CLIMIT 2019

SUMMARY

THE NATIONAL PROGRAMME for
research,development and demonstration of
CO_2 Capture, Transport and Storage (CCS)

CONTENT

CLIMIT'S PRIMARY OBJECTIVE is to contribute to the development of technology and CCS solutions by supporting the development of knowledge, expertise, technology and solutions that can make important contributions to cost reductions and broad international deployment, as well the exploitation of national advantages and the development of new technology and service concepts with commercial and international potential. The programme is a collaborative partnership between Gassnova and the Research Council of Norway. CLIMIT encompasses the Research Council of Norway's support scheme for research and development (the R&D part) and Gassnova's support for development and demonstration (the Demo part). Gassnova has the overall responsibility and manages the programme secretariat.

Photo cover: Styrk Fjærtoft
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PREFACE

A DRIVING FORCE FOR CARBON CAPTURE AND STORAGE

CLIMIT has played a central role in the development of the world's most dynamic research environments for carbon capture and storage (CCS). Close cooperation with the industry has been a critical success factor.

IN PARIS IN 2015, the international community agreed that a reinforced commitment is paramount if climate change is to be stopped. The goal set by the signatories, is to limit the increase in temperature to 2°C.

According to the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA), this goal will be near impossible to reach without capturing CO_2 from large sources of emissions and storing it deep underground. There is also broad agreement among researchers, industrial players and decision makers that CCS technology now is mature and ready for use.

CONTINUITY OF FOCUS

It has required long-term, goal-oriented effort to devise practical solutions for all parts of the value chain.

"CLIMIT has been a driving force in the development of CCS technology. Our commitment has spawned knowledge and solutions that benefit the international community," says Arvid Nøttvedt, Chairman of the CLIMIT Board of Directors. "While interest in CCS technology has recovered in Europe, after a period of decline, CLIMIT has been a stable contributer to research in this field. Norway is one of the few countries that has kept a continuous focus on CCS research and development."

Since the establishment in 2005 and up to 2019, CLIMIT has financially supported almost 500 research projects with more than NOK 2 billion. The research institutions that have received funds, represent a diverse set of competencies and approaches. Projects have been selected on the basis of a comprehensive evaluation of which parts of the innovation chain that needs funding most.

"It's the responsibility of CLIMIT's management and Board of Directors to ensure a balanced portfolio, so we can achieve the overarching goals defined in our program. Hence, CLIMIT has a strategic role," says Nøttvedt.

In addition to financial support, CLIMIT sees competence sharing as a key goal. Projects receiving funds are encouraged to communicate results to a wide range of stakeholders. Moreover, CLIMIT organizes a major conference biannually, gathering Norwegian and international expertise in this field, both researchers and industry representatives. Through presentations and panel discussions, relationships are formed and competence shared among professionals and organizations. In 2019, 270 experts from Norway and abroad participated at the CLIMIT Summit in Oslo.

AT A CROSSROADS

Technologies and solutions for the handling of CO_2 have been developed, and are ready to be used on an industrial scale. At the same time, CLIMIT continues to support projects that develop new solutions, and projects that can reduce costs and risk.

"The cornerstone of our approach is to support projects where industrial companies are engaged," says Nøttvedt. "Thus, in order to receive funding for applied research from CLIMIT, projects should obtain as much economic contributions from industrial partners as possible. This arrangement encourages the partners to create technological solutions that the industry really need."

The Norwegian full-scale CCS-project currently being planned, represents a crossroads.

In addition to keeping a steady course when it comes to building knowledge, CLIMIT maintains its focus on the full-scale project. An important goal in the time to come, will be to contribute to the successful completion of the project. One challenge is to involve more industrial plants, so that the capacity of the infrastructure is filled. And at a future point in time, scaling up capture and storage capacity must also be addressed. The forthcoming investment decision will include clear expectations on these issues.

Currently, a broad set of stakeholders are evaluating the opportunities a full-scale project will bring. Both on a national and local level, governmental entities are preparing plans describing how the infrastructure can best be used. Industrial companies have become more deeply involved and are now making necessary arrangements for implementing CCS technology. In this area, CLIMIT will contribute with financing for research projects that can pave the way for scaling up and ensuring optimal utilization of the infrastructure.

INDUSTRIAL COMPANIES PARTNERING UP

"The CLIMIT Board of Directors is very pleased and encouraged by the wide range of industrial players showing interest in CCS technology. There has been a visible upswing in involvement over the last few years," says Nøttvedt.

"We now see that industrial clusters want to implement capture technology and feed the CO_2 from their plants into the full-scale value chain," says Ingrid Sørum Melaaen, director of CLIMIT. "The CO2 Hub Nordland, the Eyde cluster in Arendal and Øra Industrial Area in Fredrikstad are such examples."

THE ROAD AHEAD

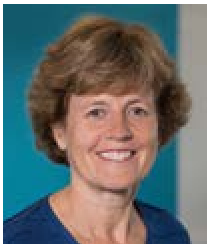
As a way to reduce CO_2 emissions, CCS is in many cases competitive with other measures. One challenge is that it's still far cheaper to discharge CO_2 than to correct damages caused by climate change.

"We lack solid business models, and this slows down the implementation of CCS," says Sørum Melaaen. "Simultaneously, it's important to support the development of new technology that drives the costs downward. CLIMIT has an important role to play in this regard."

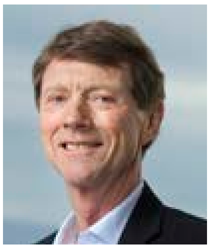
Going forward, CLIMIT has also defined new strategic areas.

Compact solutions represent one promising concept. Since many industrial sites cover small areas, it's important to develop installations that occupy little space. Key terms are compactness, standardization and modularization. Smaller units mean less steel and concrete – and less work putting it all together. This translates into lower costs. And if the operators can manage to take out a larger share of CO_2 in concentrated form – maybe up to 50 percent CO_2 in a stream – the capture becomes more efficient. At industrial plants where adapted installations are not an option, compact units may be the solution.

"We want to support a wide range of projects that can bolster cost-effectiveness. This commitment encompasses projects along the entire value chain – from capture via transport to storage," says Sørum Melaaen.



INGRID SØRUM MELAAEN
Head of CLIMIT



ARVID NØTTVEDT
Chairman of CLIMIT

A promising dimension of the research is the development of new business areas. One example is *blue hydrogen*, which opens up for a new application of natural gas, and may play a useful part in the transition from fossil-based to renewable energy sources.

"These are good examples of areas that CLIMIT will continue to stimulate – research resulting in practical applications. Moreover, CLIMIT shall think long-term and develop new technologies that can be used in 2040," says Nøttvedt

CAPTURE

A CLEANER REFINERY

Preem has ambitions of capturing CO_2 from the company's two refineries on Sweden's west coast. Tests conducted by Aker Solutions will give Preem important operational experience with carbon capture technology.

Aker Solutions's mobile test unit on site at Preem's refinery at Lysekil. Photo: Aker Solutions

PREEM IS SWEDEN'S LARGEST fuel company. The operation encompasses production, distribution as well as trading and product sale. The plants in Lysekil and Gothenburg are amongst the most modern and lowest CO_2-emitting refineries in Europe. They have a combined capacity of over 18 million cubic meters of crude oil per year and discharge approx. two million tonnes of CO_2 every year.

TEST UNIT

"Preem has a vision of being a leader in the transition towards a sustainable society," says project director Karin Lundqvist. "And carbon capture will be a necessary measure to reduce emissions of CO_2 to the atmosphere. The vision entails building full-scale capture plants at the refineries. This will decrease the discharges significantly."

After meticulous planning, Preem is now ready for testing.

Aker Solutions has developed a complete pilot-scale mobile test unit (MTU). Parts of the installation are assembled in containers, and these are fast and simple to mount on different parts of the production plant. The MTU will be in operation from May to October 2020 at the refinery in Lysekil.

The test unit will capture CO_2 from

the flue gas generated in a production plant. In a downscaled absorption tower – with a diameter of a mere ½ meter – the flue gas flows through an amine solution that absorbs CO_2. The amine is then heated in a regenerator tower, and releases the CO_2, which can be isolated in pure form at a later stage. In the last step, the amine is recycled and can be re-used in the process.

"In the test phase we want to investigate how we can optimize the process for the types of flue gases generated at our refineries," says Lundqvist. "How can we reduce the energy consumption? And how can we ensure that the removed CO_2 is as pure as required for long-term storage? We are studying how the amine behaves and how it degrades. We are also working to lower the emissions of amine as much as possible."

FOCUS ON THE CARBON CAPTURE AND STORAGE (CCS) VALUE CHAIN

What are the biggest challenges with the CCS technology?

"When it comes to operating the test unit, there are no serious challenges. Rather, it's important to acquire practical experience with carbon capture at our plant."

The next step will be to connect the carbon capture facilities at Preem's refineries to the Northern Lights long-term storage infrastructure, which is a constituent part of the planned Norwegian full-scale CCS project.

"In hooking up to this infrastructure, the challenges are not so much technical as logistical. We are also evaluating the legal challenges of transporting CO_2 on ships and over national borders," says Lundqvist.

The full-scale project encompasses a comprehensive value chain. Firstly, the CO_2 will be captured from the production process. Then, the gas will be compressed to liquid form, which occupies less space, and transported to intermediate storage at dedicated loading docks.

"If the planned Northern Lights infrastructure is built, we see this as the natural option for offloading CO_2 from our refineries. But our focus on CCS is not solely reliant on this infrastructure," says Lundqvist.

The Northern Lights route includes transport of CO_2 on specialized ships to a hub on the western coast of Norway. From there, the gas will be pumped into a geological structure deep under the sea, where it will be stored permanently.

The PREEM CCS project has the following work packages:

0. Project management and communication of results
1. Demonstration and implementation of CO_2 capture
2. Process evaluation of full-scale CO_2 capture integrated at Preemraff
3. CCS value chain analysis, CO_2 transport and integration in the Norwegian full-scale CCS project
4. Identification of measures to handle legal obstacles for ship transport and storage of CO_2 from Preemraff Lysekil for storage on the Norwegian Continental Shelf
5. Roadmap for the reduction of CO_2 emissions at Preem related to Sweden's goal of zero net emissions in 2045

The project is supported by Gassnova via CLIMIT-Demo and the Swedish Energy Agency via Industriklivet. ■

KARIN LUNDQVIST
Preem

Project:
Techno-Economic Feasibility Study of the Implementation of Carbon Capture from Major Emission Sources at Preemraff Lysekil (PREEM CCS)

Project owner:
Preem AB

Project period:
2019–2021

Total budget:
28 MNOK

Support from CLIMIT:
9.55 MNOK

Partners:
Aker Solutions, SINTEF, Chalmers and Equinor

CAPTURE

A NEW WAVE OF TECHNOLOGY FOR CLEAN ENERGY CONVERSION

Innovative looping technology may pave the way for industrial applications. Gas switching combustion may be used for power generation or hydrogen production.

SHAHRIAR AMINI
SINTEF

Project:
Demonstration of Gas Switching Technology for Accelerated Scale-up of Pressurized Chemical Looping Applications.

Project owner:
SINTEF

Project period:
2017–2020

Total budget:
1.65 Mill. Euro

Support from CLIMIT:
9.2 MNOK

Partners:
SINTEF, NTNU, Euro Support Advanced Materials B.V., Universitatea Babeş-Bolyai, HAYAT, ETH Zürich and Universidad Politécnica de Madrid.

THE REASON THAT CARBON CAPTURE technology has not been commercialized as expected, is that they all carry a significant energy penalty. If industrial companies want to capture CO_2, they will have to spend more energy. And the costs will soar.

"There is simply no off-shelf technology that companies can buy, without having to burn more fuel and spend more energy to capture CO_2," says project director Shahriar Amini at SINTEF. "So today, implementation hinges on incentives and funding from governments."

Amini heads a project called *GaSTech - Demonstration of Gas Switching Technology for Accelerated Scale-up of Pressurized Chemical Looping Applications.* The aim of this research effort is to develop cost-effective, affordable CCS-technology.

The point of departure for the project is conventional post-combustion processes.

In chemical looping combustion, there are two reactors. In the first reactor, an oxygen carrier material (i.e. a metal oxide), is oxidized by air. The next step, in the second reactor, the oxide is reduced by natural gas. The solid metal or metal oxide exists in the shape of powders. Hence, the oxygen carrying material – whether in the form of metal or metal oxide – keeps looping between the two reactors. The chemical reaction in the oxidation stage creates a very high temperature in the stream of gas, which can be used in power plants to create electricity.

LIMITATIONS OF CONVENTIONAL TECHNOLOY

However, there are certain limitations to the conventional process.

"If you want to scale up this reactor system in very large units, the circulation of solids is very difficult", explains Amini. "You would need to apply very high pressure for higher efficiency– and operating two pressurized units complicates the industrial design and operation."

Consequently, Amini and his group of researchers have taken this technology one step further. The gas switching combustion process uses one single reactor. Instead of moving the oxygen career materials from one reactor to another, a valve in the reactor inlet switches between injecting natural gas and air into the reactor.

SMALLER MODULES ARE CONNECTED

"Let's assume that the metal powder oxide in the reactor is iron oxide, FeO," explains Amini.. "At the inlet of the reactor, a valve is adjusted so that natural gas flows into the reactor. The natural gas will react with the oxygen

SINTEF focuses on developing cost-effective CCS technology that industrial companies can afford. Photo: Geir Mogen, SINTEF

of the FeO, reducing the oxide to metal (Fe). The outlet gas coming out of this reaction is a pure stream of CO_2 with water vapor. After separation of water vapor easily through condensation, a very pure stream of CO_2 is created, which then can be compressed and transported for storage.

Then, the valve is set to inject air. The Fe reacts with the oxygen of the air, converting the iron to iron oxide. This is an exothermic reaction that creates a stream of gas with temperatures up to 1000 °C. The air, deprived of its oxygen, now consists mainly of nitrogen that can be led into a thermal power plant to produce electricity.

"It's about simplicity," says Amini. "It's much easier to scale up a concept with one single reactor. And the beauty of this process, is that we don't necessarily need to build very large units. We can have smaller plants modules connected to each other to work in a cluster."

One advantage of the technology is that it's able to produce both power as well as hydrogen.

RELEVANT FOR NORWEGIAN INDUSTRY

"This technology can be very relevant for Norwegian industry, because in hydrogen production, natural gas is used as a feedstock, and you can separate CO_2 with no energy penalty."

Over the last decade, in a number of projects funded by Research Council of Norway, European Commission and ACT*, Amini and his colleagues have tested this reactor extensively. The next step will be to put the technology to work in a pilot. Hopefully, that will be the next project. ■

* ACT – Accelerating CCS Technologies – is a platform where several countries collaborate on information and knowledge sharing. A detailed description of ACT will be published later in the annual report.

CAPTURE

CLEANER HYDROGEN PRODUCTION

The calcium-copper looping technology is promising. The aim is to produce hydrogen and capture CO_2 in one step. And do it cost-efficiently.

SUNI ARANDA
IFE

Project:
The 6Cs project – CO_2 Capture by Combined Calcium-Copper Cycles

Project owner:
Institute for Energy Technology (IFE)

Project period:
2016–2019

Total budget:
8.75 MNOK

Support from CLIMIT:
8.75 MNOK

Partners:
IFE, University of Bergen (UiB), Norwegian Institute for Air Research (NILU).

IFE (INSTITUTE FOR ENERGY Technology) at Kjeller, Norway, draws on a long tradition of collaboration with industrial companies.

"Our core business is to help industries to move to the green shift with specific technologies, and we tailor solutions from there", says Suni Aranda, head of IFE's Department for Environmental Industrial Processes.

IFE possesses a comprehensive pool of knowledge in hydrogen, CO_2 capture and utilization, as well as process intensification – how to design new processes and make existing processes more efficient.

A WELL-TRAVELLED IDEA

"We have a very strong belief that working with industry from the concept stage, is key for success", says Aranda. "It's important that they are involved. Because we don't have ready-made solutions in our pockets. We seek to address the practical needs of operational environments."

The 6Cs project – *CO_2 Capture by Combined Calcium-Copper Cycles* – paves the way for hydrogen production with integrated CO_2 capture, and followed this pragmatic approach.

The 6C project was ideated as a spin-off project with origin from a European framework, and it was carried out together with international research and industrial partners.

"I think the 6C project is a successful example of how knowledge travelled back and forth between Norway and Europe, between different research communities, and between researchers and industry players", says Aranda.

WHY CALCIUM-COPPER?

In conventional hydrogen production, hydrogen is produced in several reactors, where CO_2 capture is not integrated and requires considerable energy and dedicated equipment. The calcium-copper looping technology proposes to integrate the entire process into one reactor with sequential steps, alternating gas flows and process conditions.

The 6Cs project also aimed at developing innovative materials for this process. Materials with combined functions reach even further reduction of energy demands and equipment costs. That's why it's called process intensification.

The system starts with natural gas, mostly methane, injected into the reactor.

To capture the CO_2, the researchers use calcium oxide as a sorbent. Under specific conditions, calcium oxide captures CO_2, and becomes calcium carbonate. The next step is to release the CO_2 from the calcium carbonate, in a concentrated form, ready for its utilization or storage. The sorbent is regenerated back to calcium oxide, and made available for a new cycle where it can capture the CO_2 again.

The regeneration of the sorbent takes place at a high temperature. How heat is transferred at this high temperature, is crucial in terms of

Hydrogen can become an important energy carrier in the future. Photo: iStock

how viable this process will be. In the calcium-copper looping cycle, the heat is generated and transferred via the copper in-situ, by the exothermic reduction of copper in contact with reducing gases (H_2 and CO). The heat transfer comes from solid-gas chemistry. There is no additional external source of heat for the regeneration of the sorbent.

"Copper is reduced while calcium carbonate is decomposed, and the reduction of copper is exothermic. It means that it emits heat that is necessary for the calcium carbonate to release the concentrated CO_2, and form calcium oxide for a new cycle," explains Luca Di Felice, project director.

A COMBINED MATERIAL

The crux of the process design is to merge functions in the same material. Calcium and copper are combined into composite particles.

The combined material – which contains both the sorbent and the heat carrier – must have adequate chemical, physical and mechanical properties. It has to go through the chemical cycles, withstand high temperatures and changes of temperatures, and tackle possible impurities in the gas. The focus of the research revolved around the stability of different materials.

"For example, in specific circumstances, spots within the material can melt. This is one of the challenges with copper. You have to spread it nicely, so it's stable and still reactive over cycles. This has been a scientific challenge," says Di Felice.

At the completion of the 6Cs project, the calcium-copper looping technology is way more than a concept. The research team has carried out comprehensive simulation and laboratory testing. Now the aim is set for further verification on an industrial-level scale.

Partners are such as Instituto de Carboquímica in Spain, the University of Bergen, the Norwegian Institute for Air Research and the Eindhoven University of Technology in the Netherlands. Industrial partners were Johnson Matthey, the UK developer of sustainable technologies, and a copper-mining company, Cobre Las Cruces, in Spain. ■

CAPTURE

NEW FUELS FOR CARBON-FREE POWER PRODUCTION

The BIGH2 project develops advanced combustion technology that utilizes mixtures of hydrogen and ammonia as carbon-free fuel in industrial gas turbines.

ANDREA GRUBER
SINTEF

Project:
BIGH2

Project owner:
SINTEF Energy AS

Project period:
2017–2021

Total budget:
36 MNOK

Support from CLIMIT:
17.9 MNOK

Partners:
SINTEF, NTNU, Siemens and Equinor

GAS TURBINE MANUFACTURERS aim to deliver engines that can use carbon-free fuels before 2030. The gas turbines must have the same level of performance as today's state-of-the-art equipment, powered by natural gas, and meet current requirements regarding emissions of nitrogen oxides and other pollutants.

The project explores key challenges related to the use hydrogen and ammonia as gas turbine fuels: to ensure a stable flame in the combustion chamber and avoid emissions of nitrogen oxides that exceed regulatory standards. Hydrogen represents, in many respects, an optimal fuel because it burns easily in a very stable fashion and, if certain combustion conditions are satisfied, also very cleanly as its only combustion product is water vapour. However, hydrogen also poses important logistical challenges because the gas is highly explosive and characterized by very low energy density. Therefore, it's problematic to store hydrogen safely in very large quantities.

A CONVENIENT HYDROGEN AND ENERGY CARRIER

The BIGH2 project investigates the possibility of using ammonia (NH_3) as a hydrogen carrier because ammonia is considerably easier to handle than hydrogen.

While hydrogen is a relatively new fuel in the transportation and power generation sectors, still lacking well-established logistics and infrastructure, ammonia is already produced, transported and stored in large quantities for the manufacture of fertilizers, for example.

"Ammonia is a very well-known chemical, and we draw on comprehensive, accumulated experience from all links of the value chain. An extensive distribution network is already in place, and we have effective systems and safety mechanisms for handling the chemical," says project director Andrea Gruber at SINTEF.

So, how could ammonia be used as an energy carrier in the production of power with large gas turbines?

UPGRADING AMMONIA

The challenge with ammonia is that it's a rather poor fuel, especially for gas turbines, characterized by weak ignition and combustion properties and by a rather obnoxious tendency to form atmospheric pollutants (nitrogen oxides, NO_x) in the exhaust. Hence, BIGH2 aims to find out if blending ammonia and hydrogen can result in a better gas turbine fuel than neat (pure) ammonia. A fuel mixture consisting of hydrogen, nitrogen and ammonia can be readily obtained by cracking the ammonia molecule into hydrogen and nitrogen by heating the chemical in a catalyst. Vast amounts of waste heat are often available in gas turbines as bi-product of the combustion process.

"Before sending the ammonia into the gas turbine, the chemical compound can be cracked, completely or partially, by using surplus heat – and using the resulting hydrogen, which is a highly reactive element, to upgrade the fuel mixture," says Gruber. "In this project, we try to understand how different blends of ammonia, hydrogen and nitrogen behave in the combustion chamber, compared to natural gas."

It's important to find the "sweet spot" and limit the cracking of ammonia to ensure a stable and clean combustion. This is also important because the cracking process itself uses surplus heat from the gas turbine, and this heat has alternative utility value for steam turbine cycles or district heating. Therefore, the intention of the project is to identify the optimal mixture of hydrogen, nitrogen and ammonia that requires as little cracking of ammonia as possible.

NO_X REDUCTION

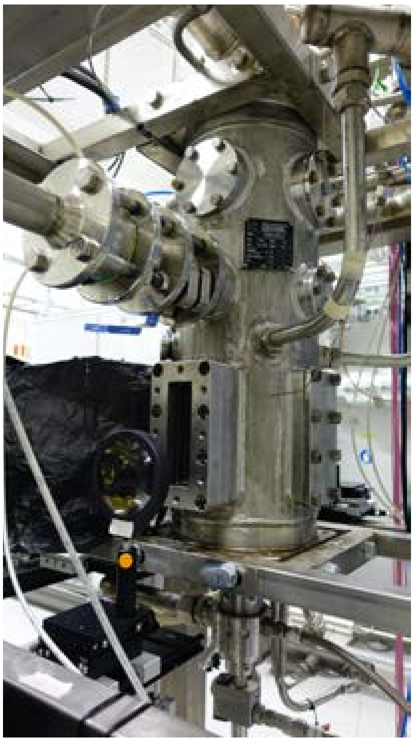
Another important challenge presented by the combustion of ammonia-containing fuels, is that toxic nitrogen oxides (NO_x) are a by-product of the process.

"So our focus is, beside flame stability, also on minimizing the formation of NO_x in the combustion chamber," says Gruber. "We are trying to identify the operating conditions that produce the lowest level of NO_x, for instance by organizing the chemical reaction process in different stages within the combustion chamber. But, if this strategy fails, we are also considering using some of the ammonia as a reduction agent for NO_x abatement in the exhaust gas."

The researchers investigate the challenges from different angles.

"At SINTEF, we are trying to deepen our knowledge of the basic combustion process. We have modelled the flames of hydrogen and ammonia, in order to better understand the effect of these new fuel mixtures. This has required a comprehensive and coordinated effort together with our research partners, NTNU in Trondheim and Sandia National Laboratories in California," says Gruber.

Laboratory experiments have also been conducted utilizing SINTEF's pressurized combustion rig (HIPROX) at Gløshaugen, where a downscaled version of a gas turbine burner is used to evaluate flame stability and NO_x-reduction strategies.



SINTEF's pressurized combustion rig.
Photo: SINTEF

CLOSE COOPERATION

"We are using a very complex and advanced Siemens gas turbine burner, where the combustion process is compartmentalized into three stages. We are conducting tests with different compositions of the fuel in the different stages. For instance, we can inject undiluted ammonia in one stage and add cracked ammonia in the other two, trying to find the optimal operation point."

At the same time, NTNU conducts experiments on simpler flames using less complicated burners compared to the Siemens' design and these experiments have spawned valuable fundamental knowledge on how these new fuel blends behave compared to natural gas.

"Ours is a fine group of partners. The combination of different research groups at SINTEF and NTNU, and the industrial locomotives Siemens and Equinor – both having concrete plans to develop hydrogen and ammonia as energy carriers – has been of immense value to the project. Sandia National Laboratories, the US Department of Energy leading research lab in the field of energy technologies, is involved in the project as an external associated partner. Together we are maturing a technology that now needs a small push to become a reality," says Gruber.

TRANSPORT

COST-EFFECTIVE SOLUTIONS IN MARITIME TRANSPORT

The CO_2 LOS project aims to reduce the costs of transporting CO_2 on ships.

"TODAY'S CONCEPTS FOR CO_2 CAPTURE are based on the assumption that much of the transport will occur through pipelines to the storage location," says project director Martin Hay at Brevik Engineering. "There has been less focus on solutions for ship transport, partly because this area has been considered a mature technology, and partly because the costs have been seen as low in comparison with the total costs for CCS-technology. However, as the costs of capture and storage are reduced, transport costs become relatively higher."

Northern Lights – the infrastructure part of the planned Norwegian full-scale CCS project – has chosen ship transport for the project's first phase, based on the current practice for CO_2 transport. This is technology equivalent to what is used for small scale transport for the food and beverage industry.

CO_2 can be transported on boats like this one – Frøya. Photo: Brevik Engineering

DIFFERENT SOLUTIONS FOR SHIP TRANSPORT

CO_2 LOS sees beyond the first phase of Northern Lights. The project evaluates different transport solutions from an onshore export terminal to an onshore import terminal, for example a process plant on the western coast of Norway, where the gas is compressed and pumped through a pipeline and out to the storage location under the sea.

The project is also considering two options for offshore unloading. Option one is to load CO_2 to a "storage tank" at sea, a *Floating, Storage and Injection Unit (FSI)*, which injects the gas into the geological storage formation. The other option is to do the injection directly from the shuttle tanker. This solution requires additional equipment onboard the ships.

The selection of method is determined mainly by whether the storage formation requires a continuous injection of CO_2 or if batch-wise injection is possible.

"The advantage of offshore unloading is that there is no need for an onshore installation and an expensive pipeline from land," says Hay.

RIGHT PRESSURE

CO_2 requires low temperature and high pressure to remain in a liquid form. The Norwegian full-scale project has decided to utilize the same pressure and temperature (approx. 15 bar/-28°C) that is currently used on ships transporting CO_2 in smaller scale for industrial purposes.

The gas pressure defines the maximum size of the tanks onboard ships. If pressure and temperature is reduced, larger tanks and, consequently, larger ships can be built. Larger ships mean reduced transportation costs per tonne of CO_2, since the CO_2-volumes for transport and the distances increase.

However, use of bigger ships presents a challenge. This solution requires larger intermediate capacity of the onshore facility. And the CO_2 must be kept liquid for a longer period of time.

"We have to strike a balance. If we only consider ship transport, bigger ships are cheaper," says Hay. "But it's not straight forward. We have to consider the entire transport chain."

DIFFERENT CONCEPTS

CO_2 LOS is evaluating four concepts for ships.

One possibility is to equip existing dry cargo ships with new CO_2 tanks. This is the cheapest solution. The project also considers barges for the water ways in Europe, which can bring CO_2 from industrial plants in the lower parts of the Rhine.

The second concept entails building a new ship, which will transport the gas at low pressure (approx. 7 barg).

The third concept is an autonomous ship that can give significant cost reductions.

The fourth concept consists of design of large ships for transport over large distances.

"All work packages are conceptual,» says Hay. «And we hope to be able to continue this work and create concrete technical solutions." ■

MARTIN HAY
Brevik Engineering

Project:
CO_2 LOS II

Project owner:
Brevik Engineering AS

Project period:
2019–2020

Total budget:
14.5 MNOK

Support from CLIMIT:
6.25 MNOK

Partners:
SINTEF, Equinor, Total, Gassco, Air Liquide, Sogestran

STORAGE

SOLUTIONS FOR FUTURE CO_2 STORAGE

In the SWAP-project, Equinor has collected strategic subsurface data in order to explore the possibilities of storing large amounts of CO_2 in a saline aquifer east of the Troll field.

RUNE THORSEN
Equinor

Project:
Strategic Well Acquisition Project (SWAP)

Project owner:
Equinor

Project period:
2019–2020

Total budget:
26.7 MNOK

CLIMIT-support:
17.3 MNOK

Partners:
Petoro, DNO and Lundin

SWAP IS PART OF EQUINOR's *Scale-up of CO2 Storage* project, and is closely connected to the company's hydrogen strategy. In the production of hydrogen from natural gas, large amounts of CO_2 are formed, which Equinor is planning to store on the Norwegian Continental Shelf. The need for storage sites will increase as carbon capture becomes a widely used technology for reducing emissions from industry in Norway and Europe.

"Our intention was to explore the potential for large-scale CO_2 storage at the Horda platform, in the Troll area, and is closely connected to the potential future phases of the Northern Lights project," says project leader Rune Thorsen in Equinor.

BETTER UNDERSTANDING OF PRESSURE

Northern Lights encompasses transport and permanent storage of CO_2 in a geological formation under the North Sea, and is a constituent part of the Norwegian full-scale CCS project. In an early phase, the Northern Lights project considered storing CO_2 at Smeaheia, an area east of the Troll oil and gas field. After the feasibility study, however, uncertainties arose regarding some of the assumptions undergirding the project.

Studies showed that there was a possibility that the reservoirs of the Smeaheia area could be linked with the reservoir sandstones at Troll. If there was a large degree of pressure communication between the areas, it could impact the storage capacity on Smeaheia. Since Troll will produce gas until 2054, the pressure at Smeaheia could also fall as the pressure falls at Troll in the years to come.

Usually, CO_2 is injected into a reservoir in a liquid state. If the pressure at Smeaheia falls significantly, the CO_2 could expand from liquid to gas, which occupies more space in the reservoir. Therefore, it might not be possible to store as much CO_2 at Smeaheia as the plans predicted.

This was one reason that Northern Lights instead opted for a storage location in the Aurora area, south of Troll Vest.

"However, in the *Scale-up of CO_2 Storage*-project, we decided to continue working internally with the area that was abandoned in 2018," says Thorsen. "We hadn't lost faith in the Smeaheia area as a future storage location, but we needed more time to find answers to the uncertainties that had been identified. The time frame for the full-scale CCS project was so tight that we had to mature other alternatives in order to reach a positive investment decision in 2020."

MORE WELL DATA

The first plans for the SWAP project appeared during the summer of 2018. Equinor had been awarded an exploration licence in the south of the Smeaheia area (PL921) during the spring of 2018. The goal was to explore for

West Hercules drilling the well in the Smeaheia area. Photo: Ole Jørgen Bratland

hydrocarbons in the Gladsheim structure. This structure is situated approx. 20 km south of the area that had been studied in the first phases of Northern Lights, and exploration drilling was scheduled to start during the fall of 2019.

The planned exploration drilling was identified as a rare opportunity for collecting additional strategic data, which could reduce the geological uncertainties identified by Northern Lights – so that the future road to CO_2 storage on Smeaheia might be both shorter and cheaper.

Towards the spring of 2019, the SWAP project assumed shape. SWAP – *the Strategic Well Acquisition Project* – became a project for gathering important subsurface data. Although these data would otherwise not have been acquired by the exploration licence, they are considered important pieces of information in order to create an understanding of the storage potential in the area around Troll.

A large part of the extra collection consisted of data from the cap rock. The data confirmed that the cap rock will remain impermeable if CO_2 should be injected into the reservoir. Core samples were taken and rock-mechanical tests executed in order to determine the quality and strength of the cap rock. The researchers also measured the porosity, permeability and fracture pressure of the rock in a thick slate, the Draupne formation. Usually, these types of samples of the cap rock are not taken in an exploration well.

PRESSURE MEASUREMENT

Below the cap rock, Smeaheia consists of several geological formations that potentially can be used for storage. As a part of the SWAP project, a set of pressure measurements were conducted in the different reservoirs, in order to measure the degree of communication with the Troll field.

"The measurements showed that the pressure was reduced in the well area," says Thorsen. "Then we knew that the sands we had hit, were connected with the Troll sands. This means that the reservoir is vast, and that it's possible to inject large amounts of CO_2 without a significant increase of the pressure of the reservoir."

"We have also taken small core samples of the different levels of the reservoirs, so-called sidewall cores (SWC), on which we will conduct different tests in the laboratory," says Thorsen.

Now the researchers are working on updating models and increasing the understanding of the reservoir. Will it be possible to use this area for injection– for example in a future scale-up of the Northern Lights project?

"There is great reason for optimism," says Thorsen. "The data suggest that the sealing is solid. The reservoir has thick rocks over a large extension. This means that the area probably can receive large amounts of CO_2."

The results of the project can also have positive repercussions for Northern Lights.

"At a future scale-up of Northern Lights, the area we are exploring can probably be used as a storage site. This means that we can potentially use the infrastructure that will be built in the first phases of the project. This way, we can achieve large cost reductions," says Thorsen.

STORAGE

LITTLE RISK OF CO_2 MIGRATION

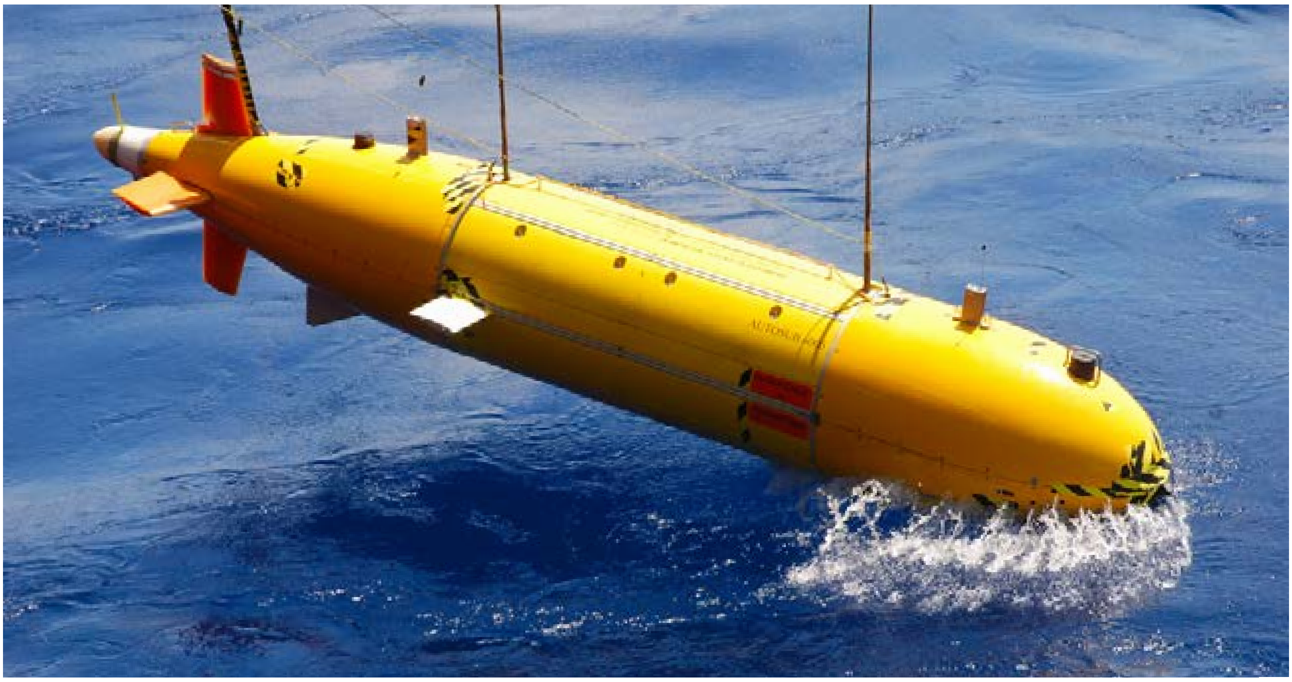
Before CO_2 is injected into a reservoir, its ability to keep the gas will be carefully examined. There is broad agreement in the research community that the risk of migration from well-known geological structures, is little. However, it's important to control the factors that impact the storage ability.

THERE IS A HIGH DEGREE of certainty that the first structures selected for storage, are impermeable. However, for CCS to be an effective way of curbing climate change, a large number of storage locations are needed. So with time, it will be necessary to store CO_2 in less optimal formations.

"The risk of storing CO_2 will still be very small – and dramatically smaller than not doing so. After all, a major part of the CO_2 we release to the atmosphere ends up in the oceans. However, we want to be as certain as we possibly can, and achieve a better understanding of what could happen in the ocean if CO_2 should seep out," says project coordinator Guttorm Alendal at the University of Bergen.

The BayMoDe project has contributed to developing methodologies for understanding such events better. The project has been conducted in close cooperation with a major EU project, STEMM-CCS, and builds on a previous project, ECO_2.

"In BayMoDe we are not investigating the risks of migration of the stored CO_2, but only scenarios where CO_2 travels through the seabed into



A remotely controlled underwater vehicle (AUV) used to investigate the seabed.
Photo: Doug Connelly, National Oceanography Center, UK.

the water column," says Alendal. "In such a scenario, CO_2 will either percolate through the seabed in the form of bubbles or already be dissolved in the sea water within the seafloor sediments. Through several projects, we have developed mathematical tools that simulate how the CO_2 will be transported."

This knowledge is necessary to design environmental monitoring programs and to assess risks associated with large-scale offshore storage of CO_2.

LIMITED CONSEQUENCES OF EMISSIONS

In a hypothetical case where CO_2 escapes in pure form in the North Sea, it will be in the form of gas bubbles through the seabed. The bubbles will ascend through the water column and rapidly dissolve in the water, and be transported by the local water bodies. Increased CO_2 content causes acidification, with possible environmental consequences. However, this impact will rapidly subside as we move away from the source. Because of the shifting current conditions, e.g. tide and local small-scale variability, the signal of the seep will soon be hidden within the natural variability.

"Our estimates show that the consequences of these types of seeps will be limited. In the rare instance that this should occur, the result could be acidification of an area similar to a football field in extension. Still, some areas are more vulnerable than others, for example breeding grounds or coral reefs," says Alendal.

MEASUREMENT PROGRAMME

A monitoring programme gives a better overview over the factors that impact the marine environment. As an example, the ongoing net transport of CO_2 from the atmosphere causing acidification of the biologically most productive surface layer, is an often under-communicated consequence of increased atmospheric CO_2 concentration.

"In fact, an effective programme for measurement dovetails with UN's sustainability goals, especially SDG14 *life under water,* through co-operation with other marine monitoring programs. Often, the SDG13 *climate measures* is used as the only argument for implementing large-scale storage of CO_2."

Because CO_2 exists naturally in the ocean, and the concentration fluctuates according to time and space, it's a challenge to separate the signals of releases from the natural variability in CO_2 concentration. BayMoDe has contributed to the development of methods to design measurement programmes that quantify and reduce the probability of false alarms.

MATHEMATICAL MODELS

The methods are based on simulations of transport in the water masses using mathematical models, so-called ocean circulation models. These models are being used in many contexts, for instance it has been used for climatological simulations in the North Sea from the 70's and onward, and they are used by weather services to produce ocean forecasts. A hypothetical source is added, and transport and dilution of the CO_2 signal are simulated and these prediction are subsequently used in simplified and statistical models.

"We have focused on identifying methods for modelling a probable footprint of a migration, by combining measurement statistics, mathematical modelling and Bayesian probability estimations," says Alendal.

The results of BayMoDe will be developed further in new projects. For instance, a web-based software is being developed in a recently started ACT-financed project, ACTOM. ■

GUTTORM ALENDAL
University of Bergen

Project:
Bayesian Monitoring Design (BayMoDe)

Project owner:
University of Bergen

Project period:
2016–2020

Total budget:
9.3 MNOK

Support from CLIMIT:
6.6 MNOK

Partners:
NORCE, Plymouth Marine Laboratory, UK, Heriot-Watt University

STORAGE

A BETTER PICTURE OF UNCERTAINTY

The CONQUER project has developed mathematical models that make it easier to control CO_2 storage locations.

PER PETTERSON
NORCE Research Centre

Project:
CO_2 Storage in the North Sea: Quantification of Uncertainties and Error Reduction (CONQUER)

Project owner:
NORCE Norwegian Research Centre

Project period:
2015–2019

Total budget:
8.96 MNOK

Support from CLIMIT:
8.5 MNOK

Partners:
University of Colorado Boulder,
University of Bergen,
ETH Zürich

IN ORDER TO MEET INTERNATIONAL climate goals, it will be necessary to inject large quantities of CO_2 into geological structures beneath the seabed. This requires a high degree of certainty that the gas will not trickle out in the future. Storing so much CO_2 that it really makes a difference, will require a high number of geological structures. And each must be characterized meticulously in advance.

MODELLING UNCERTAINTY

The first areas that are selected for storage, are situated in areas where operators have extracted oil and gas for many years, and possess deep knowledge of the geology, both from measurements and production. But with time, new areas – many of which we have scant knowledge about today – will have to be opened for storage.

"Possible storage sites cover extensive physical domains that we have to study over time. The challenge is that we often have few data for these areas. And this creates uncertainty," says project director Per Pettersson. "This is a general challenge."

A range of factors, such as porosity and permeability, determines if a structure is well suited for storage. It can be expensive to execute comprehensive seismic, acoustic and chemical measurements in order to build knowledge about the characteristics of the reservoir. Hence, there is a high level of uncertainty related to storage in these areas. So the researchers wanted to devise new models to describe this uncovered territory.

But also in the cases where the geologists can access a repository of information about a reservoir, there are still challenges. When new measurement data have been obtained, there is a need for simplification. Otherwise, the data processing will take a long time, maybe months and years. Even with powerful mainframes.

COMPLEX CHALLENGES

"Today, the geologists use models that simulate a variety of conditions in a reservoir, and these models also quantify the degree of uncertainty of the simulations," says Pettersson. "We wanted to go one step further. Hence, we are focusing on the uncertainty related to the model's estimations of uncertainty. In other words, how uncertain are the estimations of uncertainty in the models."

The mathematical challenges are often complicated by the fact that they are presented on different levels – on micro, median and macro scales. And in order to understand phenomena on a macro level, the researchers must find a way to grasp what's happening on the micro and median levels, as well. Hence, the mathematical framework must accommodate for a high level of complexity.

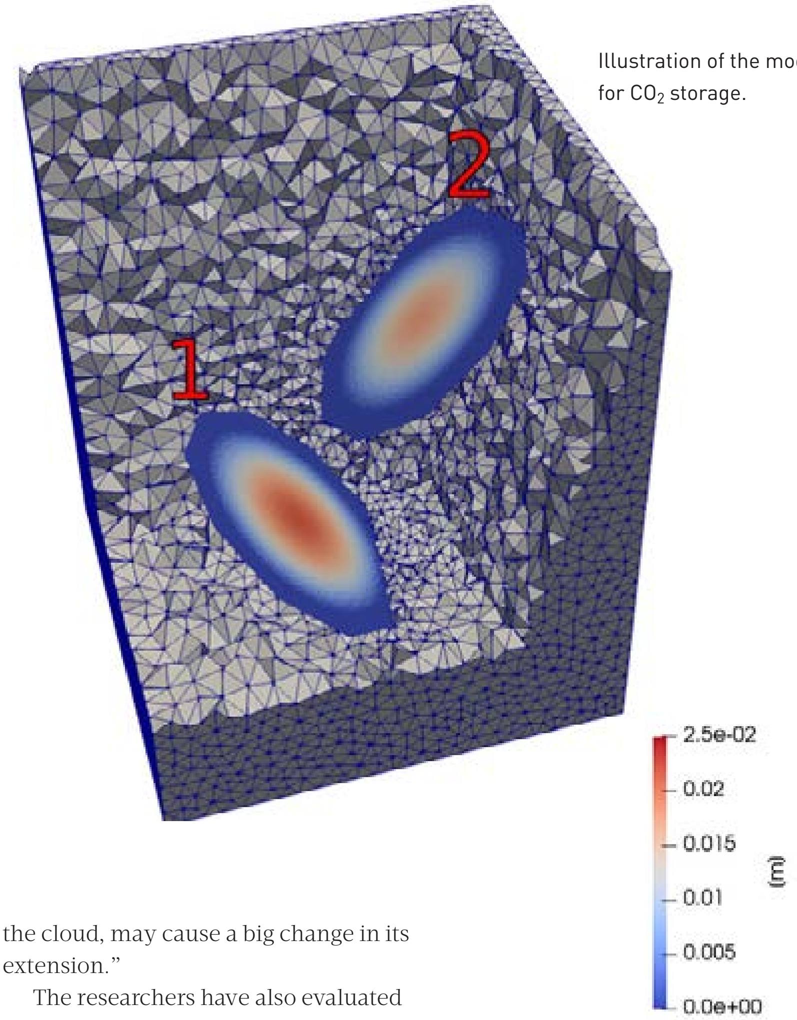


Illustration of the model for CO_2 storage.

DISPERSION IN THE RESERVOIR

One of the phenomena that the researchers address, is the propagation of CO_2 in a reservoir.

In order to store CO_2 safely and cost-efficiently, a comprehensive model of how the climate gas behaves in the reservoir is needed. That's why the researchers have simulated how the CO_2 disperses through the porous rock over hundreds or thousands of years.

CO_2 is injected either as gas or in a super critical phase, a mixture of gas and liquid. In both phases, the CO_2 has less density than the water in the formation, and CO_2 will therefore rise towards the cap rock, beneath which it will remain in the shape of a cloud.

How the CO_2 moves depends on the rock, but also on factors such as the density of the gas and the formation water. And when the CO_2 has reached the cap rock, the gas will gradually dissolve in the water, and cause acidification. Because water that contains CO_2 is heavier than the water below, the water with CO_2 will sink. In turn, water from below will rise to the CO_2 cloud, absorb CO_2 and sink. These movements cause convection currents in the reservoir.

DEEPER KNOWLEDGE

"The CO_2 has a profile that varies discontinuously. This means that a small change in the factors that impact the cloud, may cause a big change in its extension."

The researchers have also evaluated what can happen if the cap rock cracks up. Then, CO_2 may wander through the fractures and further upwards toward the seabed, and migrate into the ocean. By modelling changes in the geomechanics, the researchers seek to devise a better image of different cracking scenarios.

The CONQUER project has spawned a deeper understanding of uncertainties related to the parameters that impact CO_2 storage. This knowledge is of the essence in order to store CO_2 in a safe and cost-effective manner. ■

RESEARCH

RESEARCH ACROSS EUROPE

ACT is a driving force for closer international cooperation in the field of CCS. Norway has played a pivotal role in establishing the research programme.

RAGNHILD RØNNEBERG
Research Council of Norway

CCS IS AN INDISPENSABLE technology for reaching international climate goals. All countries must cooperate and pull together in the same direction, in order to get the technology in place.

In the global context, Norway draws on significant experience in capture, transport and storage of CO_2. CLIMIT has financed research and demo projects since 2005. Equinor commenced storing CO_2 on Sleipner in 1996, and has for many years injected 1 million tonnes annually. In 2008 storage on Snøhvit began, and every year 700 000 tonnes of CO_2 find its way into the formation.

INTERNATIONAL DRIVING FORCE

In November 2014, the Research Council of Norway started to work towards closer cooperation with other countries on developing CCS technology.

"We saw that in Norway, knowledge, competence and experience have accumulated over long time. We have kept a continuous, high level of activity in research and demo projects," says Ragnhild Rønneberg at the Research Council of Norway. "However, many European countries had reduced their activities in the CCS field for several years. This downturn caused concern. So it was quite natural that Norway assumed a leading role in facilitating broader transnational collaboration."

Ragnhild Rønneberg was charged with investigating the possibilities of tighter collaboration across borders.

"The task was to enlist funding agencies in different countries to create a consortium. We had solid backing from the Norwegian Ministry of Petroleum and Energy. As the initiative attracted attention in several countries, and we received significant support for this common effort, also financially, we obtained the platform we needed for an application to the EU Commission, under Horizon 2020."

In December 2015, the EU Commission approved the application.

"We immediately began the roll-out of ACT – *Accelerating CCS Technologies.* Our funds amounted to approx. 30 million euro from nine countries, and we received an additional approx. 12 million euro from the EU Commission. In the spring of 2016, we conducted our first transnational call with a total amount of 42 million euro."

INDUSTRIAL SOLUTIONS

ACT's overarching goal is to finance projects, facilitate competence sharing and activities related to CCS, both in Europe and in other parts of the world. The projects that receive funding must consist of partners from at least three countries. They must also include industrial partners that are willing to invest money and contribute with their experience on practical issues.

In this way the development of technology is secured – technology that can be put to use and be implemented in industrial settings where CCS will become an integrated part of future operations.

Moreover, ACT aims to create a project portfolio covering all links of the value chain – from capture at power- and industrial plants (such as cement and steel), and transport via pipeline and ships, to storage in geological structures.

DIALOGUE WITH SOCIETY

In the field of competence sharing, the programme has established the principle of open access. The research results shall be available for everyone. This way, maximum value of the knowhow and the results spawned by the projects, is ensured.

In addition to financing research and demo projects, ACT organizes workshops for the projects, so that new insight and experience are presented and discussed in the broadest possible CCS environment. The program and the ACT projects arrange seminars with decision makers and other key target groups, in order to contribute to increased understanding in society at large about the possibilities and challenges CCS represents.

"So far, we have held four conferences with participants from key European decision makers and players in the field.

Group photo from ACT Knowledge Sharing Workshop in Athens, November 2019.

There has been great interest in the results ACT has achieved and our projects have generated," says Rønneberg.

INCREASING INTEREST

Since the inception in 2015, ACT has steadily gained new member countries. The first country that showed interest in the initiative, was Germany. And in the beginning, Norway and Germany drove the effort. Soon Greece, the Netherlands, Spain, Switzerland, Romania, Turkey and the UK followed suit. Together, these countries jointly presented the application to the EU Commission.

This was the point of departure for ACT's first call and the following implementation of eight transnational CCS projects funded by ACT. These are projects that span a wide array of topics, including hydrogen production. Norwegian R&D institutions and industrial partners collaborate in seven of these projects.

The interest in ACT has continued to increase. France, Denmark, the US and the Canadian province of Alberta, as well as Nordic Energy Research, are now members of the ACT group.

ACT conducted its second joint transnational call in 2019, with approx. 30 million euro. This paved the way for the start-up of twelve new projects, of which Norwegian CCS actors participate in ten. A new call is planned to be launched in June 2020, and ACT is aiming for a similar amount of funding as the previous round.

"More than ever before, it's important to support measures halting climate change – and to connect international R&D communities and industrial partners together," says Rønneberg.

REINFORCED FOCUS

"As a part of ACT's established international cooperation, and the experiences and satisfactory results we have achieved, we are now engaged in the planning of EU's new partnership, *Clean Energy Transition*," says Rønneberg. "This effort will amount to a minimum of 100 – 150 million euros over a 6–7-year period. We are actively working to maintain ACT's position as a heavyweight in the development of CCS technology globally."

ACT has also contributed to increased awareness among decision makers in many countries and the EC system, about the potential of CCS technology.

"ACT has been the engine when it comes to making carbon capture visible and relevant in a range of countries. Unfortunately, not all countries have put CCS as high on the agenda as for instance Norway, the Netherlands and the UK. Therefore, it's important that the ACT projects generate new competence and knowledge that can be used both nationally and in an international context."

Full-scale CCS projects are being planned and developed several places in Europe. The first such project to be realized, is in Norway.

"The expectations to the Norwegian full-scale project are great and will be decisive for future CCS measures," says Rønneberg.

In parallel with Norcem's cement factory and Fortum's waste disposal plants, other industries and clusters are also assessing – for instance via the ACT-projects – practical solutions for the capture of CO_2 from their plants. This includes the use or conversion of CO_2 to new products or storing CO_2 below the seabed in the North Sea.

Because there is little time to lose. The world becomes a little warmer every year, and implementation of CCS technology is necessary in order to slow down this development.

RESEARCH

ALIGN – MERGING SCIENCE AND INDUSTRY ACROSS BORDERS

ALIGN is an ACT-project that focuses on developing technology for the entire CCUS-chain, and creating a cohesive team of researchers and industry in several European countries in the process.

THE OVERARCHING GOAL of the comprehensive ALIGN project is to stimulate the transformation of Europe's industrial regions into flourishing, low-carbon clusters by 2025. 31 partners across Europe – research institutes and industrial companies – have joined forces to facilitate the innovation and implementation of carbon capture, utilization, transport and storage (CCUS) technologies.

ALIGN focuses on solving specific challenges confronting industry and power producers, by devising novel and cost-efficient technology concepts.

The project has defined five key goals:

- Optimizing and reducing the costs of CO_2 capture technology
- Planning large-scale CO_2 transport
- Providing sufficient and safe offshore CO_2 storage
- Developing the use of CO_2 in energy storage and conversion
- Supporting the social acceptance of CCUS

WIDE SCOPE

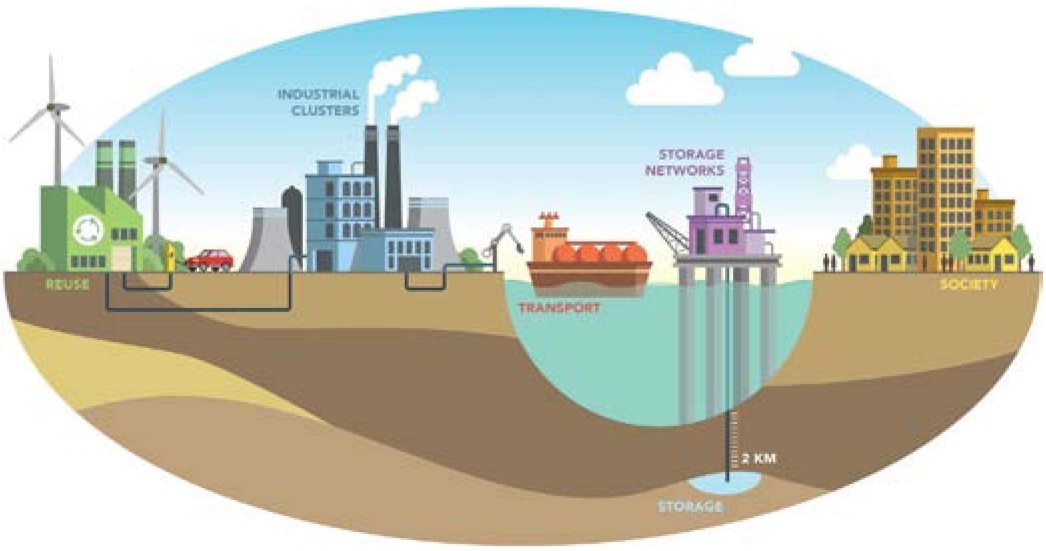
The ALIGN project aims to provide five industrial clusters throughout Europe with technological solutions in all the areas above. The regions participating include North Rhine-Westphalia, Germany; Rotterdam, the Netherlands; Grangemouth, United Kingdom; Oltenia, Romania; Grenland, Norway; and Teesside, United Kingdom.

The project consists of six work packages:

WP 1: Capture – Preparing for large-scale capture demonstration

WP 2: Transport – Preparing for large-scale transport networks for offshore storage

WP 3: Storage – Strategic storage for ALIGN-CCUS European industrial clusters



On November 19, 2019, the ALIGN-CCUS celebrated the inauguration of the new CCU-pilot at RWE's new Innovation Centre in Niederaussem. Project director Peter van Os (TNO) and Peter Moser (RWE) are holding the poster. Photo: RWE

WP 4: CO_2 Re-use – Large-scale energy storage and conversion

WP 5: Industrial Clusters – Blueprints for low carbon industrial clusters through CCUS

WP 6: Society – Implementing CCUS in society

WORKING TOGETHER

ALIGN brings cohesion to the research effort. Many research projects in Europe today lack anchoring in a wider context, and do not benefit from extensive knowledge exchange with other projects. ALIGN wanted to do something about that.

"I think one of the achievements of ALIGN is that we have been able to get players from the entire value chain to work closely together," says project director Peter van Os. "One of our main priorities has been to create arenas and mechanisms for knowledge-sharing and cooperation, and avoid that any of the research teams ends up working in an isolated bubble."

One outcome of the project will be a specific set of recommendations and guidelines for a wide range of industry players, such as designers of capture facilities, process engineers, CO_2 transport companies and operators of storage sites. They will be the users of the guidelines.

"I think our recommendations will be listened to by policy makers. We see that governments are indeed convinced that CCUS is necessary, and they have over the last years increased funding for research accordingly."

ALIGN has dedicated one work package to communicating the results of the project, to a broad sector of society.

"Creating an understanding of what CCUS really entails – not only among policy-makers, but also in society at large – is essential," says van Os. "That's why we have invested more effort and resources on communication initiatives than is usual in research projects. We need to get the message out that if we are to halt climate change, CCUS is a sheer necessity."

Project:
ALIGN-CCUS

Project owner:
TNO – Netherland

Project period:
2017–2020

Total budget:
23 Mill. Euro,
Norwegian part 46.3 MNOK

Support from CLIMIT:
30.1 MNOK

Partners:
31 in total; see www.act-ccs.eu/align

CAPTURE

COST-EFFECTIVE CAPTURE OF CO_2

Several full-scale projects are currently being planned in Europe – also in Norway. The capture part of the ALIGN-CCUS project focuses on how existing technology can become cheaper and more effective to operate.

Pilot plant used for testing at SINTEF in Trondheim. Photo: SINTEF

THE WORK PACKAGE in the ALIGN project that addresses carbon capture, focuses on operational challenges and technical-economic analysis. How can costs be pushed down, so it becomes easier for the industry to implement capture plants? And how can the plants be operated optimally for lower operational costs?

These are highly relevant challenges today, as industrial clusters in Norway and abroad direct their attention towards CCS technology.

"We have primarily concentrated on amine technology," says the project director for the capture work package of ALIGN-CCUS, Hanne Kvamsdal at SINTEF. "We draw on long experience with this technology for different industrial processes – for instance offshore, where amine is used to extract CO_2 for natural gas."

STRIKING THE BALANCE

In the process or power industry, flue gas is led into an absorption tower, where the flue gas bubbles through a few thousand litres of a liquid containing amine. The amine absorbs the CO_2. Then, the amine liquid with the CO_2 is pumped into a regenerator, where steam heats the solution. At this stage of the process, the CO_2 is separated from the amine, which is finally compressed and stored, or used for other purposes. The recirculated amine liquid is injected back into the absorption column, and the process is repeated.

"A central task has been to find practical solutions to a range of trade-offs," says Kvamsdal. "For instance, a significant part of the energy consumption is expended on heating the liquid that extracts the CO_2 after the reaction with amine. We can design plants to decrease the amount of energy used to release CO_2. But this solution entails higher investments. The challenge is to find the right balance."

REDUCING LEAKAGES

The project has also focused on operational issues.

"Recirculation of amine is a continuous process – the liquid moves in a loop between the absorption column and the regenerator tower," says Kvamsdal. "One challenge is that some of the amine has a tendency to disappear from the liquid and is converted to gas. And this amine can leak into the surrounding environment."

Hence, the researchers investigate how changes in the operational conditions – such as pressure and temperature, and the composition of the flue gas – may impact how the amine behaves. One way to counteract leakage, is to cool down and wash the amine liquid containing CO_2, when it has reached the top of the absorption column.

Another challenge is to avoid that the amine react with other substances.

"There is always a tiny surplus of oxygen after the combustion, which blends with the flue gas. Hence, we are testing different adjustments to the process to avoid that the amine reacts with the oxygen," Kvamsdal.

OPERATIONAL CONDITIONS

Moreover, the researchers work with advanced process control to ensure efficient operation of the plant. An automatic control system optimizes the energy consumption, avoiding too high pressure and temperature, and that tanks are emptied. Since large variations of the operational conditions may occur, an effective control system can give the operators a good overview of how the process is running.

SINTEF's pilot plant is equipped with a higher number of sensors than most production plants. This has given the installation a valuable opportunity to test critical points in the process. Deep understanding of the process hinges on precise measurements.

NTNU has contributed with laboratory tests and modelling, for instance in the areas of amine emissions and advanced control.

"We have invested a lot of work in simplifying the models and adjusting these to an operational setting," says Kvamsdal. "The simulator must be able to execute estimations rapidly, and then processing capacity often becomes a limitation."

ALIGN-CCUS has partners from several countries. In Germany, RWE has tested a pilot that captures CO_2 from a coal-driven power plant. University of Sheffield in UK operates a test unit that burns natural gas. TCM has also conducted tests in an amine plant at Mongstad. In addition, both TNO in the Netherlands, Herriot-Watt University in Scotland, and the University of South-Eastern Norway have carried out tests on several of these pilot plants. ■

HANNE KVAMSDAL
SINTEF

Project:
ALIGN-CCUS WP1

Project period:
2017–2020

Total budget:
37.1 MNOK

Support from CLIMIT:
23.2 MNOK

Partners
WP1: SINTEF, NTNU, TCM, TNO, RWE, Heriot-Watt University, University of Sheffield, IFE, Bellona, Norcem, Yara.

STORAGE

UNDERSTANDING PRESSURE IN RESERVOIRS

Pre-ACT focuses on challenges related to safe storage of CO_2 in the rock formations far beneath the seabed. How can we ensure conformance between modelled and observed behaviour in the CO_2 storage?

PEDER ELIASSON
SINTEF

Project:
Pressure control and conformance management for safe and efficient CO_2 storage – Accelerating CCS Technologies (Pre-ACT)

Project owner:
SINTEF Industry

Project period:
2017–2020

Total budget:
5.2 MEuro

Support from CLIMIT:
23.9 MNOK

Partners:
SINTEF Industri, NORSAR, Equinor, Total,BGS, PML, TNO, GFZ, Shell and TAQA

THE OVERARCHING GOAL of the ACT program is to accelerate the development and implementation of CCS technology. When the call for new projects was announced in 2016, researchers at SINTEF immediately started to discuss challenges related to storage of CO_2 with other research institutes and the industry.

STORAGE CHALLENGES

Pre-ACT is a comprehensive research project with a budget of approx. 5 million euro. Around 30 researchers are involved, both full-time and part-time. The project has several European partners.

The partners defined three central challenges for the project – to develop better models for the estimation of storage capacity in the reservoirs; to foster confidence in society-at-large in CCS and the solutions that the project proposes; and to develop storage and monitoring technology that operators can implement safely and cost-effectively. These are expressed as three values: *Capacity. Confidence. Cost.*

"In the early stages of the discussions with our partners, we agreed that monitoring and control of the pressure – and changes in this pressure – is a critical factor for these three and several other challenges," says project leader Peder Eliasson at SINTEF.

When CO_2 is injected into an aquifer – a geological formation that contains water – the water is displaced. However, there is a resistance in the system, depending on how easily the water moves through the reservoir, which is called the permeability of the rocks. The resistance causes the pore pressure to increase in the storage formation. And here lies a risk. The increase in pressure can lead to changes in the reservoir. In a worst case scenario, the increased pressure can create fractures in the cap rock holding the CO_2 in place.

DO THE MODELS REFLECT REALITY?

Work package 1 aims to build a model of the injection process and the reservoir's response. This must be in place before a storage project is started. What happens to the pressure when the operators start to inject CO_2? And how far will the CO_2 propagate throughout the reservoir?

The researchers also try to assess the uncertainties in those models. In fact, there are plenty of factors they do not have precise knowledge about – as permeability, porosity and the exact geometry of the storage formation. Perhaps a fault is not entirely sealed. If so, there might be a migration path, and therefore communication, through the fault.

Work package 2 encompasses methods for the monitoring of injected CO_2. What is really happening in the subsurface?

"Conventional methods measure pressure at the injection well. This is the only place where it's possible to locate a sensor," says Eliasson. "It's not possible to place sensors out in the reservoir. Hence, we utilize both numerical modelling and geophysical methods, based on acquired seismic and electromagnetic data, to estimate the pressure. This is much more complicated than direct measurement."

COST-EFFECTIVE METHODS

Pre-ACT has developed cost-effective methods to find out where the CO_2 ends up in the reservoir. But they also go one step further.

"We have also developed strategies that estimate the CO_2-saturation in the rock," says Eliasson. "We want to find out how large the percentage of CO_2 is, in the different layers in the storage formation."

Work package 3 has conducted work with quantitative methods in order to compare the models and the observations. The degree of consistency between these, is called conformance. This is a key concept in Pre-ACT, especially to reduce uncertainty in models or indirect estimates of the pressure in the reservoir.

"It's not always the case that the data we have acquired through seismics – for instance in order to estimate where the CO_2 plume is located in the reservoir – is entirely compatible with the model calculations," says Eliasson. "Perhaps the seismics confirm the model's description of the CO_2 plume's geometry and extension, but show that the plume is situated more shallow than the model predicts.

Michael Jordan handling instruments for seismic measurements during Pre-ACT's injection campaigns. Photo: SINTEF

If the discrepancy is significant, the operator must consider whether the model needs an adjustment and whether plume behaviour has to be recomputed."

Work package 4 concerns recommendations about how the operators shall handle different discrepancies between models and observations.

"Our industrial partners have been continuously involved in this part of the project," says Eliasson. "They draw on a wealth of experience in decision making in such situations."

Before an operator starts to inject CO_2, it's imperative to develop a methodology that describes possible challenges that may occur. Maybe the pressure increases more than predicted. Or migration through a fault believed to be impermeable, is discovered. What should the operator do then? Do the models need to be re-adjusted? Is it necessary to acquire more data? Should the operator stop injecting?

METHODOLOGY CREATES STRUCTURE

Pre-ACT has elaborated a methodology that the operators may use to make such operational decisions in a structured and transparent manner.

Work package 5 seeks to demonstrate the methodology from the other work packages, by means of realistic case studies. One of the cases that was selected was Smeaheia.

Smeaheia was the first structure that the Northern Lights project considered as a storage location. Northern Lights is the infrastructure part of the Norwegian full-scale CCS project, and encompasses transport of CO_2 by ships from the eastern part of Norway to a reception facility on the western coast, from where the gas will be pumped through a pipeline to a reservoir beneath the North Sea.

As part of a feasibility study, Northern Lights evaluated the possibility of storing CO_2 at Smeaheia, an area east of the Troll field. After the feasibility study, uncertainty arose about the suitability of the reservoir as a storage site, due to a large fault in the area. It was decided that since further studies were needed, Northern Lights had to use another known structure instead.

"Hence, the timing was ideal for looking closer at Smeaheia. Our investigations showed that it's possible to handle the fact that the fault may not be completely impermeable. For this reason, the reservoir might be a possible storage site in a future project," says Eliasson.

Other possible storage locations, that the project has evaluated, include an empty gas field on the continental shelf off the Netherlands and possible structures on the British shelf.

SINTEF has the project responsibility for Pre-ACT, and is the home to about half of the investigators. The other Norwegian research partner is NORSAR. From Great Britain, BGS and PML participate. The research institutes TNO of the Netherlands and GFZ of Germany are also partners.

The industrial partners are: Equinor, Shell, Total and TAQA Energy (the Netherlands).

IMPORTANT DIALOG WITH DECISION MAKERS

In order to receive financial support from ACT, the projects must share the knowledge they produce with key stakeholders in society.

"The Research Council of Norway encouraged us to emphasize the communication part," says Eliasson. "Consequently, we included seminars with key decision makers in our plans. The purpose was to disseminate information about CCS in general, and about the findings of our project on safety and monitoring of CO_2 storage."

In April 2019, Pre-ACT arranged a seminar in Trondheim. A wide array of participants joined the event. Representatives of the Norwegian Ministry of Petroleum and Energy (OED), Gassnova, Bellona, the Research Council of Norway and UK government were present. Equinor, TAQA Energy and Lundin also sent professionals. Both presentations and panel discussions were held.

"We wanted to exchange the different views on how research can contribute to safer CO_2 storage," says Eliasson.

Pre-ACT then invited key European decision makers to a seminar in Brussels in October 2019. From Pre-ACT, researchers from the different research institutions and industrial companies – partners in the project – presented research findings and implications for the future. The European Commission, Bellona, Zero and NHO were among the organizations that shared their perspectives, followed by an engaged debate on how implementation of CCS technology can become a reality as soon as possible.

During the spring of 2020, Pre-ACT is arranging a series of six webinars, open to everyone. The webinars are already a success, with 100 people registered for the second webinar. ■

STORAGE

FIRST EXPERIMENTAL CAMPAIGN AT SVELVIK CO_2 FIELD LAB

In 2019, SINTEF established Svelvik CO_2 Field Lab as an ECCSEL infrastructure at Svelvikryggen, south of Drammen. The Pre-ACT project contributed to the establishment and was then the first project to put the field laboratory to use, conducting comprehensive testing of monitoring methods.

A CENTRAL WELL AT THE FIELD laboratory makes injection of water or CO_2 possible 60-65 meters beneath the ground.

"Even though CO_2 at a depth of 65 meters behaves very differently from CO_2 in a reservoir 1000 meters below the seabed, the laboratory can teach us a lot about how to interpret geophysical data and monitor a CO_2 storage site," says Peder Eliasson, project leader of Pre-ACT.

In four wells around the injection point, measurement instruments are located so that the researchers can gather seismic and electrical data before, during and after injection campaigns. The interpretation of these data gives a description of where the CO_2 migrates, and how large amounts of CO_2 are contained in different parts of the reservoir.

"In the first part of Pre-ACT's tests at the field lab, we injected water to increase the pressure in the reservoir," says Eliasson. "We used sensors and geophysical measurements in order to monitor the change in pressure. In the next phase we injected CO_2, which displaced water in the reservoir and simultaneously caused a change of pressure. Together, the two tests offer the possibility to study how we can detect separately changes in CO_2-saturation and pressure based on geophysical measurements."

The field laboratory at Svelvik is also well suited to create a better understanding in key target groups, about what CCS really is.

At the Svelvik opening ceremony in November 2019, there were, amongst others, participants from *Stortinget* (the Norwegian parliament), the municipality of Hurum (now Asker), the Norwegian Petroleum Directorate and Gassnova. The opening was widely covered in the media. The local office of NRK (Norwegian Broadcasting Corporation), Swedish Radio, local newspapers and a geoscience magazine brought the news of the Svelvik laboratory to a broader audience.

Tomorrow's decision makers have also inspected the laboratory. Several school classes have visited the site to learn more about how CO_2 storage can contribute to solve the climate crisis, and how storage can be done in a safe and efficient manner with proper monitoring.

Even though much must have been resolved before today's pupils become leaders, it's important to teach the younger generation about the good climate measures.

Svelvik CO_2 Field Lab with an injection well, four monitoring wells, two tanks (blue) for water injection, one tank (white) for CO_2 injection and an instrument room. Photo: SINTEF

KEY FIGURES 2019

There was a great deal of interest in applying for funding from CLIMIT in 2019, and at the end of the year a total of 45 new projects had received NOK 177 million in support. These are projects which has been granted support during 2019. Several of these have started in 2020. More and more research projects continue as demonstration projects.

DEMO PROJECTS

The CLIMIT-Demo programme had 100 active projects in 2019 that received overall NOK 118 million in support during year. A total of 507 million has been allocated NOK in support of these projects above several years. 14 new projects were awarded support. Furthermore, 14 grants have been granted for new idea studies, smaller investigationsv and information measures.

Overall, this represents a commitment for support in 2019 of about NOK 103 million. 43 projects were completed in 2019.

RESEARCH PROJECTS

CLIMIT R&D had 69 active projects in 2019 that received a total of 115 NOK million in support during the year. A total of NOK 479 million has been budgeted to support these projects over several years.

In 2019, support was granted for 11 major projects, of which 7 ACT projects, 2 competence projects for businesses and two innovation projects in business.

In addition, support has also been granted for 6 smaller projects. This includes participation projects and event support.

In 2019, NOK 74 million was allocated for new projects. The reason for this somewhat low amount is a large portfolio with many ongoing projects consumes up a lot of the available funds next year. ■

Active projects by sector (MNOK)

	2018		2019	
	R&D	Demo	R&D	Demo
Institute sector	77.4	46.9	76.5	56.8
Business sector	10.5	47.1	14.0	57.9
University and college sector	18.9		20.4	1.0
Others	2.6	2.1	3.9	2.4

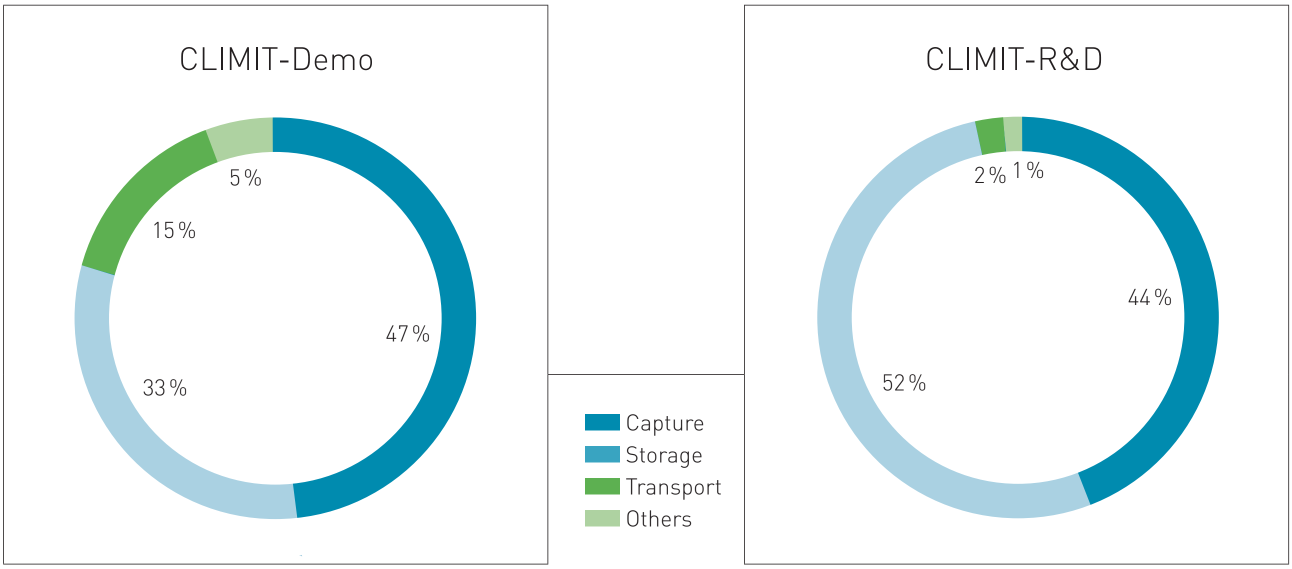
Active projects by application type (MNOK)

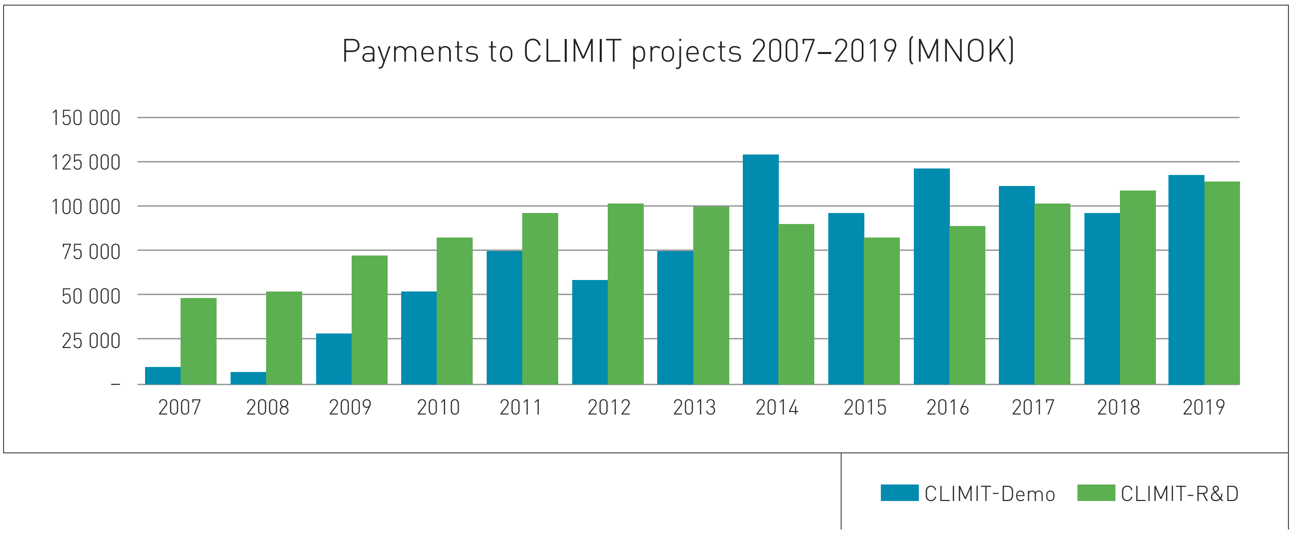
	2018		2019	
	R&D	Demo	R&D	Demo
Other support	2.5	0.2	2.1	0.3
Event support	0.6	0.8	0.4	0.6
Researcher projects	63.7		57.0	
Innovation projects in the business sector	11.2		16.9	
Competence projects for the business sector	17.3		15.1	
International projects (ACT)	14.1	7.2	23.1	9.1
Personal foreign scholarships	0.1		0.1	
Demo projects		85.6		107.1
Idea, pre-studies		2.2		1.1

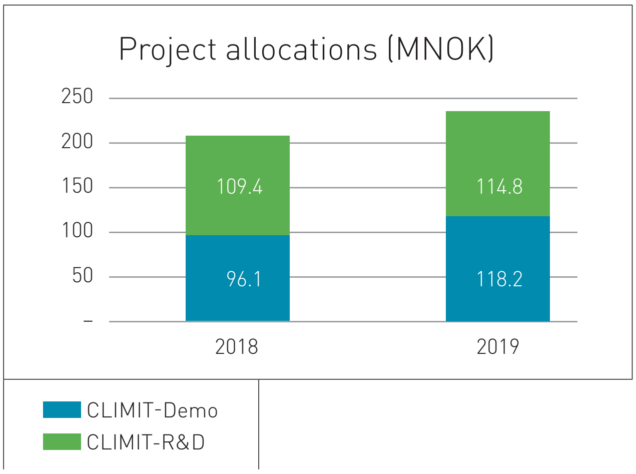
Income (MNOK)

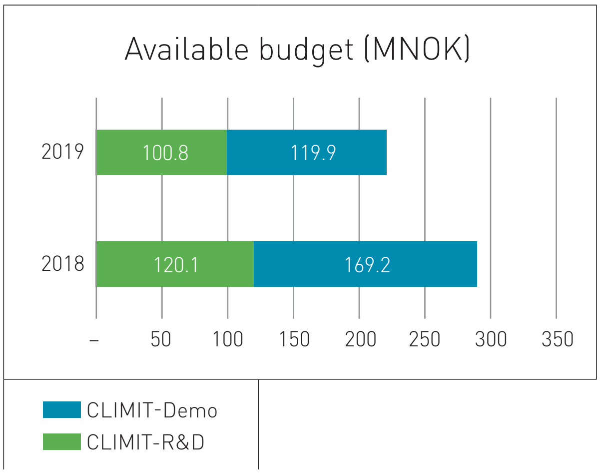
	2018		2019	
	R&D	Demo	R&D	Demo
Various	-0.1			
Ministry of Petroleum and Energy	92.1	90.0	92.0	94.5

Allocated projects









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