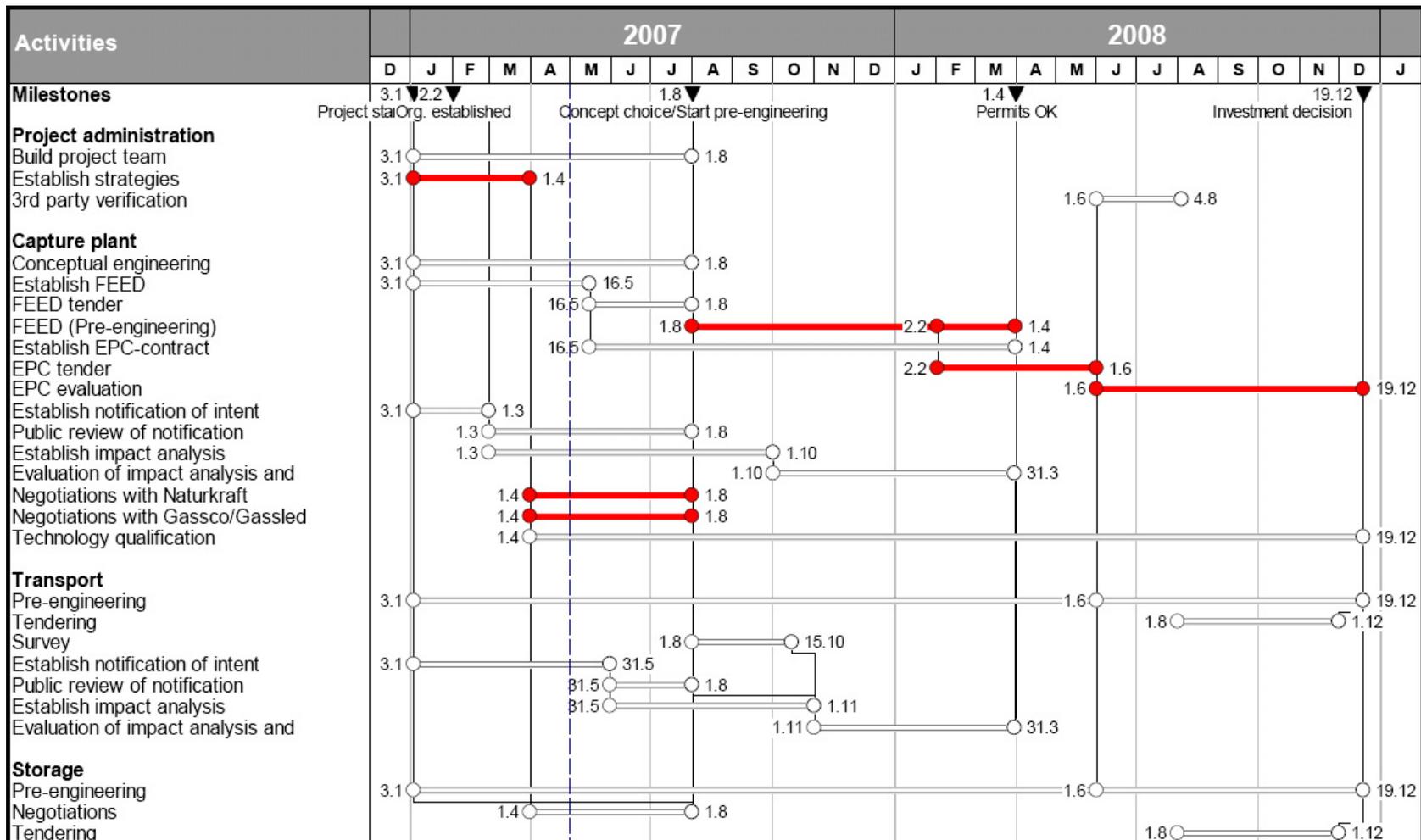


Figure 13 Schedule for the planning phase

**Table 4 Explanation of activities in planning phase**

<b>Activity</b>	<b>Sub-activities</b>	<b>Assumptions</b>	<b>Dependences</b>
Common activities			
Develop project organisation	Recruitment and hiring of personnel Establishment of cooperation with other parties Clarification of relationship with project owner Establishment and constitution of legal entity Team-building and competence development	Project manager in place by New Year Rapid mobilisation of staff Clear tender conditions Close collaboration with project owner Available financing	Preparatory efforts of Ministry of Petroleum and Energy
Establish strategies	Implementation strategy, including: Purchasing strategy Negotiating strategy Size of organisation Technology strategy Establish project schedule Establish budget Establish risk control plan	Decision-making capability	Key personnel mobilised Mandate and authority clarified
Third-party verification	Call for tenders (project owner) Survey of organisation Survey of documentation Interviews with key personnel Report to owner	Confidentiality	Overview of EPC tenders Agreements with project interfaces Implementation organisation established

<b>Activity</b>	<b>Sub-activities</b>	<b>Assumptions</b>	<b>Dependences</b>
Sub-projects (capture, transport, storage)			
Continuation of concept studies and pre-engineering	Determine scope of work and basis of design Establish contract Contact with vendors Call for tenders Carry out pilot study		Feasibility study (NVE) Strategies clarified Agreements with interfaces
EPC contract	Determine scope of work and basis of design Draw up specifications Establish contract Contact with vendors Call for tenders and evaluation Clarification and negotiations		Pilot study completed
Processing by authorities	Draw up advance expression of interest Draw up impact statement Draw up application for emission permit Follow-up by authorities	Clarification of legal situation	Legal unit in operation Storage solution clarified (before submission of impact statement and application)
Negotiations	Negotiations with Naturkraft Negotiations with Gassco/Statoil/Gassled Negotiations with Sleipner (& possibly others)	Mature attitude of opposite party Clear mandate	Goals and strategy for negotiations drawn up Alternatives analysed
Technology qualification	Tests in pilot/test plant Documentation study Factory visits and collection of documentation	Access to test plant Coordination with other projects Limited number of vendors	Technology strategy Purchasing strategy
Study of pipeline route	Tendering process Mobilisation of vessel Analysis of measurement data	Potential route identified	Weather

## 5.2 The implementation phase

A schedule for the implementation phase has been drawn up on the basis of input from the technology vendors and M.W. Kellogg's evaluations, based on their experience of major construction projects at Kårstø. The schedule is shown in Figure 14, and is not expected to differ greatly from one vendor to another. In order to illustrate the uncertainty related to the start of the implementation phase and to make the schedule more useful, it has not been linked to a contract signed on a given date. If the schedules outlined in Figures 13 and 14 are followed, CO<sub>2</sub> from Kårstø could be captured and stored by the turn of the year 2011/2012.

The length of the implementation phase is expected to be determined by the construction of the CO<sub>2</sub> capture plant, and there appears to be some slack in implementation of the transport and storage as regards completion at the same time as the capture plant. Having somewhat more time available for the transport and storage solutions and the marine operations they will require will often mean that they can be implemented more cost-efficiently (lower contract prices, cheaper to make changes), ordering steel earlier and giving the contractors flexibility with respect to weather, other contracts, etc.

The CO<sub>2</sub> capture plant will be dependent on tie-ins to the gas-processing plant and the gas-fired power plant at Kårstø. Many of these tie-ins are regarded as being possible without a complete shut-down of the gas-processing plant, but some systems, (in particular, any tie-ins to natural gas and the flare) may require the plant to be shut down. The tie-in to the power plant stack is regarded as particularly demanding, since the operation will take some time and will have to be coordinated carefully with Naturkraft. The time window within which the tie-in should take place is indicated in Figure 14, and the first complete planned shutdown of the gas-processing plant is planned for 2010 (which would appear to be suitable, as long as the project is carried out as suggested in this report).

The critical path for the CO<sub>2</sub> capture plant seems to be decided by the design and purchase of the CO<sub>2</sub> compressors. In a market which is characterised by high demand for materials and mechanical equipment, the lead time suggested by the vendors is around 22 months, exclusive of transport. This will be a critical factor as far as the Kårstø construction phase is concerned, but other types of equipment are also subject to long delivery times, which could become critical for the implementation of the project (e.g. large titanium seawater heat exchangers).

An important assumption for the implementation schedule is that the project is allocated sufficient manpower, equipment and laydown area so that the process of construction can be carried out efficiently. The construction phase in the transport and storage sub-projects, as well as delivery of the large modules to Kårstø, are dependent on weather and season, and the planning of the implementation phase will need to take this factor into account.

A five month commissioning phase has been planned for, to be followed by a start-up phase of about two months. There is a great deal of uncertainty related to the fact that this plant will be the first of its kind, a situation that is likely to lead to a number of challenges that will have to be dealt with during the commissioning and start-up of the facilities. The

difference between these two activities will not necessarily be distinct. There will also be some time between the start of CO<sub>2</sub> capture at Kårstø and the start-up of continuous storage on the continental shelf, because the commissioning process must be taken one step at a time. The activities in the schedule are described in Table 5.



**Table 5 Explanation of activities in the implementation plan**

<b>Activity</b>	<b>Sub-activities</b>	<b>Assumptions</b>	<b>Dependences</b>
<b>Common activities</b>			
Establish operating organisation	Recruitment and hire of personnel Establishment of cooperation with other parties Possible delegation of responsibility to operators Team-building and development of competence	Agreement regarding potential coordination of operation	Continuation of project organisation
<b>Sub-projects (capture, transport, storage)</b>			
Detail engineering	Process specifications Mechanical data sheets		Award of contracts
Fabrication		Drawings from the engineering phase	Engineering completed
Installation		Materials and drawings	Engineering completed
Mechanical completion			Installation completed
RFO, commissioning			Systems mechanically completed
Start-up			Commissioning
Marine operations	Trenching Pipelay Rock dumping	Study of route Purchase of pipelines Access to Kårstø	Engineering completed
Tie-in window		Shutdown at Naturkraft/Gassco	Tie-in design completed
Technology qualification		Technology strategy	Award of contracts

## 5.3 Schedule uncertainty

Both the planning and implementation schedules are based on a number of assumptions, not all of which will necessarily be met. This means that these schedules are sensitive to such changes. Some of the most important dependences are described here (see also Chapter 9).

The activities that are on the project's critical path (shown in red in Figures 13 and 14) will, in the event of delays, directly delay the project as a whole.

**Accelerated planning phase.** The target of starting CO<sub>2</sub> capture and storage during the course of 2009 has been an important consideration in NVE's efforts to date. In view of the state of the project today, this goal does not appear to be realistic, even assuming a high willingness to accept risk and generous economic limits. NVE has evaluated the possibility of implementing an accelerated planning phase with the potential to shorten the planning phase by up to eight months. Such a schedule would require the following conditions to be met:

- Very rapid mobilisation and organisation of the project team
- Pre-engineering cut down to about six months
- Third-party verification before investment decision to be dropped
- The political decision to allocate money to the execution of the project would have to be made on a much weaker technical basis.

Early selection of contractors and vendors could help to shorten the planning phase of the project. On the other hand, this would involve weakening the competitive element in tendering for these tasks, increasing the chances of ending up with less favourable contract prices and risk distribution between the contract parties. Pre-engineering can be carried out with several vendors in parallel, with fixed-price tenders for EPC contracts as the outcome. This would involve more expensive pre-engineering, but might save some time by carrying out more activities in parallel.

This solution would also mean that a number of the other activities would have to be performed more rapidly than in the baseline alternative, which would raise the level of risk, both in terms of incurring extra costs and of being unable to keep to the schedule. A lack of time for negotiations with neighbouring companies could be a significant disadvantage. NVE advises against the project being carried out in such a way.

**Long equipment lead times** will play a major role in the implementation plan. The market is in a period of high activity and high pressure on suppliers of equipment, and it is difficult to estimate and ensure delivery times for process equipment in competition with other projects. The schedule outlined in Figure 14 is believed to indicate a realistic lead time for CO<sub>2</sub> compressors, where there is a possibility for either faster or slower procurement, manufacture and transport. This will also apply to other equipment with long lead times.

In order to reduce the total duration of the implementation plan, the project owner could decide to purchase equipment early and transfer it to the building contractor. Purchases of this sort would have to be based on data from the pre-engineering phase, without detailed

engineering, and would thus increase the risk of expensive errors. This risk would have to be weighed against the value of more rapid implementation of the project.

As far as the CO<sub>2</sub> compressor is concerned, it should theoretically be possible to save as much as six months in the execution phase of the project. However, this would probably mean that other components of the plant would have a determining effect on the total execution time, with the result that these too would have to be ordered ahead of detailed engineering, or that a time saving of less than six months would have to be accepted.

**Technology qualification** reduces the risks involved in the project, and increases the possibility of controlling such risks as have been identified. The schedule as outlined here will permit the technology qualification activities that are regarded as being most important for the project to be carried out. A wish to reduce risk yet further could mean technology qualification ending up on the critical path, a result that would delay the completion of the project as a whole.

**Tie-ins** to adjacent facilities also involve challenges that are potentially capable of delaying the project. There is a need to be able to identify a relatively long period of time during which the gas-fired power plant would have to be shut down, in order to be able to tie in to the power plant's stack. There is also a potential dependence (particularly if the plant is to utilise natural gas) on making the tie-ins during the course of a scheduled shut-down; the next of these is planned for 2010. The consequences (for progress and possible costs) of not being able to tie in at the right time are potentially very serious.

**An increased scope of work** could also delay the project, just as limits being placed on the project's permitted level of activity at Kårstø could result in serious delays.

**Delayed political decisions.** As the project is completely dependent on state finance and state decisions regarding its continuation, delays in such decisions could seriously affect the progress of the project.

**Mobilisation and plant owner competence.** The schedule requires the relatively rapid build-up of a competent project organisation in order to carry the project forward with satisfactory quality. If this does not happen, delays are likely.

**Licensing** by the authorities is potentially capable of ending up on the critical path. This could be the result of lack of clarification of existing uncertainties regarding under which legislation the project should be dealt with, or if the pollution authorities regard the emissions to the atmosphere as a serious problem.

# 6 Cost estimates

## 6.1 On estimating costs

An important aspect of NVE's work has been to establish reliable cost estimates. A series of technical studies have been carried out as a basis for producing these estimates.

The technical basis for the individual estimates is at such a level that their accuracy, after an allowance has been added for contingency, is assessed at  $\pm 40\%$ , with some variation among the individual elements. This is a normal level of contingency for the stage reached by this project.

This does not mean that investment and operating costs could not be higher. The estimates are based on a series of core assumptions. These include access to work at Kårstø which will permit rational project execution, that neither the concepts nor the scope of work are significantly altered under way, that fair commercial agreements can be signed with other parties, etc. The probability of cost overruns is far greater than that of reductions if the central assumptions turn out not to be valid.

In project execution, there is a close relationship between time and costs. Ambitious implementation schedules often involve, for example:

- A greater need for parallel activities
- More rapid performance of individual activities than is normal
- The use of more resources per activity than is cost-optimal, as well as overtime, working throughout vacation periods, etc.
- Ordering equipment with long delivery times at an unusually early date, with the risk of having to make expensive modifications.

These factors all increase the risk of making errors and having to carry out parts of the work all over again. This in turn will increase pressure on available resources and the need for greater parallelism and further acceleration of the execution of activities. Once a project starts falling behind schedule, with a need to repeat work, the potential for incurring higher costs is very high. This requires the adoption of a conscious position as to whether one is being driven by time (start-up date), quality (functions, safety, emissions), or money (costs, net present value). NVE has based this study on a schedule that ought to avoid major cost overruns as a result of rapid planning and implementation. At the same time, the desire for the plant to be started up as early as possible has been given much emphasis. The costs presented here assume implementation as described in Figures 13 and 14.

The estimates presented below are based on current (2006) markets for equipment, materials and personnel. Higher activity in any of these markets will lead to higher costs for the corresponding elements, and have the potential to significantly raise both investment and operating costs. Similarly, a trend in the direction of lower macroeconomic activity could lead to significant cost reductions for the project.

It is also important to be aware of the difference between estimated costs and contract prices. Particularly where the contract for construction of the CO<sub>2</sub> capture plant is concerned, the vendors may have different strategic evaluations of the benefits and risks

involved in building what may be the largest facility of its kind in the world. This could bring vendors to offer to build it at a considerably higher, or lower, contract price than the cost estimates. This effect is very difficult to estimate until there are actual negotiations with the vendors, leading to yet more uncertainty about whether or not the cost estimates will reflect the final costs of the project.

There is also a relationship between the contract price and the distribution of risk between the parties to a contract. To make the contractors assume a significant proportion of the risk in terms of completion time, performance and emissions, etc., this will require a higher contract price (estimated investment cost). The greater the demands made of the vendors by the plant owner with respect to guarantees, the higher will be the price put on each contract by the vendors, in order to cover themselves against the increased risks involved. The estimates presented below are based on cost estimates drawn up by potential future vendors, and do not include additions for supplier guarantees over and above those that are normal for major process plants today (guaranteed performance (capture rate, energy consumption, emissions) based on performance tests).

## 6.2 Costs incurred during the planning phase

The schedule for the planning phase (from New Year 2006 until the investment decision is made) is shown and described in section 5.1. The costs incurred during the planning phase will largely result from the need for manpower and external technical studies (e.g. the FEED), and they cover all three sub-projects (capture, transport and storage). The cost estimate for the planning phase is based on an organisation that will require about 30 man-years, and which should be mobilised in the course of the first eight months of the planning phase (see Figure 15). The planning phase is estimated to last for about two years. The cost estimate for this phase is shown in Table 6.

**Table 6** Costs incurred during planning phase (MNOK)

Cost element	Estimate (MNOK)	Comments
Manpower	110	Project organisation
Studies	165	Includes FEED, route surveys, impact studies and quality assurance
Contingency	55	
<b>Sum</b>	<b>330</b>	

The most important assumption concerning the cost estimate for the planning phase is that this phase is executed as described in Chapter 5. More rapid performance might save some of the costs of manpower and external studies, but would involve a risk of considerably higher costs incurred during the implementation phase (see also Chapter 5). A decision to carry out parallel FEEDs of the CO<sub>2</sub> capture plant with several technology vendors will require the estimate to be increased by about MNOK 40-50 per supplier. An example of how a fully manned project organisation might look is shown in Figure 15.

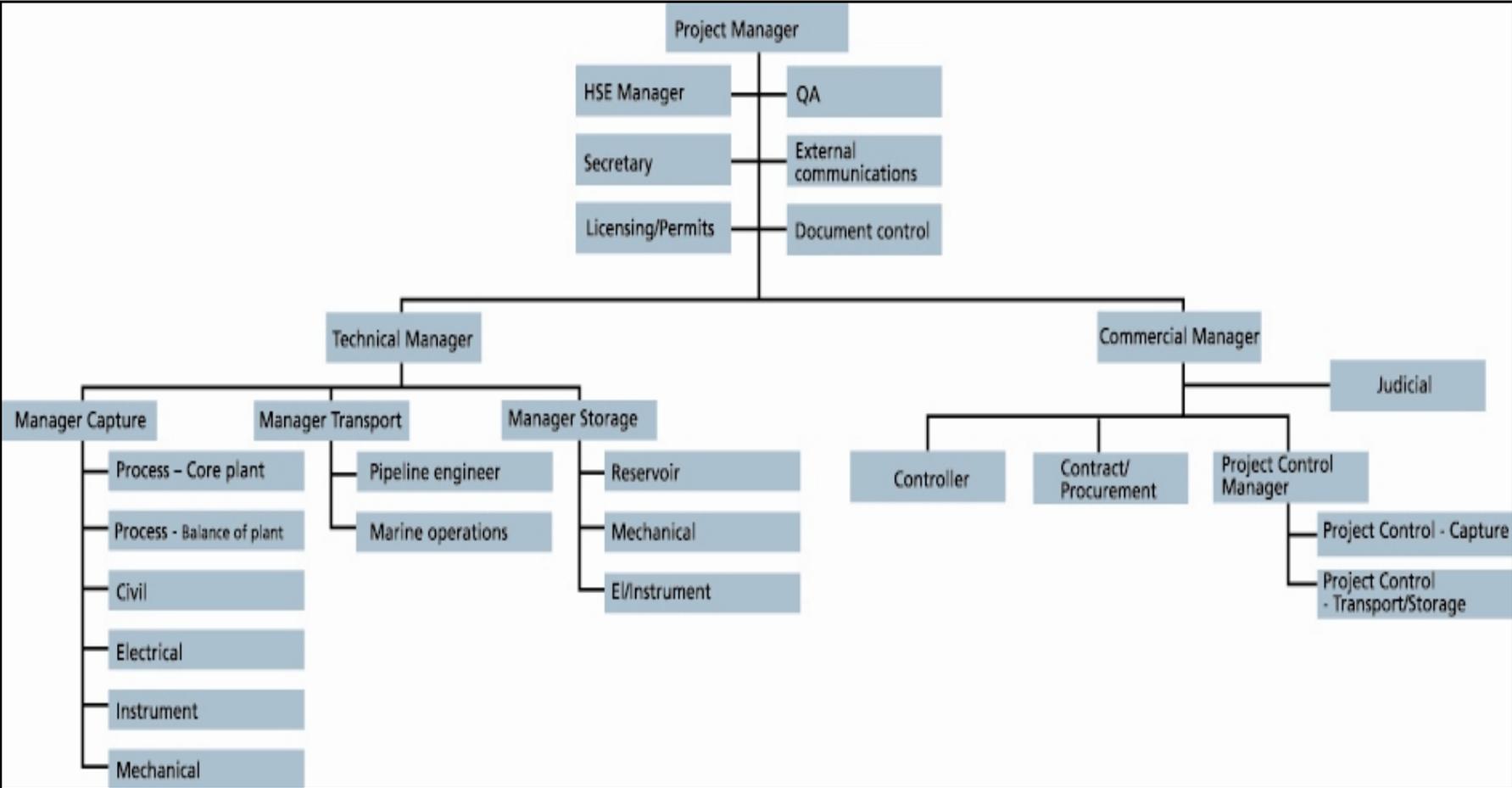


Figure 15 Example of an organisation chart of a fully manned project organisation

## 6.3 The capture plant

### 6.3.1 Investment costs

The investment costs of a capture plant suitable for the CO<sub>2</sub> from Naturkraft's gas-fired power plant at Kårstø primarily comprise of the EPC contract for construction of the CO<sub>2</sub> capture plant, including CO<sub>2</sub> dehydration and compression for transport. The investment costs also include site preparation at Kårstø, the necessary tie-ins to the gas-processing plant and payment for the necessary services that will have to be purchased from the gas-processing plant and the power plant during the construction phase. Finally, there are also the plant owner's own costs for managing the project, including technology qualification, building up an organisation etc., and a percentage supplement for contingency.

The investment cost estimate is high in comparison with previously published estimates for CO<sub>2</sub> capture plants. This is largely due to the following factors:

- Prices were obtained from current markets (2006), which are characterised by a high level of activity and high prices
- The estimate is based on actual manpower costs and productivity levels at Kårstø. Kårstø is and will continue to be a demanding construction site, with high safety standards and a need for coordination with other activities
- A supplement for contingency has been included, which reflects the stage the project has reached at present
- NVE has set strict requirements regarding the regularity of the capture plant

#### **EPC contract**

The total cost of the EPC contract is based on technical studies with four technology vendors. It is of interest to note that the cost estimates provided by the individual vendors are relatively similar, probably because their processes are relatively similar and largely consist of already known elements. The estimates drawn up by the technology vendors are based on cost levels experienced during the third quarter of 2006, and have been further refined by M.W. Kellogg and NVE.

The scope of work of the contract covers detailed engineering, procurement, construction, completion and commissioning of the plant. The scope of work is largely confined to the work that will be carried out at the site allocated to the CO<sub>2</sub> capture plant, but also includes the construction of the flue-gas ducting from Naturkraft's stack.

#### **Tie-ins**

This part of the investment costs includes site preparation, as well as tie-ins of all pipelines (steam, condensate, seawater, freshwater, wastewater, etc.) to the capture plant site, in addition to tie-ins to existing facilities for electric power and control and safety systems (see section 3.10 for further details).

#### **Purchase of services**

The project will need to purchase services from nearby companies during the construction phase. This aspect is based on monthly payments to the gas-processing plant for utilities and services such as warehousing area/workshops, storage tents, roads, quays, security services, safety courses, communications systems, radio, construction power

transformers, temporary office space, waste disposal, manpower, housing agency services, plant hire, hire of camp and on-site housing, canteen operation, gate operation etc. in this phase of the project. Support will be purchased from Statoil TSP, Naturkraft and other parties involved (such as the maintenance and modifications contractor for the gas-processing plant, currently Vetco Aibel). NVE estimates these costs at around MNOK 3 per month for the duration of construction activity at Kårstø.

### **Plant owner's administration**

The plant owner will need a full-scale project organisation in order to follow up the construction process and protect his own interests. Towards the end of the construction period and entering commissioning and operation, the owner will also need to set up an operating organisation which will have to be mobilised and trained (and be paid) well before the commissioning date of the plant. The plant owner will also have to bear the costs of technology qualification, possible external studies, etc. This part of the estimate is based on a 5% supplement to the investment costs. It is assumed that the state is a self insurer, and the costs of insurance during the construction phase have not been included in this estimate.

### **Contingency and project reserve**

In the early phases of a project (as represented by this report), experience suggests that not all the cost elements that will accrue during the project have been identified. In order to include these costs in the estimate (which have not yet been identified but which are expected to accrue) an additional cost element is added to cover the uncertainty in the estimates. In this project, a relatively high percentage (20%) is utilised for contingency, in view of the fact that the project still needs to mature a good deal, and in order to reflect the fact that some of the technology will have to be qualified. There is also the possibility of adding a project reserve in order to cover costs that have not been identified and which are not expected to accrue. This can be done in order to create room for manoeuvre if any of the central assumptions regarding the project should turn out not to be met. NVE has not added a project reserve to these estimates, but recommends that this should be considered carefully in later stages of the project.

### **Assumptions**

- Capture rate at 85%, based on the flue-gases from Naturkraft
- Plant design for 25 years useful life
- Plant to be capable of continuous operation for two years without major maintenance shutdown
- Plant to have an on-stream factor of 97% relative to the continuous operation of the power plant
- Outlet CO<sub>2</sub> pressure of 300 bar (conservative estimate)
- Interfaces as described in Chapter 3 (including HSE requirements as for the gas-processing plant)
- Hourly rates and productivities based on actual data from previous construction projects at Kårstø
- Efficient access to construction site at Kårstø
- No major changes in design basis and scope of work after award of contracts.

The estimated investment costs of the capture plant are shown in Table 7.

**Table 7 Estimated investment costs of the capture plant**

	<b>Cost (MNOK)</b>	<b>Percentage</b>	<b>Comments</b>
EPC contract	2260	65	Based on studies with technology vendors
Tie-ins	450	13	Estimated by M.W. Kellogg
Purchase of services	90	3	
Plant-owner's administrative costs	130	4	Including training, recruitment, contract follow-up, factory acceptance tests, etc.
Contingency	530	15	New technology, early project phase
<b>Sum</b>	<b>3460</b>	<b>100</b>	

### **Local steam generation**

NVE has carried out a study of the possibility of the capture plant generating its own steam, as an alternative to purchasing it from the power plant. This was a simplified study, in that it did not take into account the capture and storage of CO<sub>2</sub> from the steam boiler, as would be expected to be done if the capture plant were to meet its own needs for low-pressure steam. The additional investment required was estimated at around MNOK 440. This additional cost would be offset by the fact that it would no longer be necessary to purchase steam from Naturkraft, although it would be necessary to buy a corresponding amount of energy in the form of natural gas at Kårstø.

### **Separate seawater tunnel**

Estimates have also been drawn up of the cost of establishing new seawater capacity at Kårstø as an alternative to purchasing such capacity. The additional investment required is estimated at a little less than MNOK 130.

### **Separate freshwater supply**

There is some uncertainty regarding the capacity of the existing freshwater supply at Kårstø, and which bottlenecks would have to be removed in order to assure a sufficient supply to the CO<sub>2</sub> capture plant. There is also considerable uncertainty with regard to the rate of consumption on which operation of the plant would be based (see section 2.4.5). The above cost estimates do not include a significant cost element for increasing the capacity of the freshwater system at Kårstø.

## **6.3.2 Operating costs**

The operating costs of the CO<sub>2</sub> capture plant consist of a fixed part and a variable part.

### **Variable operating costs**

The variable costs are dependent on the annual operating hours of the CO<sub>2</sub> capture plant, which in turn depend on those of the power plant. Costs of energy, consumption of absorbent, getting rid of waste products and seawater cooling are the largest elements of the variable costs.

### Fixed operating costs

The fixed costs are largely made up of site rental, manpower, maintenance, service agreements with nearby companies, property tax and operation of auxiliary systems.

### Assumptions:

- The baseline calculation is based on 8000 hours of full load operation per year
- No costs or income have been included covering the effect on the purchase or sale of CO<sub>2</sub> quotas
- Electric power is assumed to be purchased from the power plant at a long-term price of 36 øre/kWh, distribution tariffs will not be paid
- Naturkraft will be compensated for lost electricity sales due to steam being extracted. It is estimated that this will come to about 36 MW at full production, and the electricity price assumed is the same as used for the purchase of electric power
- The cost of site rental is based on an estimate provided by Statoil, on the basis of a site of approximately 15 000 m<sup>2</sup>
- It is assumed that operations will be coordinated with neighbouring plants. This gives an assumed manning level of one operative on each of the six shifts in addition to five administration man-years to be paid for by the capture plant
- Annual maintenance costs of the CO<sub>2</sub> capture plant are estimated at around 2.5% of investment costs
- It is assumed that a service agreement will be signed, covering raw water, fire-water, sewage, access control, the use of roads and pedestrian ways, communication systems, security and reception, fireguard and contingency planning, canteen services, warehousing, office and space in the control room
- An annual cost element for waste treatment has also been included
- It is assumed that the plant owner is a self insurer. An insurance premium is not included in the estimate.

Operating costs based on 8000 hours of operation a year are shown in Table 8.

**Table 8** Operating costs based on 8000 hours of operation a year

	MNOK	Comments
<b>Variable operating costs</b>		
Energy	190	Electric power and steam
Other variable costs	46	Absorbents, seawater, etc
<b>Fixed operating costs</b>		
Manpower	13	
Maintenance	70	
Service agreements	8	Gassco, Naturkraft
Misc.	17	Property tax, site rental
<b>Sum</b>	<b>344</b>	

### Annual hours of operation

The variable operating costs are highly dependent on the hours of operation of the power plant and the CO<sub>2</sub> capture plant. If the hours of operation are few, the operating costs,

seen in isolation, will be significantly lower, but the CO<sub>2</sub> abatement cost expressed in NOK/tonne will be high, because there will be fewer tonnes of CO<sub>2</sub> to divide the cost by (see section 6.6.2).

A less direct consequence of the operating hours and the pattern of use of the power plant and the CO<sub>2</sub> capture plant will be the costs associated with starting up and shutting down the capture plant. The more often the power plant starts and stops, the less efficient will be the operation of the CO<sub>2</sub> capture plant, which will have to be phased in after the power plant has reached a steady state. In the mean time, CO<sub>2</sub> will be released to the atmosphere. Furthermore, the consumption of steam and power to start up and maintain absorbent circulation without CO<sub>2</sub> capture could be high. This power will partly have to be drawn from the external electricity grid, and will thus be paid for at full network price. Moreover, some absorbents (such as MEA) are potentially corrosive, leading to challenges in maintaining permanent control of flow rates and avoiding corrosion in the plant's internal systems. This could lead to extended periods during which the plant is not capturing CO<sub>2</sub> efficiently (alternatively, the use of more high grade materials in the capture plant, and consequently, higher investment costs).

### **Electricity prices**

Given that energy costs are the dominant operating cost element, the price of electricity will play a significant role in determining operating costs. Figure 16 below shows the variable operating costs of the plant as a proportion of the total costs of the capture plant, and Figure 17 illustrates a sensitivity analysis of the effects of different electricity prices.

### **Separate operating organisation**

The operating costs estimates are based on coordinating operations with other operating organisations at Kårstø. If this cannot be done, a large number of operators will be needed, and higher investment costs for control rooms, workshops, stores, etc., will be incurred.

## **6.4 Transport and storage**

### **6.4.1 Potential concepts**

In collaboration with NPD, NVE has identified potential storage solutions for CO<sub>2</sub>. Cost estimates for the transport and storage for the Sleipner and the coastal Utsira alternatives (see section 4.1. for more detailed descriptions) are presented below. The estimates for transportation pipelines have been drawn up by Lucon, while those for CO<sub>2</sub> storage were drawn up by NPD on the basis of actual data from previous projects.

NVE has collaborated with Statoil as operator of the Sleipner license in identifying technical concepts and cost estimates for the use of the existing storage solution at Sleipner for CO<sub>2</sub> from Kårstø. As in the case of the interfaces with Naturkraft and other companies at Kårstø, these estimates are not based on actual agreements, and the estimates must be regarded as being on the account of NVE.

### **6.4.2 Investment costs**

The transport solution covers equipment at the capture plant (pig receiver, valves, etc.), the landing at Kårstø, route preparation, installation, trenching, rock dumping, crossing

existing infrastructure, tie-ins, RFO, engineering and the procurement of the pipeline itself.

The technical solution for CO<sub>2</sub> storage in Utsira from the Sleipner field appears to be relatively simple; i.e. bringing CO<sub>2</sub> through a spare J-pipeline up to the Sleipner A platform, and tying in downstream the injection pump of the existing CO<sub>2</sub> storage facilities. This means that the necessary modifications to Sleipner A will consist of piping, valves and pipeline inspection and maintenance equipment, as well as some instrumentation.

A solution for coastal Utsira will require a seabed template in addition to a well, and control from shore or from a nearby offshore installation via a combined power and control cable.

### Assumptions

- Transport and injection capacity of 160 tonnes/hour
- 10” o.d. pipeline
- Price of steel for pipeline: NOK 15/kg
- Pipeline solution is flexible with respect to pipelay technology, and allows for a design pressure of more than 300 bar without additional cost
- Budget estimates for pipelay obtained from current contractors.

The cost estimates for transport and storage are shown in Table 9.

**Table 9 Investment costs of transport and storage (MNOK)**

<b>Investment costs</b>	<b>Sleipner</b>	<b>Coastal Utsira</b>	<b>Comments</b>
Transport			
Pipeline and equipment	465	355	NOK 15/kg steel (as pipe)
Installation and RFO	545	420	Budget estimates obtained
Engineering and administration	70	55	Including route studies
Contingency	220	170	
<b>Sum transport</b>	<b>1300</b>	<b>1000</b>	
<b>Storage</b>			
Platform modifications	200	-	
Well	-	200	
Seabed template and control cable	-	440	
Engineering and administration	20	55	
Contingency	40	130	
<b>Sum storage</b>	<b>260</b>	<b>835</b>	
<b>Total</b>	<b>1560</b>	<b>1825</b>	

### Smaller pipeline dimension

Depending on the final choice of concept for CO<sub>2</sub> storage, with limited requirements for offshore supply pressure (as for injection into the Utsira formation) it should be possible to reduce the size of the transportation pipeline to 8” o.d. This would reduce the

flexibility of the pipeline as far as carrying future CO<sub>2</sub> flows from Kårstø is concerned, and might prevent the pipeline from being extended to other fields in the future, unless the capacity is reduced. It would also result in a greater pressure drop along the pipeline and a need for more electric power for pumping from Kårstø, although this cost would be low relative to the reduction in investment costs. For the Sleipner alternative, the saving in pipeline costs would be around MNOK 220 if an 8" pipeline were to be preferred [5].

### Cost of materials

About one third of the total costs of transport are typically due to the costs of purchase of the pipeline itself. The market price of steel constitutes a dominant part of this cost. The steel price on which this estimate is based is high in historical terms, and may move in either direction, having an effect on the final cost of the pipeline.

### New well on Sleipner A

There is a degree of uncertainty as to whether the existing CO<sub>2</sub> injection well on Sleipner has the capacity to accept all the CO<sub>2</sub> from both Kårstø and Sleipner under all operating conditions. This uncertainty will have to be subjected to further evaluation in subsequent phases of the project. If it turns out that a new well down to the Utsira formation will be needed, this could cost as much as MNOK 100.

### Cable from an offshore installation

As Table 9 shows, the costs of a power and control cable from shore can be a significant proportion of the costs of storage in the coastal Utsira alternative. A variant for reducing the costs and the uncertainty of control signals over long distances could be a cable plus the purchase of services from a nearby installation.

## 6.4.3 Operating costs

The operating costs of transport and storage are due to routine operation, maintenance and inspection. There will also be costs of measuring and monitoring stored CO<sub>2</sub> and reporting stored quantities to the authorities. The full cost of energy for CO<sub>2</sub> compression is ascribed to the CO<sub>2</sub> capture plant.

Assuming that CO<sub>2</sub> goes to simple storage, NVE has decided to base this estimate on a fixed annual compensation for services rendered on Sleipner. The operating costs are shown in Table 10.

**Table 10** Operating costs of transport and storage (MNOK)

Operating costs	Sleipner	Coastal Utsira	Comments
Transportation pipeline	11	8	Inspections
Storage	14	20	CO <sub>2</sub> monitoring Inspection, maintenance
<b>Sum</b>	<b>25</b>	<b>28</b>	

The operating costs of transport and storage will be much lower than those of the capture plant. For this reason, a sensitivity analysis was not performed on these estimates.

## 6.5 Total estimated costs

Table 11 summarises the estimated costs of investment and operation, based on storing CO<sub>2</sub> in Utsira, either via Sleipner or based on a coastal solution.

**Table 11 Total estimated costs (MNOK)**

	Investment costs		Operating costs	
	Sleipner	Coastal	Sleipner	Coastal
Capture	3460	3460	344	344
Transport and storage	1560	1825	25	28
<b>Sum</b>	<b>5020</b>	<b>5285</b>	<b>369</b>	<b>372</b>

The planning costs of around MNOK 330 until the investment decision has been made must be added to the above figures.

## 6.6 Life-cycle evaluations

Estimates of the net present value of the total costs of CO<sub>2</sub> capture, transport and storage have been made. The results are illustrated by means of the abatement cost concept. CO<sub>2</sub> abatement costs are defined here as the income that the project must attain per tonne of CO<sub>2</sub> captured for the project's net present value to be equal to zero.

Doing this, it is important to distinguish between CO<sub>2</sub> captured and CO<sub>2</sub> avoided:

- **CO<sub>2</sub> captured** is the quantity that is physically separated and stored in a CO<sub>2</sub> value chain.
- **CO<sub>2</sub> avoided** involves making a comparison with a baseline alternative under which CO<sub>2</sub> capture does not take place, and involves an overall calculation for the power plant and the CO<sub>2</sub> capture plant.

Given that CO<sub>2</sub> capture and transport require energy (and thus themselves produce CO<sub>2</sub>), the quantity of CO<sub>2</sub> captured will be greater than the quantity avoided. Similarly, the costs of abatement per tonne of CO<sub>2</sub> avoided will be greater than those of abatement per tonne of CO<sub>2</sub> captured. The difference between CO<sub>2</sub> captured and CO<sub>2</sub> avoided will typically be around 20% in the case of capture from a gas-fired power plant using current technology, and is due to the fact that CO<sub>2</sub> capture itself is an energy-demanding process.

NVE have chosen to utilise the concept of **CO<sub>2</sub> captured** in this report, in order to make the calculations independent of Naturkraft's gas-fired power plant.

Assumptions involved in the baseline alternative:

- Calculation rate of interest: 5%, economic lifetime of 25 years
- Electricity price: 36 øre/kWh
- Annual hours of operation: 8000 hours at full load
- Construction period: three years; allocation of investment cost of capture plant: 20/40/40; allocation of investment costs of transportation pipeline and storage: 0/50/50
- No revenues from sales of CO<sub>2</sub> or CO<sub>2</sub> quotas
- Storage solution based on Sleipner.

### 6.6.1 Cost distribution

Project costs are made up of several elements. Figure 16 illustrates the relative size of the individual cost groups. The investment costs of the CO<sub>2</sub> capture plant are also divided into cost elements.

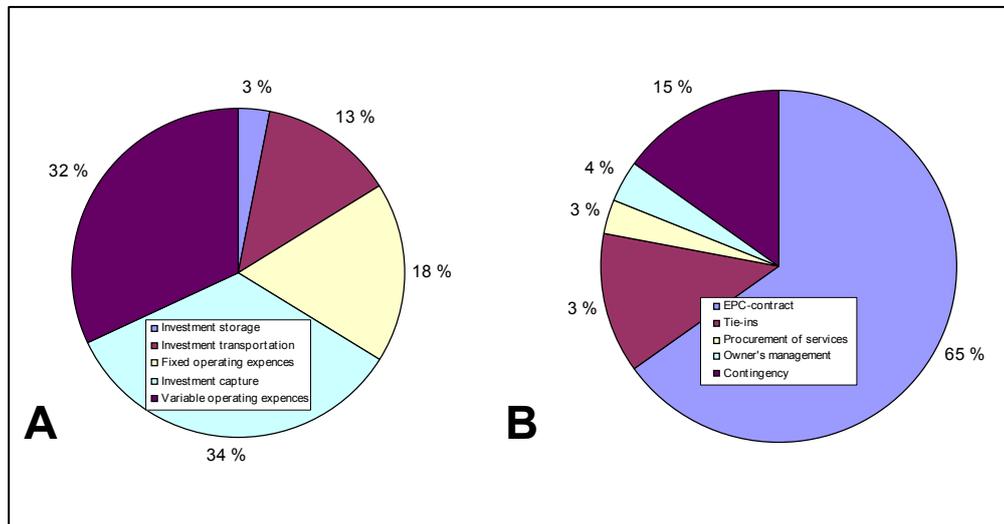


Figure 16 Distribution of costs of A) the whole project and B) investments in CO<sub>2</sub> capture plant

The figure illustrates that about half of the total CO<sub>2</sub> abatement costs are made up of operating costs, while the other half comprises investment costs. The operating costs are dominated by the variable operating costs (mainly costs of energy and consumption of chemicals), and these account for about as high a proportion of the total costs as the investment in the CO<sub>2</sub> capture plant.

### 6.6.2 Annual operating hours

Table 12 shows the CO<sub>2</sub> abatement cost for different annual hours of full load operation.

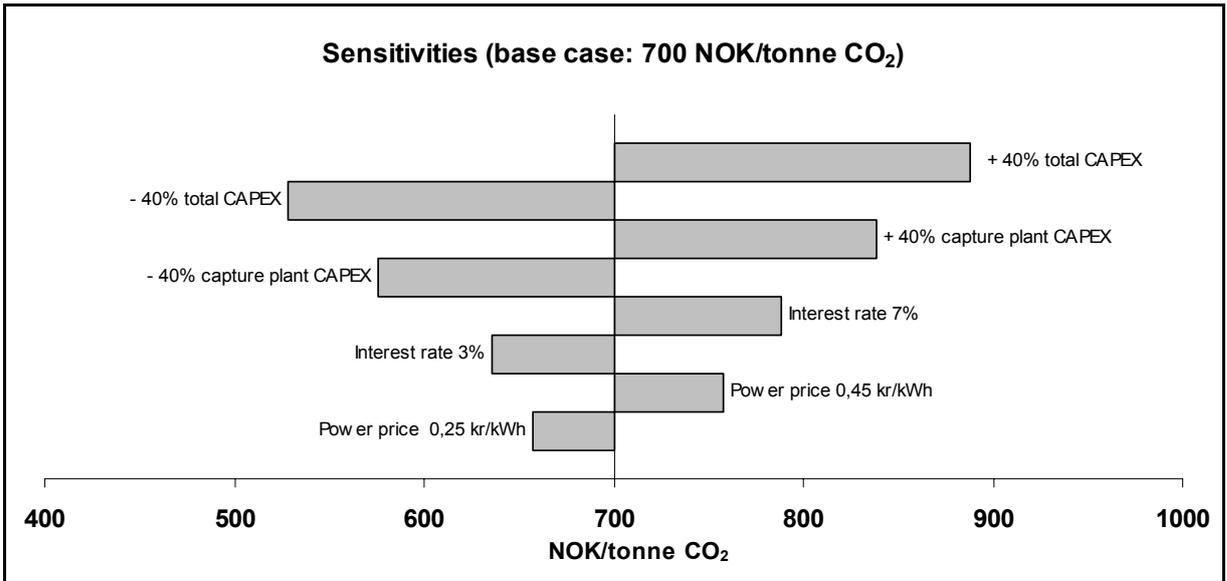
Table 12 CO<sub>2</sub> abatement cost for different annual hours of operation (NOK/tonne)

	2000 hours	5000 hours	8000 hours
Abatement cost	2200	1000	700

The table shows that the CO<sub>2</sub> abatement cost are extremely sensitive to the operating hours, and that when these are low, a significant level of capital will have been invested for each tonne of CO<sub>2</sub> captured at Kårstø. However, a low number of hours of operation will also produce low levels of emissions and reduced energy and chemical costs.

### 6.6.3 Summary

Figure 17 shows how the CO<sub>2</sub> abatement cost vary when other key assumptions than those in the baseline alternative are employed.



**Figure 17 Cost sensitivity**

The figure illustrates how the high capital costs incurred in the early phases of the project account for a large proportion of the total abatement costs. The choice of calculation rate of interest and the price of electric power are other important factors. However, none of the factors illustrated in Figure 17 affect total costs to the same extent as do hours of operation (see Table 12) and none of the sensitivities examined will alone reduce the abatement costs to below NOK 500/tonne CO<sub>2</sub> captured.

# 7 Health, safety and environment

The Kårstø facilities are subject to strict design, construction and operating requirements with regard to health, safety and the environment. A CO<sub>2</sub> capture plant that utilises amines to capture CO<sub>2</sub> will offer certain environmental challenges in terms of emissions of amines, possible additives, reaction products and ammonia. It will also raise levels of discharge of cooling water and be an extra source of noise at the Kårstø terminal. The flue gases from the CO<sub>2</sub> capture plant will have a high content of water vapour, and collected water from the plant may contain ammonia, amines, glycol and waste oil, which will have to be sent for special treatment or be treated on-site.

## 7.1 Amines and amine mixtures

Amines and amine compounds will be released from the absorption tower together with the flue gases from the CO<sub>2</sub> capture plant. The replacement of degraded amines will also require the destruction of large amounts of degradation products. Very small quantities of amines will also follow the CO<sub>2</sub>-rich flow out to the storage site. This is not believed to be an environmental problem, but it may be a matter for discussion in terms of the London and OSPAR Conventions. Finally, some water drained from the capture plant will probably have to be dealt with as containing amines, increasing the volume of liquid that will have to be sent for destruction.

To date, no permits for the release of amines to the atmosphere have been issued in Norway, and this issue will therefore have to be studied and evaluated. NVE have studied how such emissions would diffuse throughout the region, and has thus obtained an estimated figure for maximum emissions per square metre [11]. The structure of amines is similar to that of ammonia (NH<sub>3</sub>), but with one or several hydrogen atoms replaced with an alkyl molecule (C<sub>n</sub>H<sub>m</sub>). In comparison with those of nitrogen and ammonia, the effects of amines are relatively unknown. Some amines are toxic, and amines are also biodegradable to various degrees. The quantity of amines that would be received per square metre in the areas where precipitation is greatest does however appear to be very small.

NVE does not have a full picture of all the components and additives that the individual technology vendors use in their amine mixtures, as these are commercial secrets that are subject to strict confidentiality clauses. Balancing confidentiality requirements against the requirements of the pollution authorities regarding potential emissions will be a challenge in the licensing process.

## 7.2 Emissions to the atmosphere

**Amines and amine-related emissions:** as described above, there will probably be emissions of amines to the atmosphere at single-figure ppm levels. There are also likely to be emissions of additives that vendors use in their amine mixtures to prevent corrosion, unwanted reactions, etc. Furthermore, reaction products may be released from reactions between amines and other substances in the flue-gases than CO<sub>2</sub> (e.g. O<sub>2</sub> and NO<sub>2</sub>). Any emissions of additives and reaction products will be in extremely small amounts; less than 1 ppm. One possible exception is the potential release of acetaldehyde, at

concentrations of up to 5 ppm. Both estimates and measurements of emissions are difficult, because the chemical reactions involved are complex and the concentrations are low.

**Ammonia (NH<sub>3</sub>)** will be formed in the absorption stages of the capture plant, and will be released together with the flue gases. There will also be some ammonia from Naturkraft's NO<sub>x</sub> removal. Some of this will be absorbed by the water phase of the flue-gas cooler, taking the form of a release of ammonia to water. Ammonia is covered by the Gothenburg Protocol, and it contributes to nitrogen deposits and eutrophication.

**NO<sub>x</sub> and VOC** will not be produced by the CO<sub>2</sub> capture plant unless it needs to produce its own steam by combusting natural gas or has its own amine waste incinerator. Such internal steam generation, combined with the capture of CO<sub>2</sub> from the flue gases from the separate steam boiler, will bring about the less than optimal result that the concentration of NO<sub>x</sub> will first be reduced in Naturkraft's SCR plant, only to rise again in the capture plant's steam generator. The quantity of NO<sub>x</sub> that might be emitted by the incinerator is estimated to 600 kg/year at most, and is thus a very small discharge.

CO<sub>2</sub> will also be released in the course of operating the CO<sub>2</sub> capture plant, but only around 15% of the CO<sub>2</sub> produced by the power plant will be released to the atmosphere.

More accurate figures for emissions than those estimated in section 7.4 cannot be produced until the concept to be employed by the CO<sub>2</sub> capture plant has been finally decided, and even then they will be subject to uncertainty. Such emissions depend on both the process design and the choice of absorbent. The technology vendors themselves possess only limited knowledge regarding emissions to the atmosphere, as there is a lack of actual and measured data from this type of plant available.

Studies carried out by NVE have provided information about the emissions that can be expected, and about the measures that can be implemented to limit them. Water wash at the top of the absorber and a plant for dealing with degraded amines will be the most effective measures. It may prove necessary to perform long-term tests of absorbents and emissions before the approval of the authorities can be gained and an investment decision made.

NVE contracted the Norwegian Institute for Air Research (NILU) to perform studies of dispersion on the basis of the properties of the flue gases and emission figures provided by the vendors [11]. Amines are basic, corrosive and highly soluble in water, and are expected to have similar effects on freshwater and plants as ammonia. At sufficiently high concentrations, amines can also lead to problems of odour. The NILU studies have shown that maximum hourly mean concentrations at ground level will be 0.2 µg/m<sup>3</sup>. This is far less than 1% of the permissible limits and odour threshold levels that have been identified. Emissions of amines and other nitrogen compounds from the CO<sub>2</sub> capture plant will be low in comparison with existing contributions to nitrogen levels at Kårstø. Any releases of acetaldehyde are assessed as having less negative consequences for the environment than emissions of amines.

## 7.3 Other emissions

**Discharges of cooling water** from the plant will be high. Kårstø already has permission to release quantities of cooling water equivalent to the capacity of the existing tunnel (see section 3.4). Discharges of cooling water over and above this volume will require a new discharge permit, but this is not expected to be a serious problem.

**Water vapour** in the flue gases will be visible, which may be regarded as negative. The vapour will be visible for up to three kilometres from the point of release. It is not expected to give rise to any problems of icing [11].

**Waste flows** will be generated in several parts of the CO<sub>2</sub> capture plant. In order to limit the amount of water that can be contaminated, the vendors have suggested constructing roofs over and collection tanks under units where minor leaks of amines and/or other chemicals could be anticipated. Typical units would be heat exchangers and filters. Collected rainwater would therefore normally be pure enough to be sent to Kårstø's existing drainage system. Water that becomes contaminated by amines will be filtered before being pumped back into the amine plant or being transported out as hazardous waste. Water contaminated by glycol, waste oil or other chemicals will have to be treated separately or shipped out for destruction.

Any **Surplus water** from the process will be neutralised if necessary before it is carried off to the sea. An interesting possibility that ought to be evaluated would be to purify and demineralise such water, thus enabling it to be used as process water by other processing facilities at Kårstø.

**Reclaiming.** Most of the amines used in the capture process will be reclaimed and recycled, but degraded amines from the process will have to be separated out continuously or at regular intervals. The quantity of separated degradation products will vary widely according to the combination of amines selected by the supplier. If a conventional reclaimer is used, the degradation product will have to be extracted and dealt with. This waste product will have to be sent for destruction outside of Kårstø or incinerated or cleaned on-site.

**Captured CO<sub>2</sub>** for transportation to storage can also be regarded as pollution if it contains other substances. For a CO<sub>2</sub> capture plant at Kårstø, this is not regarded as a problem, as the purity of the CO<sub>2</sub> that will be sent for storage is expected to be above 99.9%, containing only small amounts of water, oxygen and nitrogen as well as traces of amines and other waste products from the capture processes.

**Noise** will also be produced by the CO<sub>2</sub> capture plant, but this can be reduced by suitable design and construction techniques. Noise has been an important topic of the studies carried out by the technology vendors. Requirements were set regarding the measures that will be necessary to ensure that the capture plant does not lead to the Kårstø facility as a whole exceeding existing noise restrictions. The strict requirements have been conveyed to the vendors, who have confirmed that they understand the challenge and that their processes and cost estimates take the strict noise requirements into account.

## 7.4 Typical quantities of emissions

Table 13 shows expected quantities of the most important emission components. These may vary widely from one supplier to another. Furthermore, the quantification of emissions in terms of ppm is somewhat imprecise, as values will be affected by temperature and the water content of the flue gases. At present, it is not possible to quantify the emissions of additives in the amine mixtures. The figures in the table include emissions generated by the gas-fired power plant.

**Table 13** Typical quantities of emissions (including emissions generated by the power plant)

Component	Emissions (ppm)	Emissions (kg/hour)	Emissions from 8000 hours of operation (tonnes/year)
Amines to atmosphere	1 – 4	5 – 20	40 – 160
Acetaldehyde	0 – 5.5		
Trace elements	<0.2		
NO/NO <sub>2</sub>	<2 / <0.2		
NH <sub>3</sub>	2 – 8	3 – 12	24 – 100
Degradation products <sup>2</sup>	-	40 – 380	320 – 3040
Excess water <sup>3</sup> (typical pH = 5.5)		0 – 75000	
Typical NH <sub>3</sub> content	90 – 100	5.4	43
Cooling water	-	20 000 m <sup>3</sup> /hour	

## 7.5 Technical safety

The preferred siting of the plant is such that its equipment will need to be designed to withstand radiated heat from the flares at Kårstø when these are in use. Heat radiation values and related information have been sent to the vendors, and these requirements have been taken into account in their proposals.

Since the plant will be located in the immediate vicinity of the gas-processing plant and natural gas at high pressure, equipment and buildings have been designed to withstand maximum anticipated explosion loads. Furthermore, all equipment and potential ignition sources will also be designed to be explosion-proof.

Concentrated amines can be inflammable. For this reason, a fire-safety ring is incorporated around the site of the CO<sub>2</sub> capture plant. In other respects, the capture plant itself is an unlikely source of fire or explosion hazard, as it will use little or no natural gas.

<sup>2</sup> Will not be released locally.

<sup>3</sup> A certain amount of water contaminated with amines, glycol, other chemicals and waste oil will also be collected and sent for special treatment. The amount involved will depend on rain and snowfall and other factors.

Leaks of CO<sub>2</sub> could involve a local asphyxiation risk, particularly within enclosed spaces and at low points in the terrain where there is little air exchange. Gas detectors will therefore need to be installed in such places, in order to prevent undesirable occurrences.

HAZIDs have been performed as part of the technical studies for the CO<sub>2</sub> capture plant. A HAZID is a systematic survey of a process and the operation of a process, aimed at revealing any weaknesses/faults that could lead to accidents, injuries or problems that could put the plant out of operation. A number of points have been identified in connection with the design, construction and operation of the plant where particular care will have to be taken.

No new or surprising conditions were identified. Nevertheless, it is important that similar, more detailed, studies are carried out in the later stages of the project.

# 8 Licensing

## 8.1 The authorities and legislation

The project will require permits in order to comply with various sets of regulations, such as impact assessment regulations, pollution legislation, climate quota legislation and petroleum legislation, safety and construction regulations and possibly, new specially adapted legislation.

An emission permit will be required in order to meet the requirements of the **Pollution Act**. This permit will primarily cover emissions to the atmosphere of amines, additives, reaction products, NO<sub>x</sub>, ammonia and water vapour. Approved methods for treating amine salts and contaminated water must be in place. Requirements regarding noise will have to be clarified, and a permit may be required for discharging cooling water to the sea via a previously approved system. Transport and storage of CO<sub>2</sub> may also require an emission permit; see below.

Although the capture plant will emit less CO<sub>2</sub> than it receives, large quantities of CO<sub>2</sub> will still be released (typically 15% of the CO<sub>2</sub> in the flue gases, as well as emissions from the plant's possible own steam generation). For the period 2005 – 2007, the gas-fired power plant has been allocated free quotas through the **Greenhouse Gas Emission Trading Act**. Before a capture plant is commissioned, it is expected that it will be necessary to clarify the allocation of quotas and responsibility for CO<sub>2</sub> from its generation in the power plant until it is stored offshore. The capture plant and the storage solution may also require an assessment according to this Act.

Because of the size of the CO<sub>2</sub> capture plant and the potential effects of emissions, the plant may be required to perform impact studies in accordance with the Planning and Building Act. If this is the case, it will have to be decided which authority will require the study programme to be implemented and approve it for projects of this sort.

The capture plant itself will not be a cause of particular fire or explosion hazard, but it will be sited in an area where such a hazard already exists, and it may therefore be required to implement measures to prevent the consequences of explosions on neighbouring sites. The plant will also have safety implications. The capture plant and its ancillary installations will therefore have to be evaluated in accordance with the regulations managed by the **PSA**, which will also deal with safety aspects of the CO<sub>2</sub> pipeline and storage solution.

The projected site lies within an area which has been regulated for industrial use and construction will not require new area plans. On the other hand, it may need to be dealt with by the local authority according to the building regulations in the **Planning and Building Act**.

A general permit or license for a CO<sub>2</sub> capture plant is not required according to current legislation, but this may be subject to change.

Laying the CO<sub>2</sub> pipeline may require an impact study according to the Planning and Building Act, which in this connection only applies out to the mean low-water mark. Safety aspects will be evaluated with respect to the regulations that are managed by the

PSA. Since the pipeline is to carry CO<sub>2</sub> rather than hydrocarbons, it is not obvious that requirements regarding such a project can be based on the **Petroleum Act** or the **Natural Gas Regulations**. However, the storage of CO<sub>2</sub> in abandoned oil or gas reservoirs and its possible subsequent use for EOR may mean that it will have to be dealt with according to the Petroleum Act. The legal regime under which the authorities will deal with this matter and issue permits for the plant to transport and store CO<sub>2</sub> should be clarified as soon as possible, so that the lack of clarity does not become a factor that could delay the project.

## 8.2 CO<sub>2</sub> storage: Framework and requirements

Injecting CO<sub>2</sub> into geological formations is covered by international agreements such as the OSPAR and London Conventions. Discussions have taken place regarding what can be permitted. The challenges involved include requirements regarding geology, preventing leaks from the wells, the potential mixing of other substances with the CO<sub>2</sub>, and requirements regarding the sensitivity of local ocean areas in the event of leakages.

Transport of CO<sub>2</sub> from shore has been accepted in the London Convention, and the question will be discussed with regards to the OSPAR Convention in early 2007. How measures of this sort will be evaluated in terms of the United Nations Framework Convention on Climate Change and the Kyoto Protocol has yet to be clarified, and a potential source of revenue from saved climate quotas may still be uncertain at the time of the investment decision.

Irrespective of the concept chosen, storage will require documentation and monitoring. The reception of larger amounts of CO<sub>2</sub> by Sleipner may require a new emissions permit, with its associated requirements for structured documentation. No guidelines concerning the choice of storage site with regard to control of emissions have been identified.

At international level, there is scepticism with respect to storing CO<sub>2</sub> that contains other substances, which means that the highest degree of purity of CO<sub>2</sub> destined for storage is desirable. This requirement appears to be attainable in this case (see section 7.3).

## 8.3 The licensing process

Parallel to the technical and commercial aspects of the planning phase (see section 5.1), the project will have to ensure that all the necessary permits are issued by the authorities, so that progress is not delayed by their absence. A potential process is described below.

**Impact analysis:** An impact analysis may be required for parts of the project and possibly also for the project as a whole. See the regulations regarding impact analyses, Appendix 1, section 4 b: Integrated chemical installations, where the Norwegian Pollution Control Authority (SFT) is the responsible authority. A further reference for evaluation is § 3 section 1 e: Chemical Industry, waste installations, etc. Due to the limited dimensions of the CO<sub>2</sub> pipeline, Appendix 1, section 30, Pipelines for transport of oil, gas or chemicals is probably not applicable. The same may be true of section 2 b: Industrial installations for gas transportation.

The wording of these sections does not make it clear that an impact analysis will be required for such a project concerning the capture, transport and storage of CO<sub>2</sub>. On the other hand, this is a relatively large installation of a type of which there are relatively

little previous experience, and from which there are emissions, possible effects on fisheries, etc.

**The Petroleum Act:** Pipeline transportation and simple storage of CO<sub>2</sub> are probably not covered by the Petroleum Act. On the other hand, a project in which CO<sub>2</sub> is used for EOR or is directly integrated in some other way into petroleum production activity, might need to be treated according to this Act. CO<sub>2</sub> projects might thus be dealt with in different ways according to the use made of the CO<sub>2</sub>, and the use of CO<sub>2</sub> from one and the same plant may change in the course of time.

For this reason, **new legislation** regarding impact analyses and processing of applications for CO<sub>2</sub> projects may be necessary. Such legislation would ensure that field-level consequences for all CO<sub>2</sub> projects is properly analysed and dealt with, and could also ensure overarching licensing of all stages of a CO<sub>2</sub> project. Such a law could replace licensing the project according to the impact analysis regulations, which appear to cover the CO<sub>2</sub> capture plant at most. NVE expects that OED will consider this question and submit a proposal in the case that new legislation is envisaged.

**Emissions:** Emissions to the atmosphere and to water will probably not have major effects, but the emissions are unusual and somewhat uncertain. NVE assumes that an emission permit will be required for the capture plant, and that this will also cover transport and storage.

The response of OED or SFT to a proposed impact study programme is expected to take about five months. Dealing with an application for an emissions permit, with its impact analyses and a possible new application in accordance with new legislation, is estimated to take six months. It is assumed that the process of clarification with respect to the Greenhouse Gas Emission Trading Act (including the relationship between the power plant and the CO<sub>2</sub> capture plant) with preparatory work performed by SFT and a final decision made by the Ministry of Environment, will be carried out in parallel with the processing of the application for an emission permit.

Since the emissions of amines and additives will differ according to the chosen vendor, NVE assumes that it will be possible to issue an emission permit on the basis of estimated emissions. When definitive information becomes available, a modified permit can be applied for.

Neither pipe lay nor pipeline operation is expected to produce any significant pollution hazards. Operation does not result in fire or explosion hazard. It is assumed that the emission permit for Sleipner will have to be updated if it receives large additional quantities of CO<sub>2</sub>. This will be applied for and is expected to be handled at the same time as the application for an emission permit for the CO<sub>2</sub> capture plant.

**Safety:** The project will also require permits to satisfy the regulations managed by the Petroleum Safety Authority. This applies in particular to the framework regulations and to the regulations regarding safety inspections. On the Kårstø site itself, Gassco will have to reconsider its contingency and safety measures and propose necessary new measures for the CO<sub>2</sub> capture plant. Such an evaluation can only be carried out once the main choice of development concept has been made. It appears to be clear that it is the Petroleum Safety Authority rather than The Directorate for Civil Protection and

Emergency Planning (DSB) which deals with safety questions related to capture and storage of CO<sub>2</sub>. Transport and storage will also require clarification in accordance with these regulations. How these matters are to be dealt with, including estimates of the time required to do so, must be clarified with the Petroleum Safety Authority early in 2007.

On the basis of the above considerations, NVE has estimated the time required for the processing of applications by the authorities in Table 14.

**Table 14**      **Licensing schedule**

<b>Activity</b>	<b>Time required</b>
Draw up proposal for impact study programme for CO <sub>2</sub> capture plant and storage solution	2 months
Consultation round and definition of impact analysis programme	5 months
Draw up impact statement, OED application and emissions permit application	In parallel with consultation round plus 2 months
Consultation and processing of impact analysis and applications	6 months

If relationships with the authorities can be followed up efficiently, processing in accordance with current rules and regulations is not expected to lead to delays in the progress of the project. The most critical aspect in this respect appears to be the regime for handling CO<sub>2</sub> projects, which remains to be clarified. If the most rapid possible realisation of the project is the goal, the possibility of creating new legislation in this area is a question that will need to be dealt with rapidly.

## 9 Risks and uncertainties

The establishment of a CO<sub>2</sub> capture plant with subsequent transport and storage of the CO<sub>2</sub> involves a significant degree of uncertainty in terms of costs, progress and performance. Uncertainty may result in either improvement or degradation of the end result in comparison with the baseline expectations. This chapter looks at what are regarded as the most important uncertainty factors, as well as potential measures for reducing uncertainty. The factors that are assumed to have most impact on the end result are discussed first.

### 9.1 Hours of operation of the power plant

The profile of operation of the gas-fired power plant at Kårstø is uncertain. The relationship between electricity price, gas price and Naturkraft's CO<sub>2</sub> costs will change over time. This may result in anything from base-load operation of about 8000 hours per year in some years to others with only a few thousand hours of operation, potentially combined with a high frequency of start-ups and shutdowns.

Since a large proportion of total costs consists of fixed costs that are unaffected by operating hours, the costs per tonne of CO<sub>2</sub> captured or kWh generated can vary widely. By far the lowest costs are incurred by continuous base-load operation of the gas-fired power plant for the foreseeable future. Reducing the number of hours of use from 8000 per year would raise the costs per tonne of CO<sub>2</sub> captured (see section 6.6.1). Smaller variations in the number of hours of use, even with only a few years at a low number of hours, could also raise costs considerably. Frequent shut-downs of the power plant also offer significant technical challenges, including poorer capture rate and higher operating costs. The ability to operate with frequent starts and stops will vary from one technology vendor to another as a function of the corrosive properties of their absorbents and their use of high-grade materials. The operating philosophy of the power plant is for its owner to decide, and a wish for a high rate of hours of operation on the part of the CO<sub>2</sub> capture plant will have little influence on his decision.

### 9.2 Energy costs

Energy (electricity and steam) is by far the largest operating cost element of the project, and this cost may vary widely in the course of the operating hours of the capture plant. This is partly because energy consumption per tonne of CO<sub>2</sub> captured is somewhat uncertain, but primarily because the price of the energy itself is volatile. As far as energy consumption is concerned, a range of variation of 10% in comparison with baseline assumptions may be envisaged, while the price of energy may vary over a much wider range; see section 6.6 for estimates at different energy prices. Rising energy prices can hardly be influenced by the capture plant, and this is an uncertainty that investors will have to live with.

### **9.3 Interfaces and Kårstø as a construction site**

The costs of the plant will be largely dependent on the commercial agreements made with Naturkraft, Gassco and Statoil with respect to the site, purchase of energy, cooling water and CO<sub>2</sub> storage. Advantageous agreements with neighbouring companies may also result in significantly lower costs than if it proves necessary for the plant to establish its own solutions. Early clarification of these issues will be of decisive importance for the progress of the project,

The baseline alternative assumes that energy (steam and electric power) will be purchased from Naturkraft. The alternatives include on-site steam generation based on natural gas and the possible coordination of steam generation with the rest of the gas-processing plant. It is also assumed that the CO<sub>2</sub> capture plant will be able to buy capacity from the existing cooling water system so as to avoid having to install a new seawater inlet. The availability of sites, raw water supplies and safety requirements are other elements of uncertainty with respect to establishment at Kårstø.

Kårstø is expected to experience a great deal of construction activity in the near future, where a large number of companies and projects will be competing for limited capacity within a framework of operations and logistics that must be responsible in terms of safety. This may result in a slow rate of progress and an inefficient construction phase, with cost increases and delayed start-up as an outcome. A large number of simultaneous activities will also increase the risk of injuries and other serious occurrences during the construction phase.

On the measures side, stress will have to be placed from the very first day of the project on starting preparatory activities for, and actually carrying out, negotiations with neighbouring companies. The results of these negotiations will be of decisive importance for the start of the process and design studies, which in turn will play a decisive role in determining the rate of progress. Emphasis will also have to be placed on studying alternative solutions within the capture plant's interfaces. The project will also be able to improve the overall situation at Kårstø by preparing for a high degree of modularisation and as independent a construction site as possible. Any increase in costs in these areas will have to be incorporated into the basis for the investment decision. The advantage, weighed against other major uncertainty factors, is that these costs will largely be known before the final investment decision is made.

### **9.4 First large-scale facility of its kind**

The Kårstø plant will be about ten times as large as the largest existing amine-based CO<sub>2</sub> capture plant (in Bellingham) for flue-gas from a gas turbine power plant. It appears to be highly probable that a large plant will function in technical terms, with about the expected degree of CO<sub>2</sub> capture and expected consumption of energy and amines. However, the increase in size raises the level of uncertainty with regard to performance, consumption and successful construction and operation than would be the case if several equivalent facilities had already been built. One of the principal challenges appears to be that of achieving an even distribution of the amine solution throughout the whole volume of flue-gas in such a large absorption tower. Another concern is whether the high oxygen content of the flue gases will lead to a high rate of degradation of the amines.

The consequence of this could be a long, difficult commissioning and start-up period. There is also a risk that the plant will be unable to deliver the performance on which the contracts will have been based when signed. There may also be a need for technical modifications, with shut-downs during the first few years of operation. The expected costs of this large-scale facility have been incorporated in the baseline alternative, but scaling up does add a certain degree of uncertainty, with a potential for cost increases.

Measures aimed at avoiding surprises could include technology qualification, in which small-scale tests of energy optimisation and minimisation of emissions are tested. The need for this step will depend to some extent on the experience of the technology vendors concerned. Some of the risk involved in scaling up can also be placed with the technology vendors, via the obligations that they accept in their contracts, but the contract price will rise as more risk is left with the technology vendors. Full contractual security in this area is regarded as being impossible to achieve. An investment decision will involve the risk that the plant will be unable to provide the performance on which the decision was based. It is expected that this risk will have to be given an upper limit for the chosen vendor, which means that the risk in the case of major problems will largely be left with the plant owner.

## **9.5 Price of materials, equipment and manpower**

The prices of materials, equipment and manpower have all risen in the course of the past few years, and it is possible that they will continue to do so. If they do, this will affect the costs of the shore plant and the pipeline. The baseline estimates of this report are based on prices that reflect the market of today, but changes in prices until the date of order involve a cost risk that may move in either direction. When pipelines are being purchased, the possibility of linking this purchase to purchasing agreements of major Norwegian steel purchasers should also be considered, if this is regarded as appropriate.

The costs of manpower may also increase. This is particularly the case for qualified manpower that would be employed at Kårstø in competition with other projects. Although the construction of the capture plant can be based on modules manufactured elsewhere, there will be a significant need for manpower at Kårstø in the course of a long construction period. High manpower costs as a consequence of pressure on limited resources may lead in turn to higher costs for the owner of the capture plant and for other projects in the region.

## **9.6 Choice of storage concept**

Sleipner has been proposed as the storage site. However, the operating philosophy of Sleipner, the loss of the possibility for EOR at Volve, the legal situation and other factors could make it impossible to sign agreements for the storage of CO<sub>2</sub> here, or make the costs of such storage too high. In such a case, the alternative would be the establishment of a separate storage site at Utsira, with preparatory studies, drilling of wells, new technical reception solutions and a separate monitoring system. Other storage solutions may exist, but the costs of such future possibilities are not known, and such a choice could lead to challenges as far as the need for progress of the project as a whole is concerned.

## 9.7 Mobilisation and progress

The schedule assumes that the project will continue after the turn of the year 2006/2007, and that a competent project organisation capable of taking the project further with satisfactory quality will be built up relatively rapidly. If such a mobilisation proves to be difficult to achieve, it will have serious consequences for the project's ability to follow the schedule outlined in this report.

In its subsequent phases, the project will also have to have the ability, and the mandate, to make decisions and to make commitments regarding its use of time and resources. It is not possible both to achieve sufficient progress and to keep all one's options open.

## 9.8 Competence of plant owner

A sufficiently rapid build-up of a staff with high competence and considerable experience in engineering, contractual, legal and financial aspects offers a major challenge. A plant owner who wishes to ensure that these aspects of the project are taken care of satisfactorily will also have to utilise well-established and proven quality-assurance and risk-control systems. Limiting uncertainty needs to start with putting significant resources into establishing competence and systems in this area, for example by hiring existing centres of competence.

## 9.9 Other sources of uncertainty

Besides the above-mentioned risk factors, which may have serious consequences for the overall level of costs and/or rate of progress, there exist other sources of uncertainty.

**Coordination of several projects:** The schedule assumes that several different sub-projects (capture, transport and storage) will be synchronised and can be fitted together. Experience suggests that such a situation offers considerably greater challenges as regards progress and costs than do isolated projects. On top of the project consisting of several sub-projects, it is also dependent on Naturkraft as well as other companies both at Kårstø and offshore, a situation that increases its complexity.

**Environmental and safety requirements:** Uncertainty as regards the scope and effects of emissions to the atmosphere may result in longer processing time on the part of the authorities, and the possibility of extra conditions being imposed. However, given the measures that have already been imposed as regards water scrubbing of gases, for example, little more can be done in practice, apart from restricting the technology vendors who will be allowed to offer their technologies. The alternative would be to refuse an emissions permit, an outcome regarded by NVE as unlikely. The other environmental aspect that involves a certain degree of uncertainty is the reception plant for CO<sub>2</sub>, and the delays and costs that could be associated with it. Measures in the fields of noise, seawater systems, waste treatment and the CO<sub>2</sub> pipeline may involve extra costs, but the measures involved here are well known. The Kårstø safety requirements will also involve additional costs, but an attempt has been made to include these in the original cost estimates.

**Regulatory regime:** The fact that the regulatory regime for the CO<sub>2</sub> pipeline has still to be clarified will be a challenge for the progress of the project as a whole. The project's

CO<sub>2</sub> abatement cost and its effectiveness as a climate change measure will be highly dependent on a number of external factors such as the climate regime after 2012, the costs of quotas and how they are managed, storage as an approved climate-change measure, and the possibility of, and then revenues from, EOR. These factors will largely determine whether capture and storage make up a competitive climate-change measure, and will not necessarily have been clarified before the decision to invest will have to be made.

**Technical challenges:** A number of technical conditions may be capable of causing operational problems and raising cost levels. In the CO<sub>2</sub> capture plant, oxygen and other substances in the flue gases may affect amine consumption and efficiency. Other factors include corrosion protection, preventing unwanted suction of air into the flue gases and pressure drop, and ensuring sufficiently stable operation. In the compression plant, systems for monitoring and adequate drying of the CO<sub>2</sub> flow will be a challenge.

Safe pipeline transportation is dependent on the removal of free water. The possibility of low pressure occurring at the well-head, with separation of the gas into two phases in the pipeline, could be a problem for pipeline transport. It will also be necessary to prevent leakages and offer the possibility of safe pressure relief in the pipeline that takes into account low oxygen concentrations where large amounts of cold CO<sub>2</sub> are released. It will also be necessary to protect the pipeline against external forces such as trawl gear. These factors are all potential causes of increased costs, and will have to be followed up carefully in subsequent phases of planning.

The most important measures that can be implemented in order to eliminate the effects of such sources of uncertainty are different types of technology qualification.

**Storage:** Alternatives to Sleipner have only been evaluated at a general level, and technical solutions for seabed templates and seabed reception have not been studied to the same level of detail as the rest of the project. Selecting such a solution will increase the degree of uncertainty in terms of viability, costs and progress compared to reaching an agreement with Sleipner.

**Revenues:** There is a potential for payments to the project through the allocation of CO<sub>2</sub> quotas that can be sold, or from future sales of CO<sub>2</sub> from Kårstø for EOR offshore. The project might also be able to sell spare capacity in its transport and storage systems to other projects.

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## ABBREVIATIONS

Abbreviation	Explanation
AKET	Aker Kværner Engineering & Technology
DSB	Directorate for Civil Protection and Emergency Planning
DNV	Det Norske Veritas
EEA	European Economic Area
EOR	Enhanced Oil Recovery
EPC	Engineering, Procurement, Construction
FEED	Front End Engineering and Design
HSE	Health, Safety and Environment
MD	Ministry of the Environment
MEA	Monoethanolamine
MHI	Mitsubishi Heavy Industries
MNOK	Million Norwegian Kroner
MWKL	M.W. Kellogg Ltd.
NILU	Norwegian Institute for Air Research
NOAH	Norsk avfallshåndtering
NPD	Norwegian Petroleum Directorate
NVE	Norwegian Water Resources and Energy Directorate
OED	Ministry of Petroleum and Energy
OSPAR	The Convention for the Protection of the Marine Environment of the North-East Atlantic
PSA	Petroleum Safety Authority
R&D	Research and Development
RFO	Ready For Operation
SFT	Norwegian Pollution Control Authority
TFO	License award in pre-defined areas
TSP	Technical Service Provider
VOC	Volatile Organic Compounds

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