Accelerating CCS Technologies

ACT final report on granted projects

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ACT – Accelerating CCS Technologies

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1. This is ACT

ACT was established in 2016 with 10 partners from 9 European countries as a response to the H2020 call in 2015 on low carbon technologies. This consortium joined forces with the aims to accelerate and mature CCUS technologies by making funds available for R&D and innovation projects and a solid basis for knowledge sharing in an open mind approach.

ACT has since it was kicked off in February 2016 become a widely known program within the transnational CCUS R&D initiatives in Europe and beyond, and extended the consortium with funding agencies from Europe, India, Canada and USA. A total of 16 funding agencies are involved since 2020.

The background for ACT is based on the fact that the level of carbon dioxide (CO_2) released into the atmosphere has increased significantly since the industrial era, and it is well documented that burning fossil fuels emits CO_2 with serious and negative impact on the climate.

Carbon Capture, Utilisation and Storage (CCUS) is part of a portfolio of technologies to combat climate change. CCUS can help mitigate CO_2 emissions from electricity production and is a prerequisite for reducing CO_2 emissions from industry such as steel, cement, chemicals and petrochemical refining.

ACT has contributed to accelerating CCUS Technologies by making available funds for transnational research and innovation activities. CCUS has an important role in the transition to a low-carbon economy.

The CCUS technology involves capturing CO2 from large CO2 emission point sources, such as fossil fuelled power plants and large, energy intensive industrial plants, compressing it for transportation and then injecting it deep into a rock formation at a carefully selected and safe site, where it is permanently stored. In addition, CCUS projects which deal with innovative and cost reducing utilisation of CO2 have also been in the scope for ACT.

Figure 1: Geological storage of CO2

The IPCC 1.5 degrees report makes it very clear that CCUS must be part of an affordable and socially acceptable energy transition. The thematic priority CCUS is essential to the climate-neutrality goal of Europe, which has been underlined in a number of policy documents issued by EC and others the recent years.

The ACT calls have asked for RD&I projects that can lead to deployment of CCUS. Project proposals with high industrial relevance and industrial involvement have been prioritised. Of major importance is also that the projects being funded contribute to the SET Plan implementation plan for CCUS and the Mission Innovation research priorities for CCUS. We welcome your visit to the ACT webpage [ACT (act-ccs.eu)](act-ccs.eu) for updates on activities, events and projects results.

Even if ACT formally ended as an EC initiative 30 September 2021, the follow-up, monitoring and close interaction with the running projects will continue. The ACT2-projects end in 2022 and the ACT3-projects will end in 2024.

2. Executive summary

ACT is a fit-for-purpose, partner-driven, flexible and an easy-to-join funding scheme that serves our ambition: **to make CCUS a commercially viable climate mitigation technology**.

ACT has undertaken three successful calls (in 2016, 2018 and 2020), and ACT has established itself as a powerful multilateral funding scheme for research and innovation dedicated to CCUS.

A total of 33 projects have been funded with a total amount of ~100 mill EUR.

Results relevant to the industry and policy makers have been provided, and are still being provided from the ACT projects. The ACT-projects have delivered results of significant value, some examples below:

- Paved the way for large scale CCUS deployment, e.g. provided results of relevance to development of Longship, Porthos, the Scottish CCUS cluster in the UK, etc.
- Delivered results aligned with the European SET plan implementation and Mission innovation.
- Each ACT project is more than the sum of national efforts.
- Collaboration between partners (in Europe and across the world) who without ACT would not have found each other (not at all or not that easily).
- Annual ACT knowledge sharing workshops since 2016; all ACT projects present and share knowledge and ideas.

The ACT projects are in different stages of their life: the ACT1-projects were completed in December 2020, the ACT2-projects are in their last year of operation and the ACT3-projects are kicked off in the autumn 2022 and will run for 3 years.

In the following pages a more detailed report is given for each of the calls and the projects.

3. ACT1- Cofunded projects

The first call from ACT (ACT) was launched in June 2016, only 5 months after ACT as an EC cofunded action was kicked off. The total amount of funds made available from the ACT1-funders was close to was 36 M€ from the ACT partners and the European Commission (approx. 11.2 M€ from EC). The total budget of these projects was approx. 50 M€.

At the end, when the projects were finished, the reports and spendings approved, the total funds were 32.9 M€ (22.1 M€ from the ACT partners and approx. 10.8 M€ from EC).

After a two-step evaluation process (with external experts in the second stage) the ACT board decided to fund 8 high level projects. The table below shows the project acronym, their activity, total amount of funds from the ACT-partners and the country for the R&D partners involved in the projects Germany, the Netherlands, Norway, Romania, UK, Switzerland, Spain and Turkey).

Project	Activities	ACT, M €	Norway	Netherlands	UK	Germany	Romania	Switzerland	Spain	Turkey
ALIGN	Chain integration, clusters	14,5	x	**X**	x	X	X			
ELEGANCY	Chain integration, hydrogen	8,9	**X**	x	x	X		x		
PRE-ACT	CO2 storage, pressure handling	4,5	**X**	x	x	X				
ACORN	Full chain CCS / infrastructure	2,0	x	x	**X**					
DETECT	CO2 storage, risk assessment	2,0		**X**	X	X				
ECOBASE	CO2-EOR SouthEast Europe	1,2	**X**	x			x			x
GASTECH	Gas switching technology	1,7	**X**	x			x	x	x	x
3D-CAPS	3D printed sorbents	1,5	X	**X**			x			

The 8 projects started from September 2017 and the project period was planned for 3 years. One project, ACORN, was according to their plan completed in February 2019. The 3D-CAPs project was finalised in September 2020, and the project Pre-ACT was finalised in 3 years in August 2020. Due to the outbreak of COVID-19 pandemic, the other 5 projects requested and gained approvals from the national authorities for 3-4 months extension. Therefore the 5 projects were completed by the end of 2020.

During the implementation of the projects, the ACT Consortium frequently interacted with the projects. As a rule, ACT was represented at project meetings. ACT organised annual ACT knowledge sharing workshops. The ACT project leaders and funded project consortium members were also actively disseminating their work at conferences, through scientific papers, through webinars, social media and other means. The ACT consortium also encouraged and stimulated the projects to communicate about their ambitions and results.

The ACT Consortium has a register of numerous communication activities of the ACT1 funded projects. Also, all ACT1 projects have a project website, where public deliverables can be found. The ACT Consortium has ensured that the legacy of the ACT1 projects is well accessible to the public.
The project final reports have been evaluated by the national funding organisations according to the objectives of ACT programme, national procedures and ACT monitoring guidelines. The concerned national funding agencies have assessed together the results, the impact as well as the public accessible information of each project. Collective feedback from the ACT Consortium has been given to the project coordinators of those projects – and the feedback taken into consideration for the further progress/process of the project.

The results of the 8 projects have demonstrated the added value of the joint innovation actions of the 9 European countries.

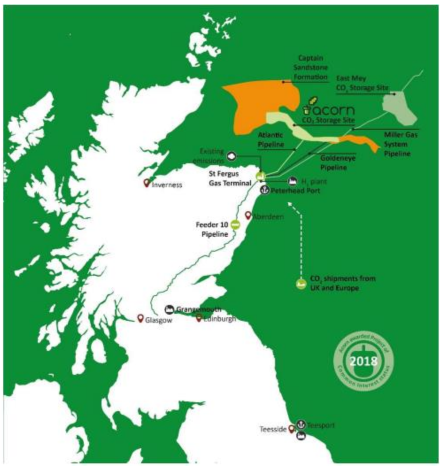
ACT has made the final reports of the projects downloadable from the ACT website (http://www.act-ccs.eu). Public deliverables of each project can be found on the websites of each project.

In the following pages, the main results of each ACT1 project will be presented.

3.1 ACORN

The ACT project Acorn is specifically designed to accelerate CCS deployment through development of the Acorn CCS project in the UK, and to support learning and knowledge dissemination with other CCS initiatives across Europe.

Acorn CCS is a low-cost, low-risk carbon capture and storage project specifically designed to make best use of existing oil and gas infrastructure and a well understood offshore CO2 storage site to unlock large-scale CO2 transport and storage solutions for the east coast of the UK and beyond.



Main results

The findings from ACORN in combination with some additional transport feasibility studies mean that the ACORN CCS project should be ready to enter front-end engineering and design (FEED studies) – prior to an investment decision and, ultimately, construction.

ACORN CCS is now well placed to be an operating project by 2023, firmly realising an option for the UK to deliver CCS at scale in the 2030s and supporting many industrial clusters around the North Sea in their need to significantly decarbonise.

On the 24 November 2021 it was announced that Storegga who is the lead developer of the UK's ACORN CCS and Hydrogen project, providing essential infrastructure to help the UK meet its net zero targets ACORN, has signed an agreement with the Norwegian company Sval Energy for a collaboration to explore carbon storage on the North Continental Shelf (see this link).

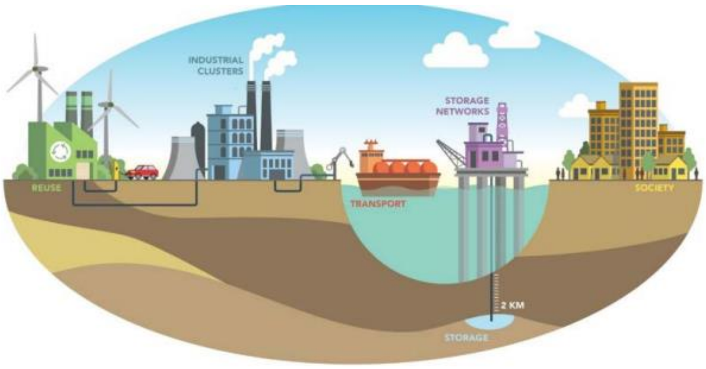
Public accessibility of deliverables

Project website: https://www.actacorn.eu Final report from ACORN Download

3.2 ALIGN-CCUS

ALIGN-CCUS covers the whole Carbon, Capture, Utilisation and Storage (CCUS) chain. It was one of the first projects where capture, transport, storage, utilisation, clusters and public perception interact to deliver the overall project objective: to accelerate the transition of current industry and power sectors into a future of continued economic activity and low-carbon emissions, in which CCUS plays an essential role.

ALIGN-CCUS addressed specific issues across the CCUS chain for industrial regions in ERA-NET ACT countries, enabling large scale, cost effective implementation of CCUS by 2025. All the chain elements contributed to this overall objective.



Dissemination was an important part of ALIGN-CCUS. Dissemination of project results was actively pursued.

The professional dissemination team was proactive in branding ALIGN-CCUS and making the project known by the public and scientific community.

Main results

The main results of ALIGN CCUS can be presented as the main results per work package, and as the main results per country. At the ALIGN final webinar, each work package – in other words, main topic – presented a video and infographics about the main results per work package. These results are accessible through the ALIGN-CCUS website.

The important results include a spectacular long-time pilot run (12,000 hours) with capture from real-life industrial flue gases at the RWE pilot plant in Niederaussem, a 'Storage Readiness Level' index to facilitate the discussion of storage locations, a demonstration of synthetic fuels in a vehicle, and the unravelling of the variations in public perception across the ALIGN CCUS countries.

On a country-by-country basis, the results of ALIGN CCUS supported the acceleration of CCUS in the following way:

In the **Netherlands,** CCUS is focused on the industrial and the Waste to Energy (W2E) sectors, and the storage activities around the North Sea area. In ALIGN-CCUS important work was done to support the development of the Porthos (https://www.porthosco2.nl/) and Athos (https://www. athosccus.nl) projects, which are both projects that plan to transport and store CO2 from an industrial cluster under the North Sea. The European Commission has nominated in October 2020 Porthos and Athos for a subsidy of respectively 102 million euro and about 15 million euro for further development, so this development moves on.

For the research institutes from **Norway** the knowledge gained in dynamic operation and online measurements is mostly taken further in follow up projects like LAUNCH (ACT), NCCS and REALISE (H2020). Important lessons learned were in the CO2 transport. The findings have been further followed up through the CO2LOS II project, and to be taken further in a CO2LOS III project that is under preparation. Regarding storage, the Norwegian partners in ALIGN-CCUS have outlined and discussed possibilities for a large CO2 storage hub in the region around the Northern Lights storage site. This Horda Platform CO2 storage hub could likely serve a significant fraction of the storage needs for Scandinavia and Northern Europe.

Especially the demonstration of the technical feasibility of the full CCU chain attracted a lot of attention at **German** stakeholders. Especially the delivered facts about the potential of synthetic fuels - which are produced from CO2 - for climate protection, emission reduction, long-term energy storage and security of supply contributed to the public discussion about the transformation of the energy supply system in Germany. The project was successfully presented in meetings with representatives of (inter alia) the Federal Ministry for Economic Affairs and Energy, the Ministry for Economic Affairs, Innovation, Digitalisation and Energy of North-Rhine-Westphalia and the Energy Agency of North-Rhine Westphalia. ALIGN-CCUS has contributed valuable input for future projects targeting commercial large-scale applications, but also projects aiming to advance the technology by using the lessons-learned in ALIGN-CCUS.

There has been marked increase in recognition and need for CCS to reduce process emissions from industry and for domestic and commercial heating by large-scale production of hydrogen and CCS in the **UK** during the ALIGN-CCUS project. ALIGN-CCUS research, based on emerging concepts and published strategies, has become of increasing relevance and interest with announcement of a net-zero emissions strategy and government support for decarbonisation of industrial clusters in 2018. Two of the five UK clusters, Teesside and Grangemouth, identified for industrial decarbonisation were investigated in ALIGN-CCUS to reduce the cost of CO2 transport and storage and assess a public-private business case, including sharing of risks and liabilities. The research in ALIGN-CCUS has stayed very closely in-step with UK emissions reduction ambitions, including incorporation of plans for CO2 storage by the Net Zero Teesside Project via TVCA and the H21 North of England Project from Equinor. During confidential discussions an industry contributor noted their future intentions for multisite storage beyond current plans would be accelerated and cost reduced by research based on the ALIGN-CCUS selection, appraisal and simulation of CO2 injection.

In **Romania**, the use component in the CCUS chain is less present in the discourse of stakeholders, since the variants of projects considered so far relied on onshore storage. Further, the engagement of stakeholders in potential CCUS projects is modest, due to the fact that the decision factors are not perceived as prioritizing CCUS development. Moreover, the main challenge identified by stakeholders referred to the important funds needed for the implementation of CCUS projects, funds that could not be provided by the industrial units. Therefore, even if the greatest part of stakeholders (among the 17 stakeholders interviewed in WP6) expressed their positive opinion and support for CCUS, they also mentioned that they are sceptical with regard to the future perspectives of CCUS in Romania.

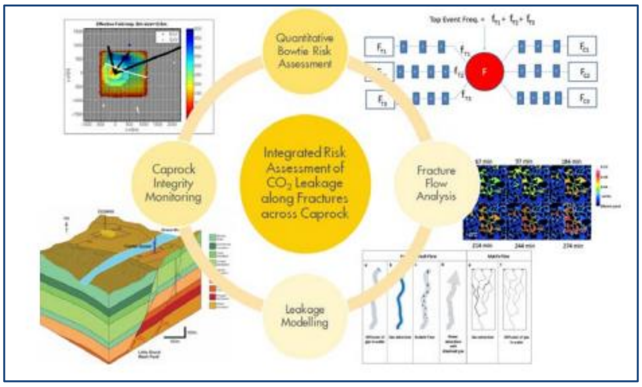
Public accessibility of deliverables

Project website: https://www.alignccus.eu/ Final report from ALIGN Download

3.3 DETECT

Solid, substantiated risk assessment and mitigation measures ensuring safe and efficient CO2 storage improves public trust and facilitates societal acceptance. This is essential to enable large-scale deployment of Carbon Capture and Storage (CCS). DETECT has generated guidelines and technologies for determining the risk of CO2 leakage along fractures across the primary caprock using an integrated monitoring and hydro-mechanical-chemical modelling approach.

For this purpose, the project has performed laboratory studies to provide relevant parameters for CO2 leakage modelling at small, meso, and large scales, incorporating analogue data where possible.



The project has tested the approach using the Green River natural CO2 leakage site in Utah, USA (as an analogue) and the North Sea Captain Fairway (as a potential CO2 storage site). This resulted in an improved understanding of realistic leakage geometries and rates for several representative scenarios.

Further, potential containment monitoring technologies that are capable of detecting such caprock integrity issues were identified and assessed. The work built on experience gained from the risk-based Measurement, Monitoring and Verification (MMV) programme for the current Quest and the former Peterhead CCS projects.

Main results

Fractures and faults are common in the geological subsurface and depending on the scale of the deformation, such structures can be localised through geophysical methods. Below geophysical resolution, assumptions on fracture density, connectivity and mineralogy are required. The project studied carbonate precipitation as a function of fluid chemistry and nucleation surfaces, swelling of clays in contact with CO2 as well as the change in fracture apertures upon changes in pore pressure. This project provides fundamental and new data and provides input to upscaled modelling.

DETECT has progressed insights and modelling capabilities, by systematically following a multiscale approach: investigating fundamental parameter controls by systematically integrating experimental data into both empirical and sophisticated single-fracture models, into meso-scale fracture network models and into large-scale models covering reservoir to surface and laterally a wide area including multiple faults.
An integrated fine-to large-scale fracture characterisation and modelling workflow has been developed to predict the potential range of leak rates at any level of interest (e.g., top primary seal; top storage

complex; seabed). The large-scale model results can feed directly into qualitative and quantitative containment risk assessment, with the caveat that further validation against natural analogues or large-scale leakage tests is recommended to further validate the quantitative reliability of the workflow.

Containment monitoring technologies capable of detecting leakage across caprocks/seals are key elements of active barriers in a containment bowtie risk assessment framework. The work done here offers a guide for stakeholders to efficiently select and assess appropriate containment monitoring technologies within a bowtie risk assessment framework.

Finally, the quantitative risk tool allows rapid prediction of CO2 flow rates via fractures, without the need for specialist, resource-intensive simulation. Although the tool is provided with a fully populated data store for a typical North Sea storage site, this can be replaced with data relevant to a specific project.

Public accessibility of deliverables

Project website: https://geoenergy.hw.ac.uk/research/detect/ Final report from DETECT Download

3.4 ECOBASE

The objective of the ECO-BASE project was to investigate the potential of commercially deploying carbon capture, utilization and storage (CCUS) by screening available data, developing CCUS roadmaps and exploring for potential CO2 Enhanced Oil Recovery (CO2-EOR) pilots in South-East Europe (SEE).

ECO-BASE has assessed the potential for CCUS (i.e. CO2-EOR) through the following activities of creating an inventory of CO2 sources (potential capture projects) & sinks (potential sites for CO2 usage through CO2-EOR) in Romania and Turkey, identifying possible source/sink clusters and performing case studies to evaluate the business potential of combining CO2-EOR & permanent CO2-storage, setting up regional CCUS development plans through CO2-EOR roadmaps, and organizing knowledge transfer workshops for local CCUS stakeholders.

Through selected case studies in Romania and Turkey, the ECO-BASE project provided insight into prospective revenue streams and business models for CO2-EOR in SE-Europe, with a long-term view to large-scale CCUS regional deployment.

Main results

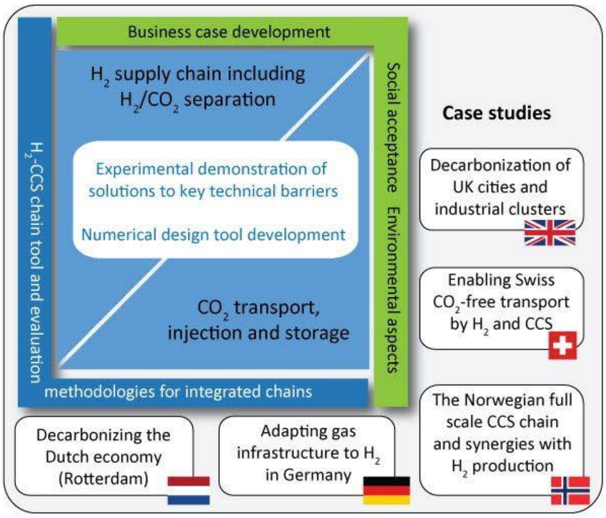
The main merit of the ECO-BASE project is that for the first time a methodology was developed and applied to actual case studies, despite the limited accessibility to field-specific data. This enabled the ECO-BASE team of researchers to assess the economic feasibility of CO2 capture from industrial plants in Romania and Turkey, with CO2 capture and transport to nearby producing oil fields.
At the oil fields the CO2 is injected both for Enhanced Oil Recovery purposes and for permanent sequestration of the CO2 (the so called 'EORStore' concept). The methodology developed and presented to stakeholders in Romania and Turkey (i.e. government and industries) was aimed at initiating a discussion on possible next steps to further mature the concept of EORStore in Romania and Turkey.

Public accessibility of deliverables

Project website: https://ecobase-project.eu/ and the Final report from ECOBASE Download

3.5 ELEGANCY

ELEGANCY aimed to help fast-tracking the decarbonization of Europe's energy system via hydrogen and CCS. This has been achieved by overcoming specific scientific, technological and economic/legal barriers and by undertaking five national case studies adapted to the conditions in the partner countries.



The case studies carried out in Germany, the Netherlands, Norway, Switzerland and the UK on the deployment of CCS with H2, highlighted that H2 from both natural gas and renewable sources are needed and that the countries are interconnected.

The project helped to:

- establish the H-vision consortium committed to decarbonizing the Rotterdam (**NL**) industrial cluster
- identified the key opportunities and constraints for the design of a **UK** H2 and CCS infrastructure, including potential H2 and CO2 storage capacities, and presented UK business case solutions
- identified the role of H2 and CCS for reaching the **Swiss** climate targets
- revealed the need for a two-pronged approach for CCS in Switzerland due to the characteristics of Swiss geology that are challenging for the deployment of CCS
- performed a multi-disciplinary evaluation of decarbonization strategies for the **German** gas infrastructure using public acceptance, legal and macro-economic insights
- and showed that large-scale H2 production in **Norway** can enable economies of scale in the development of a Norwegian CCS infrastructure.

Main results

The project developed effective CCS technologies with **high industrial relevance**; identified and promoted business opportunities for industrial CCS enabling by H2 as a key energy carrier by performing five national case studies; Validated key elements of the CCS chain by frontier pilot- and laboratory-scale experiments using inter alia ECCSEL and EPOS research infrastructure; optimized combined systems for H2 production and H2-CO2 separation by combining basic science with the technology developments necessary for increased TRL of these systems; de-risked storage of CO2 produced from natural gas reforming for H2 production by providing experimental data and validating models; enabled safe, cost-efficient design and operation of key elements of the CCS chain by developing cutting edge, innovative design and simulation tools; provided an open source techno-economic design and operation simulation tool for the full CCS chain, including H2 as energy carrier; assessed societal support of key elements of CCS, enabling early identification and mitigation of risks.

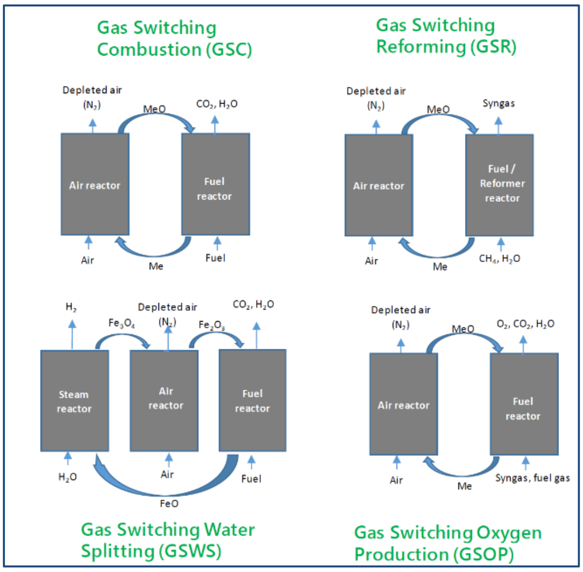
Public accessibility of deliverables

Project website: https://www.sintef.no/elegancy/ Final report from ELEGANCY Download

3.6 Gastech

GasTech focused on the selection, testing and manufacturing of suitable oxygen carrier materials for the four gas switching processes: combustion (GSC); water splitting (GSWS); reforming (GSR); and oxygen production (GSOP).

Shortly after the beginning of the project it became apparent that the selection of oxygen carriers solely based on results/compositions that have been declared as “promising” in the literature cannot be realized.



The majority of published works have employed small-scale testing equipment using powdery oxygen carriers, thus significantly simplifying the process conditions that are encountered in a scaled process of industrial significance. Spray-dried oxygen carrier particles were classified as successful under certain conditions.

Four chemical looping applications combustion, reforming, water splitting, and partial oxidation) were investigated for experimental demonstration of the selected GST processes using the material developed in this project.

Main results

For Gas Switching Combustion (GSC): Autothermal operation (without external heat supply) was achieved in each reactor using CO as fuel under atmospheric conditions. The gas composition and temperature profiles were repeatable over several cycles. Complete conversion of CO was achieved with about 99.99% CO2 purity and 98.9% CO2 capture efficiency. No CO2/CO was observed in the oxidation stage, indicating no carbon deposition. However, particle elutriation was a major problem that hampered the automated pressurized cluster operation.

For Gas Switching Dry Reforming (GSDR): Autothermal and pressurized operation over wide operating and feed conditions. The ability to control the syngas quality (H2:CO ratio) was demonstrated by adjusting CO2:CH4 ratio and addition of steam. The H2/CO molar ratio between 0.25 – 2 was achieved with up to 90% syngas purity suitable for different GTL (gas-to-liquid) processes.

For Gas Switching Water Splitting (GSWS): The experimental demonstration of this process was completed in a three-stages process using two iron-based oxygen carriers. The first GSWS demonstration with 35 wt.% iron-based oxygen carriers showed good reactor performance with no agglomeration but H2 purity was compromised due to gas mixing that takes place when switching between the process stages.

For Gas Switching Partial Oxidation (GSPOX): A Lanthanum-based oxygen carrier was tested in this process for combined syngas and H2 production in a three-stages process. Over 70% CH4 conversion to syngas (at the fuel stage) and about 30% H2O conversion to H2 (at the steam stage) was achieved at 950˚C and atmospheric conditions.

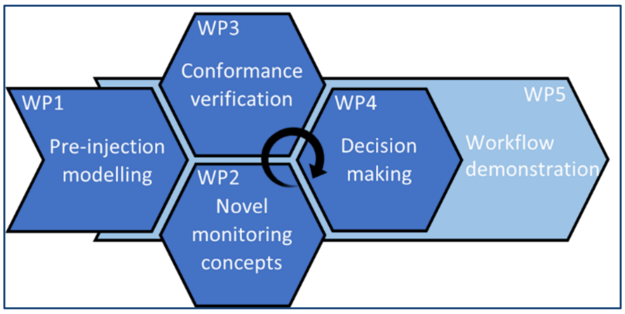
Public accessibility of deliverables

Project website: https://www.sintef.no/gastech-act/ Final report from GaSTech Download

3.7 Pre-ACT

The Pre-ACT project brought together a partnership of 10 research institutes and industrial companies to target three key challenges for CO2 storage: capacity, confidence, and cost. The focus of the project was on improving strategies for monitoring and management of the pore pressure distribution within a storage complex.

Pre-ACT has developed methodologies for monitoring and assessment of conformance (relative to expected performance) for CO2 storage sites at all scales, from pilot to mega storage projects. This unique overview of monitoring methods ensures that the results of the Pre-ACT project are universally applicable, and not limited by scale or geology.



Early input from industrial partners highlighted the need to produce quantitative assessments of conformance based on cost-effective monitoring strategies. The workflow developed in Pre-ACT tried to answer this need. It has been applied to various case studies, presented at international conferences, and has received positive feedback from industry.

Active and passive monitoring techniques have been studied with measurements ranging from direct borehole pressure measurements to indirect surface geophysical measurements aiming at monitoring pressure and saturation changes due to CO2 injection. Three North Sea case studies, each one being headed by a different research group and linked to an industrial partner, have been conducted. Operational data from a Pre-ACT experimental campaign at the onshore Svelvik CO2 Field Lab have also been considered. Based on input from industrial partners, Pre-ACT aimed at supporting site operators when confronted with challenging questions like: Is my site conforming to expectations? How reliable is my conformance assessment? The proposed solution consisted in a mathematically complex, but intuitively accessible, tool providing a means to answer such questions.

Main results

The project has investigated subsurface pressure and saturation changes during injection operations in heterogeneous environments. This has ensured that a suitable degree of complexity has been included in the modelling realisations whilst the work has enhanced knowledge of the capacity of water production to control pressure build up during CO2 storage. These studies have resulted in a significantly improved understanding of the spatial build-up and distribution of pressure and saturation changes during CO2 injection and water production.

Pre-ACT has also assisted in the re-establishment of the Svelvik CO2 Field Lab by input on a suitable well layout, by providing additional instrumentation of the wells and specialized equipment for geophysical monitoring of pressure and saturation, by performing the first experimental campaign at the lab, and by co-arranging the lab inauguration and disseminating the experimental results of the campaign. These unique experiments have allowed the innovative geophysical investigations, targeting controlled pressure and saturation, build-up with techniques that can be used in the monitoring of large-scale CO2 storage projects. For the first time, Pre-ACT has presented a verifiable pressure-saturation discrimination experiment monitored with a comprehensive suite of tools. This is a world class facility undertaking cutting edge scientific experiments.

Pre-ACT researchers, with help from the involved industry partners, have set up three offshore case studies, and these were used to demonstrate various aspects of the developed conformance workflow. The case studies are Endurance (led by BGS and linked to Shell), the Smeaheia site (led by SINTEF and linked to Equinor), and the P18-4 case (led by TNO and linked to TAQA). For maximum impact, Pre-ACT has focused on reporting the project findings applied to these major potential European storage sites.

All in all, the ten most important achievements are:

1) Studies of effects of uncertainties and heterogeneities on prior reservoir modelling
2) Studies of the effect of hypersaline discharge
3) Novel methods for pressure/saturation quantification
4) Svelvik CO2 Field Lab instrumentation and first Svelvik campaign
5) Development of quantitative conformance workflow
6) Development of methods for data acquisition optimization
7) Studies of optimal timing for the purchase of monitoring data
8) The three case studies
9) The three stakeholder meetings, and
10) The webinar series.

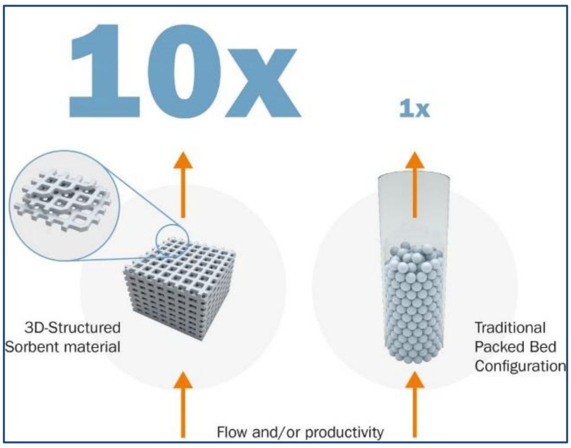
Public accessibility of deliverables

Project website: https://www.sintef.no/pre-act/ Final report from Pre-ACT Download

3.8 3D-CAPs

The 3D-CAPS project aims to reduce the size of the equipment needed to remove and recover CO2 from industrial gases, using two promising new adsorption-based technologies with an inherently small energy footprint. The 3D-CAPS project is carried out by an international consortium of end-users in the oil and gas industry, a technology provider, an SME, and European research and academic institutes. The objectives of the 3D-CAPS project are: to achieve a 10-fold productivity increase for two sorbent-based technologies in CCS, and to optimize sorbent shapes with Computational Fluid Dynamics (CFD) and other modelling tools, with direct realization in 3D-printed objects for testing under relevant conditions.

Two development lines for structured sorbents are elaborated in the project: amine functionalised silica-supported sorbents (ImmoAmmo) for operation in post-combustion conditions in the 40-130 °C temperature range; and hydrotalcites (HTC), suitable for operation under pre-combustion conditions at elevated pressure (up to 30 bar) in the 350-550 °C temperature range. The project covers 3D printing with both silica and hydrotalcites, test and characterization, modelling and business development.



Main results

A Direct Light Processing (DLP) 3D-printing machine was successfully put in operation to produce 3D-printed structures of both silica and hydrotalcites. Good quality printed structures of silica as support for amines were repeatedly obtained for further characterization and testing in the project; 3D-printing of HTC materials was more challenging and printed structures could be prepared only for small scale testing.

With the results obtained from the experimental work, the model development and validation and the systems analyses for ImmoAmmo and HTC, the key objectives of the project were reached. Evidence suggests that the targeted productivity increase of a factor 10 can be obtained, leading to more compact capture technologies, and to reduced cost of CO2 capture; Market research on CO2 capture applications mapped the market needs and end-user interests for compact capture solutions. A business model based on the Business Model Canvas concept was developed to commercialize the technology.

Public accessibility of deliverables

Project website: https://3d-caps.eu/ Final report from 3d-CAPS [Download]()

4. ACT2-projects

The second ACT call (ACT2) was launched in June 2018 and 12 projects selected for funding were kicked off in autumn 2019. The ACT2 projects cover the main areas of CCUS in capture (ANICA, AC2OCem, LAUNCH, NEWEST-CCUS, MemCCSea, Prisma, FUNMIN), storage and storage monitoring (ACTON, DigiMon, REX-CO2, Sense, SUCCEED). The projects cover wide range of scientific research, such as solvents, membranes, oxyfuel, chemical looping processes, mineralisation, negative emissions, EOR, monitoring of storage sites, and acceptability of CCUS in society.

The projects cover a wider geographical area compared to ACT2 projects, with France, Greece, and the USA as additional active funding partners. The total budget was 43.5 M€ of which 31.5M€ from the ACT-partners. This Call was not cofounded from the EC.

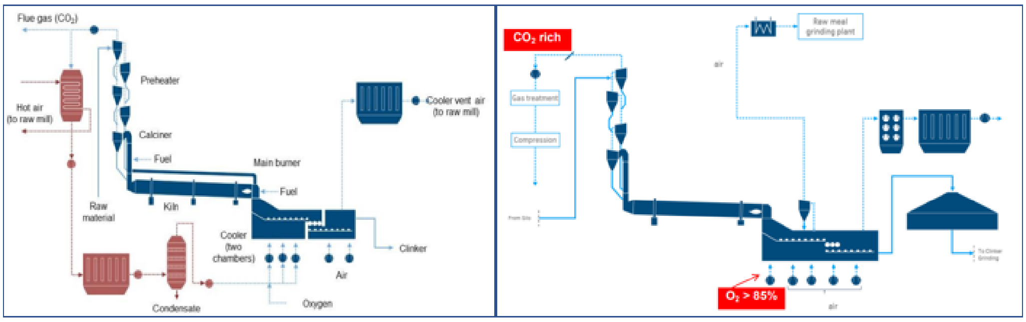
Projects	Activities	ACT, M€	France	Germany	Greece	Netherlands	Norway	Romania	Spain	Switzerland	Turkey	UK	USA
AC2COM	Oxyfuel technology in Cement production	3,0	x	x	x		x			x			
ACTOM	Offshore Monitoring	1,5				x	x					x	x
ANICA	Carbonate Looping Process in cement industry	2,4		x	x							x	
DIGIMON	Digital Monitoring of CO2 storage projects	5,0		x	x	x	x	x				x	x
FUNMIN	CO2 mineralisation into anhydrous MgCO3	0,7	x						x			x	
LAUNCH	CO2 capture in various industries	5,1		x		x	x					x	x
MemCCSea	Membrane systems for CO2 capture and storage at sea	1,7		x	x		x						x
NEWEST-CCS	Negative Emissions in the Waste to Energy Sector	2,2		x		x	x					x	
PRISMA	Sorbent Materials for energy efficient carbon capture	2,1					x			x		x	x
REX-CO2	Reusing existing wells for CO2 storage	2,5	x			x	x	x				x	x
SENSE	CO2 storage sites - ground surface monitoring	2,7	x	x			x		x			x	x
SUCCEED	CO2 storage Coupled with geothermal Energy Deployment	2,5				x					x	x	

In June 2021, after 18 months of operation, mid-term review events took place for all the ACT2 projects. All projects were assessed by the national funding agencies and external independent experts. Each project has individually received written feedback on their project implementation, including recommendations for the second half of the projects. The mid-term review helps ACT to build up strong relationship with project partners, and further facilitate successful project implementation and ensuring that ACT projects are on track to reach the objectives of ACT.

In the following are given some highlights of each of the ACT2 projects.

4.1 AC2OCem

In AC2OCem, pilot-scale experiments, as well as analytical studies, are ongoing to bring the key components of oxyfuel cement plants to TRL6, with the aim of reducing the time to market of the oxyfuel technology in the cement sector.

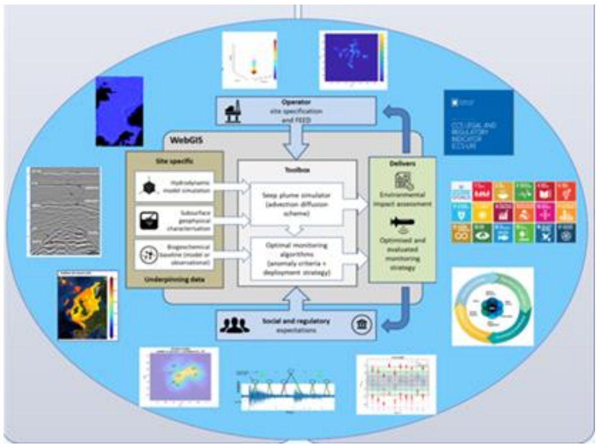


AC²OCem explores the 1st generation oxyfuel technology for retrofitting, focusing on optimization of the oxyfuel calciner operation and advancing the kiln burner technology for combusting up to 100% alternative fuels with high biogenic share to bring this Bio-CCS solution to TRL6.

The innovative 2nd generation oxyfuel technology for new-build cement plants, in which the flue gas recycle loop is excluded, is going to be promoted from TRL2 to TRL6 in key components. An unprecedented oxyfuel kiln burner for highly enriched up to pure oxygen combustion will be for the first time developed and tested in a pilot scale facility that replicates cement kiln conditions. A novel process design for the 2nd generation oxyfuel technology, associated with high cost-saving potentials, is introduced. This process design is optimized and subsequently assessed economically through a techno-economic feasibility study.

Website: http://ac2ocem.eu-projects.de/

4.2 ACTOM



ACTOM works for the advancement of offshore monitoring to ensure alignment of CO2 storage projects with national and international regulations and societal concerns. An interdisciplinary consortium is applying methods to critically assess secure storage as this technology becomes implemented internationally as a key greenhouse gas emissions reductions strategy. The project team builds a web-based toolkit that collects algorithms for designing optimal monitoring programs for offshore geological storage sites.

Routines related to detecting subtle signals of a leak in a highly varying environment are implemented in the toolkit. Through the interdisciplinary approach, the tool assists operators in their pre-operational phase in defining assurance monitoring programs that are aligned with regulations.

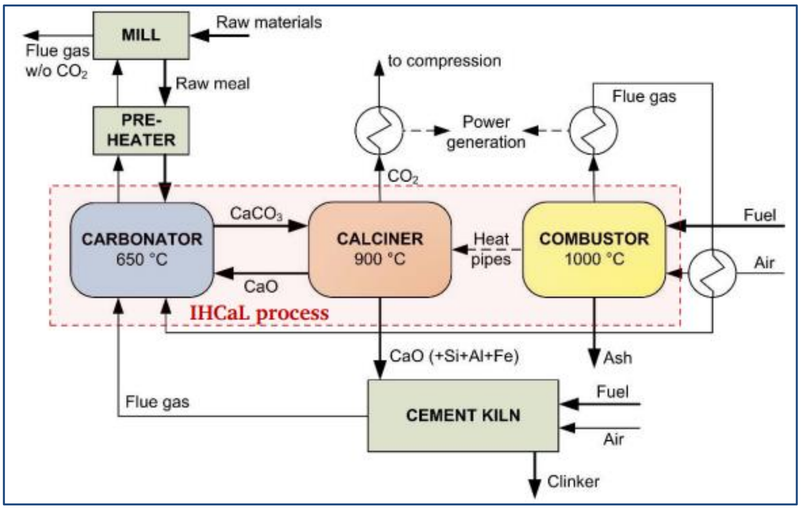
The inevitable uncertainties in all measurements are assessed, and methods on how to quantify and represent them are recommended. Responsible Research and Innovation (RRI) is an approach to anticipate and assess implications and expectations of new technologies grounded in the humanities and social sciences, a framework increasingly being used in marine environmental studies and in biotechnology and innovation.

Website: https://actom.w.uib.no/

4.3 ANICA

The ACT-project ANICA (Advanced Indirectly Heated Carbonate Looping Process) develops efficient concepts for CO2 capture in cement and lime production plants by means of indirect heating. The novel concepts aim at low energy penalty and high integration potential of mass and energy streams into such plants.

Compared to the standard oxy-fired carbonate looping (CaL) process, no air separation unit (ASU) is needed for the IHCaL process, since the heat for calcination is transferred via heat pipes.



The indirect heating improves the purity of the separated CO2 stream, which leads to less costs of post-treatment for further usage.

Furthermore, synergies in the IHCaL process and production process of cement and lime are offered, since same solid materials are used in both processes.

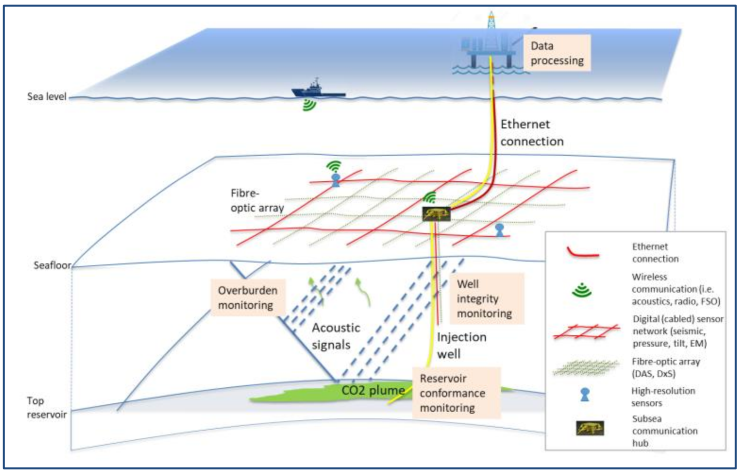
A sorbent utilization of more than 90% is expected to be achievable with the novel integration of IHCaL process. When combining the utilization of waste derived fuels with a high biogenic fraction with CO2 capture, this novel concept offers a high potential for net negative CO2 emissions.

Website: https://act-anica.eu/

4.4 DigiMon

The overall objective of the DigiMon project is to "accelerate the implementation of CCS by developing and demonstrating an affordable, flexible, societally embedded and smart Digital Monitoring early-warning system", for monitoring any CO2 storage reservoir and subsurface barrier system, receiving CO2 from fossil fuel power plants, oil refineries, process plants and other industries.

The DigiMon approach integrates a broad range of technologies for MMV at CO2 storage sites (i.e. distributed fibre-optic sensing technology (DxS), seismic point sensors and gravimetry), combined with ethernet-based digital communication and near real-time, web-based smart data processing software.



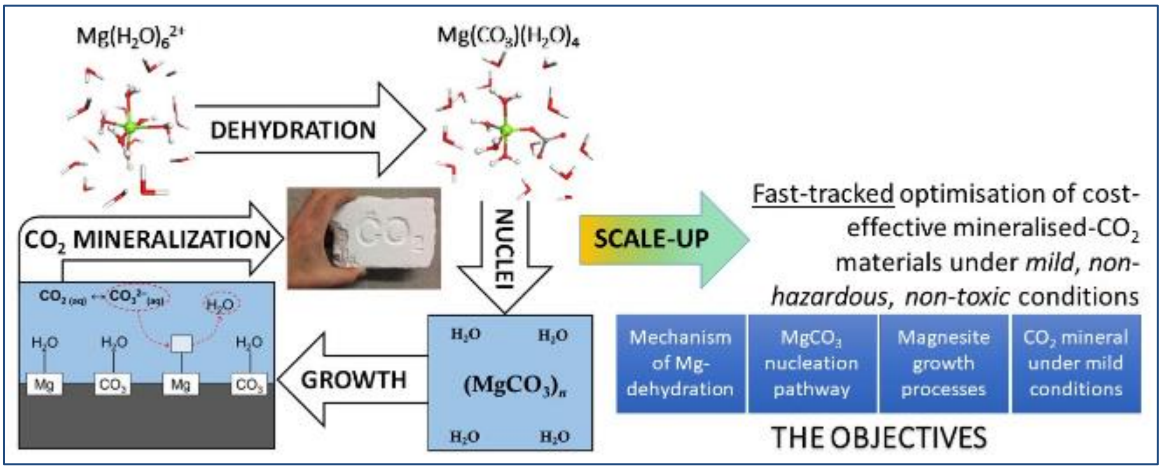
In addition, it uniquely considers the possibilities of monitoring technologies for CCS from the point of view of societal acceptability and benefit.

Website: https://digimon.norceprosjekt.no/home

4.5 FUNMIN

Mineralization of carbon dioxide represents a principal raw material feedstock for carbonate-based materials. Such direct transformation of CO2 gas to solidified added-value carbonates represents an industrially effective route to utilisation, generating stable, inert, non-hazardous, ready-to-use profitable materials. Magnesite (MgCO3) is an ideal carbonate used in cement and agriculture. Promisingly, vast amounts of raw magnesium (Mg) silicate minerals and Mg-rich industrial wastes exist worldwide that may be carbonated, reducing reliance on mined MgCO3 imported from Russia and China.

The principal challenge for speeding up CO2 utilisation via mineralization as a cost-effective CCUS technology, is the slow rate of mineral precipitation from solution; magnesite in particular. Driven by this challenge, as-faced by Cambridge Carbon Capture Ltd (our industrial partner) and related industries working on CO2 mineralization, FUNMIN is an industry-driven project focusing on discovering & optimizing conditions for speeding up MgCO3 formation.

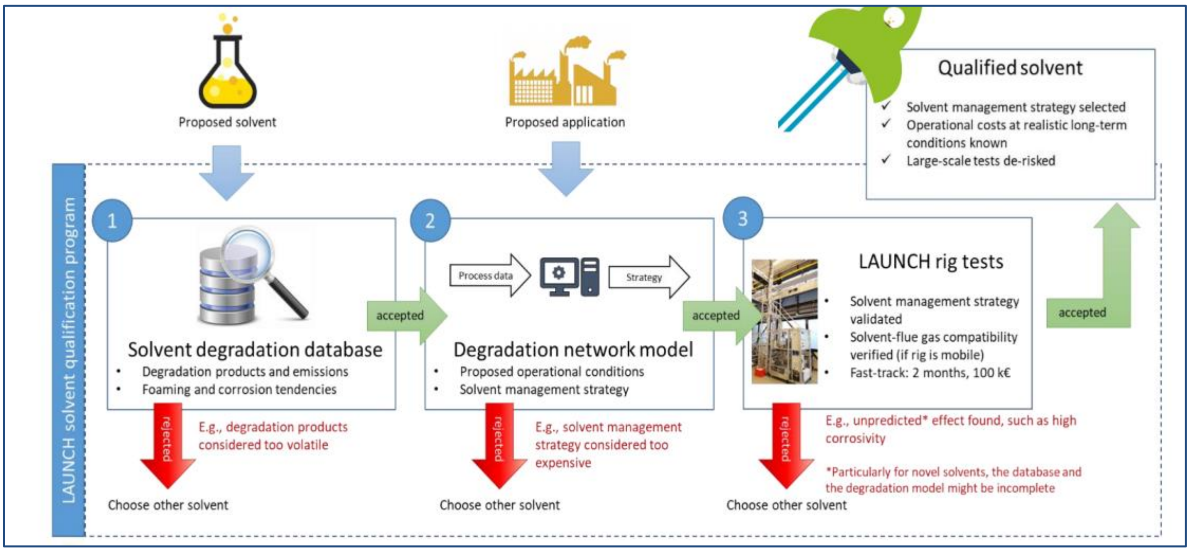


Website: http://research.sbcs.qmul.ac.uk/d.ditommaso/funmin/about.html

4.6 LAUNCH

Solvent degradation is a known drawback of using chemical absorbents as it leads to increased costs due to: solvent replacement, liquid waste treatment, gas compound treatment and increased corrosion.

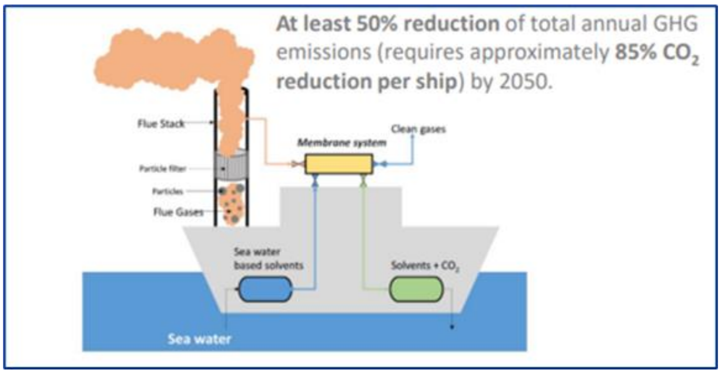
The work of the project will increase our knowledge of solvent characterisation and degradation behaviour, a major step forward in understanding capture materials and processes. By improving the economics of post-combustion CO2 capture systems, we aim to support the growth of a CCUS industry that will facilitate a low-carbon future for Europe's energy and industrial sectors. The LAUNCH project will test first, second and third generation solvents and will include at least 10 open-access solvents.



Website: https://launchccus.eu/

4.7 MemCCSea

The MemCCSea aims at developing hyper compact membrane systems for flexible operational and cost-effective post-combustion. CO2 capture in maritime applications, including Liquefied Natural Gas (LNG) carrier ships and floating vessels (FSRU and FPSO) used by the offshore oil and gas industry.



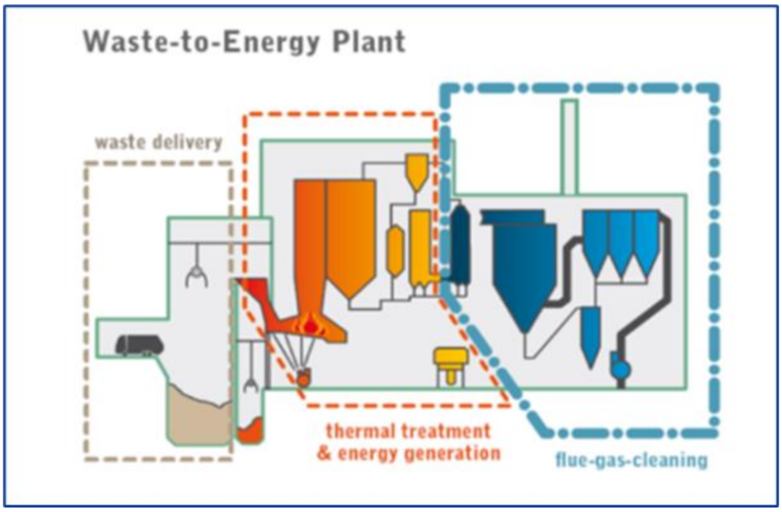
The ultimate goal of the project is to provide a feasible design and pilot demonstration capable to achieve higher than the state-of-the-art performance, meeting the key targets: recovery of the main engine CO2 emissions greater than 90%, overall CO2 emissions reduction (including added emissions by the capture plant and utilities) greater than 50%, a-10 fold reduction of system volume and a reduction of operating costs greater than 25% compared to conventional amine-based scrubbing systems.

The key technological challenge of the MemCCSea is the development of customized compact carbon capture and separation membrane systems and potential CO2 storage options, taking into account the unique challenges posed by the maritime environment, stringent safety requirements and the need for energy efficiency. Two types of innovative membrane-based CO2 capture technologies are investigated: i) Ceramic Gas-Liquid Membrane Contactors and ii) Polymeric Mixed Matrix Membrane Permeators and the developed systems will be evaluated and optimized in laboratory- and pilot-scale experimental facilities and through extensive modelling and simulation at component and system levels. At the end of the project both membrane technologies will attain the goal of TRL 5-6. Process simulation activities will evaluate the feasibility of these technologies at TRL 7, while model-based assessment will explore the applicability of the proposed solution at TRL 8-9.

Website: http://memccsea.certh.gr/

4.8 NEWEST-CCUS

NEWEST-CCUS aims to de-risk and accelerate the development and deployment of CO2 capture technologies tailored specifically for waste-to-energy (WtE) applications. Innovations within the project focus on progressing the Technology Readiness Levels (TRLs) of technologies for WtE sites through a combination of pilot-scale testing and modelling, including: Oxy-firing technologies, focusing on developing circulating fluidised bed technology with the potential for higher efficiency with solid recovered fuels; Membrane-based CO2 separation, considering its application as a hybrid method using partial flue gas recirculation and oxygen enrichment; Solvent-based post-combustion capture and, in particular, knowledge and technologies addressing the need to handle a more diverse range of combustion impurities in challenging fuel flue gases associated with typical WtE plants.

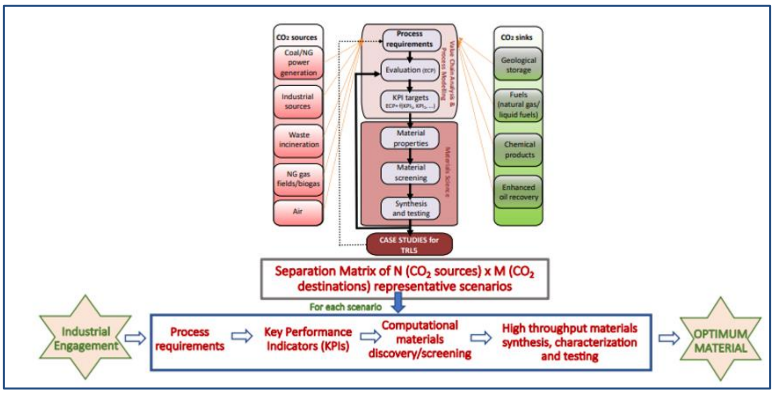


Specific objectives of NEWEST-CCUS that support the successful delivery of these aims include: - Providing a full overview of technical possibilities and limitations of several CO2 capture technologies for residential and industrial waste types; Improving net efficiency of CO2 capture solutions for WtE through improved understanding of performance management options, building on insights from pilot-scale testing and process modelling to explore thermodynamic integration options; Investigating operational issues for CO2 capture processes operating with waste-derived flue gases; Demonstrating promising CCUS technologies for WtE, developing these options to TRL 5-8.

Website: https://www.newestccus.eu/

4.9 PrISMa

The project is an integration of process design and material science.

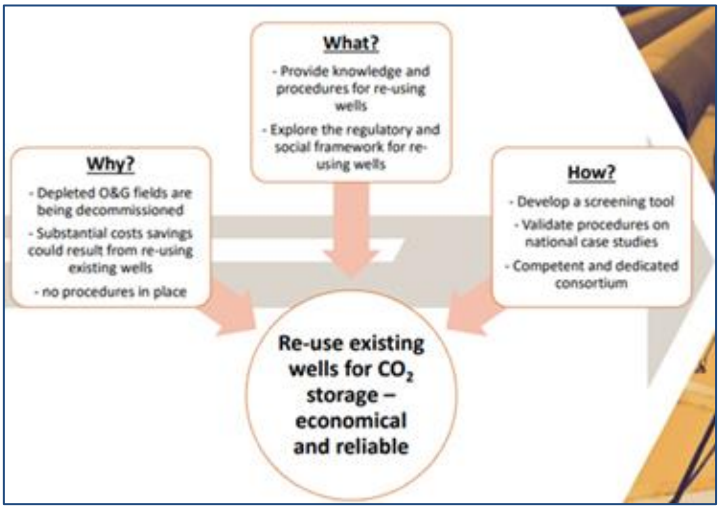


The main activities are: To establish a methodology, based on an effective carbon price (ECP) metric, that allows translation of specific carbon abatement requirements for industrial and CO2 delivery sites into key performance indicators (KPIs) of capture processes for screening and synthesis of novel materials; To effectively design new and advanced materials at the molecular level with the optimum process-informed properties and guided by process-derived KPIs; Efficient high-throughput synthesis and characterization of promising novel sorbent materials that have been molecularly found to be optimal for a given separation; To standardize and evaluate rapidly and efficiently the dynamic performance of novel sorbent materials under relevant process conditions; To evaluate the competitiveness of advanced sorbent-based capture technologies in terms of cost, environmental impact, scale and reliability. To outreach, communicate and exemplify novel breakthrough materials and CCUS technologies to society.

Website: https://prisma.hw.ac.uk/

4.10 REX-CO2

Existing oil and gas industry installations which cover large parts of the potential CCS chain are already in place, and an increasing number of reservoirs have come to the end of their production lifetime and are earmarked as major targets for initiating large-scale CCUS operations. The existing wells in these assets present both opportunity and challenges. Substantial savings could be realized by re-using these wells as CO2 injectors, monitoring wells, or for water production (pressure management).



On the other hand, the existing well infrastructure poses a risk as a potential CO2 or brine leakage pathway.

The project takes a fresh look at this problem and provide a novel solution. The re-use of wells is the inverse of the problem of identifying defective wells. The process of certifying well integrity can also be used to identify wells suitable for continued use in a CO2-rich environment.

The project develops a qualification process that will simultaneously save CO2 storage projects money and time by identifying existing infrastructure that is safe to re-use, while determining which wells must be remediated to ensure long-term storage.

Re-use can benefit projects in all geological settings but may be particularly crucial for off-shore environments, such as the North Sea or the Gulf of Mexico, where well development costs could otherwise be prohibitive. Developing a procedure and tools for evaluating the re-use potential of existing hydrocarbon fields and wells requires a dedicated investigation encompassing the interrelated technical, environmental, economic and social aspects.

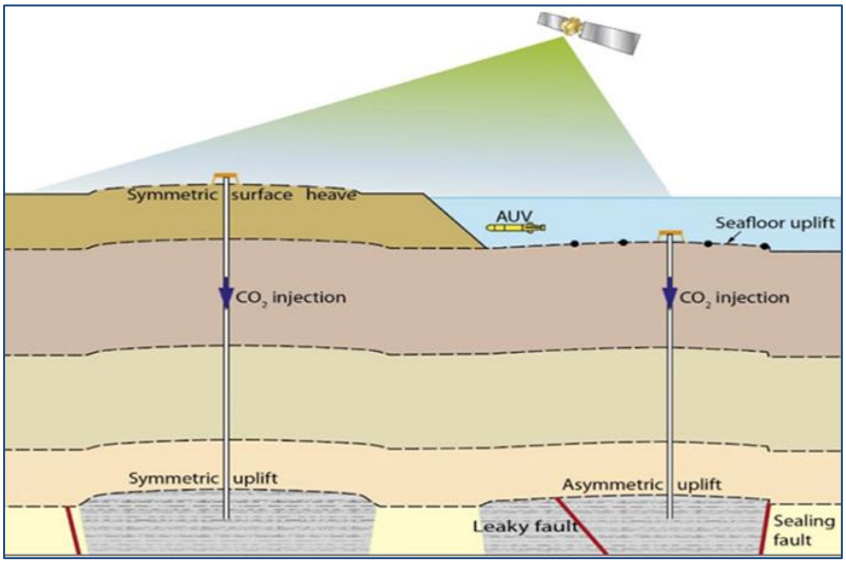
Website: https://rex-co2.eu/index.html

4.11 SENSE

The primary objective of SENSE is to demonstrate reliable, cost-efficient CO2 storage monitoring using ground surface deformation detection combined with geomechanical modelling and inversion to provide information on pressure distribution and hydraulic behaviour of storage sites.

The goal of the SENSE project is to demonstrate how ground surface movement can be used as an integral part of the monitoring program to effectively verify safe storage of CO2 underground.

The research activities are focused towards injection demonstration sites both onshore and offshore and include: demonstration of continuous monitoring of surface deformation and subsurface pressure distribution using satellite data, inclinometers, water pressure sensors, fiber optics and seafloor geodesy; develop advanced quantitative characterization of critical geomechanical and hydraulic parameters as well as automatization routines for data interpretation; optimization of sampling arrays to provide cost-effective monitoring and long-term safety.



The main findings will offer storage site operators a cost-effective monitoring option that can form part of an effective site assurance/monitoring program and feed into workflows to set up an early alert system for unexpected changes in the subsurface.

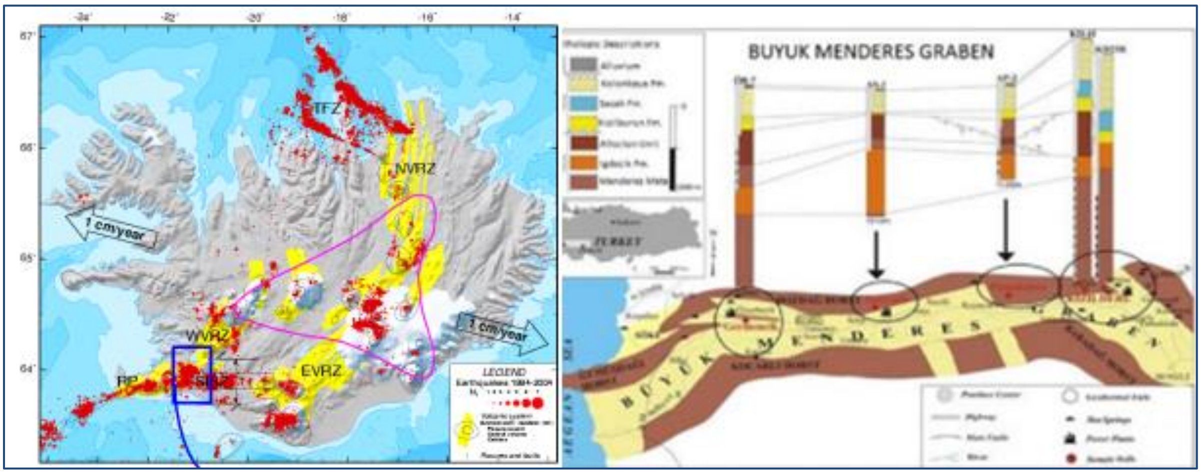
Website: https://sense-act.eu/

4.12 SUCCEED

The project aims at accelerating and maturing the use of CCUS by developing, testing and demonstrating measurement, monitoring and verification technologies that can be used in most CO2 geological storage projects.

The team is working with two existing facilities at Kizildere in Turkey and Hellisheidi in Iceland, where CO2 is actually injected in the subsurface at geothermal energy projects.

The objectives of the project are: Research and demonstrate the feasibility of utilising produced CO2 for re-injection to improve geothermal performance, while also storing the CO2; Develop further, test and demonstrate innovative monitoring technologies; Test and demonstrate the industrial CCUS opportunity for geothermal field operators; Utilise advantageous operational field environments, facilitated by thermally and hydrologically active geothermal fields which are currently in production, for accelerated testing of CO2 utilisation, supercritical and dissolved CO2 injection, reactive transport and storage; Use a real field environment for the testing of supercritical and dissolved CO2 injection into a reservoir and provide the geothermal energy sector with the means to address the current climate change challenge through CO2 utilisation and storage.



Website: https://www.imperial.ac.uk/energy-futures-lab/succeed/

5. ACT3-projects

The third ACT call for projects (ACT3) was launched in June 2020, and the decision for funding 12 new projects was taken in June 2021. Furthermore, two additional projects were also candidates for funding, provided that some of the ACT funding agencies were able to come up with additional funding. One of these two projects were granted funding from ACT in November 2020, and the final decision for the second project will be taken December 2020

The projects (identified by acronyms), their main activities, and countries/regions involved in the 13 new ACT3-projects are shown in the table below.

Project	Activities	Alberta	Denmark	France	Germany	Greece	India	Italy	Netherlands	Nordic	Norway	Romania	Switzerland	Turkey	UK	USA
ABSALT	Solid adsorption looping technology				x	x		x					x		X	
ACTION	CCS Networks	x		x					x			x			X	x
CEMENTEGRITY	Well integrity and cementing								x		X				x	
CoCaCO2La	Converting CO_2 to Ethylene					x									X	x
CooCE	Convert CO_2 to biofuels and chemicals		x			x		x							x	
CREATE	Conversion of CO2 from cement plant	X		x									x			
ENSURE	Microseismic monitoring	x		x							X				(x)	(x)
EverLoNG	Ship-based CO_2 capture				x				X		x				x	x
LOUISE	Chemical looping combustion (CLC)				X	x					x			x		
NEXTCCUS	Convert CO_2 to methanol			x		x		X				x			x	x
RETURN	CO2 storage in depleted reservoirs	x			x				x		X				x	
SCOPE	CO2 capture				x		x		x		X				x	x
SHARP	Storage risk reduction		x				x		x		X				x	

- The projects cover the range of key areas of CCUS on capture, transport, storage and utilization, for example in topics of solid adsorbents, solvent management and emissions, conversion of CO2 into fuels or chemicals, and monitoring and containment risks of storage sites.
- The industry involvement in the ACT3 projects is more pronounced than in ACT1 and ACT2. The reason may be that climate action is increasingly important and measures to support climate action and mitigate CO2 emissions are more pronounced than earlier. The need for climate neutrality and negative emission technologies are much more in focus now compared to some years ago.
- The geographical distribution of ACT3 projects reflects the expanded ACT Consortium countries and regions. ACT3 projects include partners from the province of Alberta in Canada, Denmark, France, Germany, Greece, India, Italy, the Netherlands, Norway, Romania, Switzerland, Turkey, United Kingdom, and the USA.
- Total budget of the projects is 47 M€ (incl. in-kind and industry funds), of which 29.5 M€ is requested from the ACT-partners.

The ACT3- projects will be kicked off during autumn 2021 and run for 3 years and end late 2024.

More information about the ACT3-projects can be found on the act-web-page here, and soon they will launch their own web-pages where more details can be found. Links to the project websites will also be accessible from the ACT website.

6. SET Plan and Mission Innovation targets facilitated by ACT Projects

The SET Plan Implementation Working Group (IWG) on CCS and CCU has defined its targets in 2017 and they have been updated in 2021. The ACT Calls support the targets of the IWG. They also support the Challenges defined in the Mission Innovation Challenge on CCUS.

To illustrate the way in which ACT is supporting such targets, we clarify in the table below how the projects from the ACT Calls are relevant for the SET Plan targets. ACT funded projects broadly cover the SET Plan Targets, and in this way, ACT helps realise the IWG ambitions.

The ACT-projects are also aligned with several of the 30 Mission innovations research priorities (see the ACT Final report on our web for a total overview).

SET Plan Targets (2030) (summarized)	ACT1 projects	ACT2 projects	ACT3 projects
Delivery of 15 commercial-scale CCS projects linked to industrial sources	ALIGN, ELEGANCY	LAUNCH	ABSALT, ENSURE, SCOPE
Delivery of 10 commercial-scale CCS project for clean flexible power and heat	ALIGN	LAUNCH	ABSALT, ENSURE, SCOPE
SET Plan countries have roadmaps for dedicated CO2 transport infrastructure for the EU Ten-Year Network Development Plan.	ALIGN, ELEGANCY	0	ACTION
10 additional EU Projects of Common Interest for CO2 transport infrastructure	ACORN, ECOBASE	0	0
Inventory of geological storage capacity	0	0	0
CO2 capture pilots for different industrial and climate-neutral applications, TRL 7-8 and TRL 5-6	GasTECH, 3D-Caps	LAUNCH, NEWEST-CCS, ANICA, EC2OCEM, PRISMA, MEMCCSEA	ABSALT, EverLoNG
6 New storage sites in preparation or operating by 2030, in different settings	Pre-ACT, DETECT, ECOBASE	SUCCEED, DIGIMON, ACTOM, REX-CO2, SENSE	RETURN, SHARP, CEMENTEGRITY
Several CCU demonstration installations for fuels and chemicals based on CO2	ALIGN	FUNMIN	CoCaCO2La, CooCE, CREATE, LOUISE, NEXTCCUS
By 2030, first large-scale commercial CCU installations, supported by regulatory framework			CREATE, LOUISE
All European countries have identified the role of CCS/CCU in meeting climate neutrality by 2050	All	All	All