15th International Conference on Greenhouse Gas Control Technologies, GHGT-15

15th 18th March 2021 Abu Dhabi, UAE

ALIGN-CCUS: the results of an ACT project on the full CCUS chain to accelerate implementation of decarbonisation in industrial areas

Peter van Os[a*], Hanne Kvamsdal[b], Hans Aksel Haugen[c], Maxine Akhurst[d], Peter Moser[e], Lydia Rycroft[a], Emma ter Mors[f], Diana Cismaru[g], Tom Mikunda[h]

[a]*TNO, Leeghwaterstraat 46, 2628CA, Delft, Netherlands*
[b]*SINTEFIndustry, Sem Saelands vei 2A, 7465 Trondheim, Norway*
[c]*SINTEF Industry, Kjølnes Ring 30, 3918 Porsgrunn, Norway*
[d]*British Geological Survey, Lyell Centre, Riccarton, Edinburgh, EH14 4AP, United Kingdom*
[e]*RWE Power AG, Ernestinenstrasse 60, 45141 Essen, Germany*
[f]*Leiden University, Faculty of Social and Behavioural Sciences, Pieter de la Court Building, Wassenaarseweg 52, 2333 AK Leiden*
[g] *National University of Political Studies and Public Administration, Bulevardul Expoziției 30A, București 012244, Romania*
[h]*Ministry of Economic Affairs and Climate Policy, Bezuidenhoutseweg 73, 2594 AC, Den Haag, the Netherlands*
**peter.vanos@tno.nl*

Abstract

ALIGN-CCUS (**A**ccelerating **L**ow Carbo**N** **I**ndustrial **G**rowth through **C**arbon **C**apture **U**tilisation and **S**torage) is a project supported by the ERA-NET Co-fund ACT program. In the first call of this program nine European countries, together with the European Horizon 2020 program have joined forces by making funds available for research and innovation actions related to carbon dioxide (CO_2) Capture,Storage and Utilisation (CCUS). The participants of ALIGN-CCUS project represented the ERA-NET ACT countries of The Netherlands, Germany, Norway, Romania and the United Kingdom. The ALIGN-CCUS consortium involved 30 partners from industry, research and academia and has considerable involvement of industrial companies and enterprise organizations. The industrial partners not only supported the research but also committed to directly invest and participate in the R&D and demonstration activities in the project, boosting the credibility of the project's potential for accelerating and maturing CCUS technologies. The project has ended in November 2020 and its results are already being used in various CCUS projects around the globe. More than 100 reports have been produced, of which 57 are public and available from our website www.alignccus.eu. Many detailed results will be presented at conferences and in other papers. In this paper a high-level overview is given of the research performed in ALIGN-CCUS and its immediate impact in the CCUS community.

1. Project participants and structure

In ALIGN-CCUS , 29 partners and one associated partner (shown in the table, below) worked jointly in one of the biggest full-chain CCUS projects in the world. an impressive volume of research has been completed in the field of CO2 capture, transport, storage, utilization, cluster development and public perception (Fig. 1), supported by a working budget of around 22 million Euro.

Table 1. Partners in ALIGN-CCUS.

Organisation	Country
TNO	Netherlands
SINTEF IND	Norway
British Geological Survey	United Kingdom
RWE Power	Germany
Leiden University	Netherlands
Asahi Kasei Europe	Germany
Bellona Europe	Norway
CO_2 club association	Romania
FEV GmbH	Germany
Forschungszentrum Jülich	Germany
GeoEcomar	Romania
Heriot-Watt University	United Kingdom
IFE	Norway
Imperial College London	United Kingdom
Mitsubishi Power Europe	Germany
Norcem AS / Heidelberg Cement	Norway
Norwegian University of Science and Technology	Norway
National University of Political Studies and Public Administration	Romania
PicOil Info Consult	Romania
Rijksuniversiteit Groningen	Netherlands
RWTH Aachen University	Germany
Scottish Enterprise/ Scottish Government	United Kingdom
TAQA Energy BV	Netherlands
Technology Centre Mongstad	Norway
Tees Valley Combined Authority	United Kingdom
University of Southeast Norway	Norway
University of Edinburgh / Scottish Carbon Capture & Storage	United Kingdom
University of Sheffield	United Kingdom
YARA	Norway
Bosch (Associated partner)	Germany

To assure an effective focus for each of the CCUS chain elements, the project was divided into six technical Work Packages and one Work Package focused on management and dissemination (see Fig. 1).

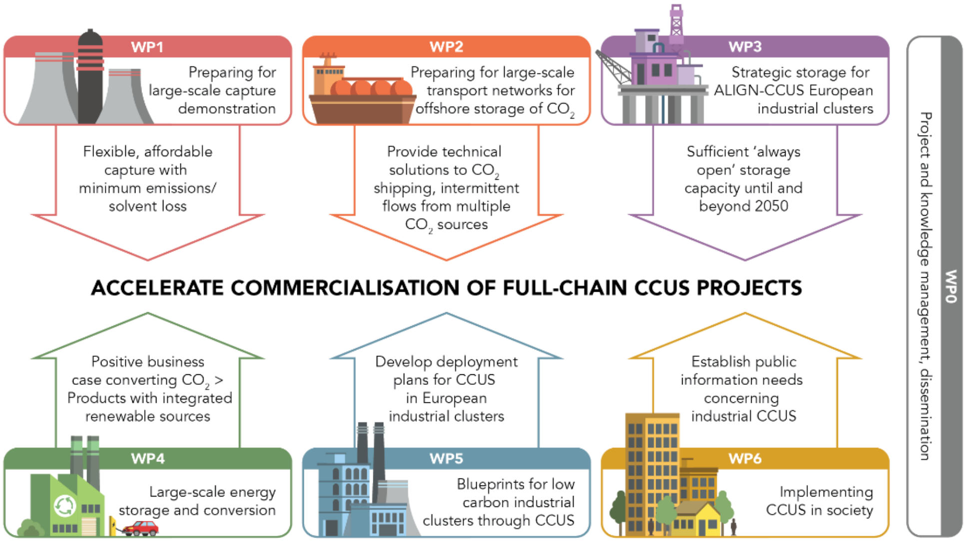

Fig. 1: Work packages in ALIGN-CCUS

All chain elements worked closely together to achieve the goal of ALIGN-CCUS: to enable the acceleration of CCUS implementation in specific industrial regions in the countries involved in ALIGN-CCUS. These regions are: Teesside (UK) and Grangemouth (UK), Rotterdam (NL), North Rhine-Westphalia (DE), Grenland (NO) and Oltenia (RO), as shown in Fig. 2. Each region has its own specific circumstances and needs. Actionable blueprints are presented for each region, in which CCUS enables low-emission industries, through geological storage and/or utilization of CO_2. The blueprints are developed for the regions in ALIGN-CCUS but can be applied also for other regions globally.

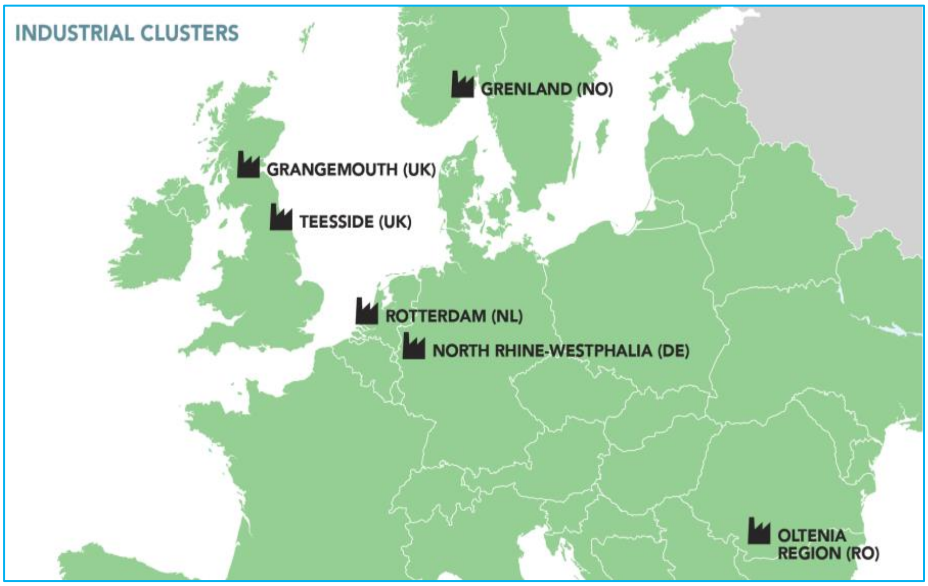

Fig. 2: Industrial regions addressed in ALIGN-CCUS

2. Overview of the main results per Work Package

2.1. WP1: Enable near-term deployment of integrated capture facilities and cluster development

Work Package 1 focussed on CO2 capture and has addressed specific capture topics: emissions, solvent management, process dynamics and control and benchmarking and cost drivers. Solvents investigated in ALIGN-CCUS are MEA and CESAR1 (an AMP and piperazine blend). There were two 18 months testing periods in ALIGN-CCUS with these solvent systems. The continuous operation for 18 months is unique and has never been done before.

The most important results regarding the reduction of the risk for the implementation of commercial capture plants and to accelerate the implementation of CCUS are:

- In general, volatile emissions can be well controlled by installing water- and acid washes. The dry bed may be an interesting addition, as it has the potential of lowering the OPEX (operational costs) of the acid wash.
- Options to control aerosol-based emissions include the turbulent pre-treatment (TPT) and the dry bed. For the TPT and the dry bed, additional investigations are suggested. Although not tested in ALIGN-CCUS, Brownian demister unit (BDU) seems a promising emission mitigation tool that significantly lowers emissions. Long term performance needs to be backed up with experience at pilot scale.
- The wet electrostatic precipitator (WESP) is not recommended as a technology for mitigating aerosol-based emissions. The OPEX and equipment costs are higher than that of a BDU. But most importantly, there is no evidence that a WESP can control emissions; on the contrary, and depending on the operational conditions, the WESP could even lead to increased aerosol emissions.
- CESAR1 degrades much more slowly than MEA and has a lower specific reboiler duty. On the other hand, CESAR1 has higher emissions and is more expensive.
- "Bleed and Feed" as solvent management strategy would require a full replacement of the solvent holdup and careful cleaning of the capture plant to be effective.
- Reclaiming by ion exchange seems to be a more promising management strategy, but a careful analysis of the waste streams must be carried out and further investigation is needed.
- Online measurement techniques are important instruments in a broader sense for plant control.
- Mitigation measures like oxygen removal for the solvent has potential to significantly reduce the operational costs by extending the lifetime of the solvent.
- ALIGN-CCUS has generated new impetus for further development of measuring procedures, laboratory experiments and modelling activities on emission and degradation, some of those are taking further in the ACT2 project LAUNCH (www.launchccus.eu).

Extensive testing of plant dynamics and control based on Non-linear Model Predictive Control (NMPC) showed that:

- A smooth transfer from one capture rate to another could be obtained, from 85% up to 99% capture rate. This facilitates the possibility of using a dynamic real time optimizer that can minimize the capture cost over a longer horizon e.g., to optimize the operation during one day with cyclic variations in the electricity price.
- Good control over changes in flue gas flow rates due to changes in the electric output from the power plant could be achieved. The NMPC uses the planned change rate in the flue gas in its predictions for future control steps.
- The NMPC managed purity fluctuations, such as changes in CO_2 concentration.
- The dynamic process model of the plant was well suited for control purposes.

For the benchmarking and cost drivers, we have investigated the costs of CO_2 capture for three use cases: power, waste-to-energy, and cement plants. For each use case, the CO_2 capture process was proposed and simulated using both the MEA and CESAR1 solvents, and different scenarios were also considered for each case. In general, it is concluded that emission mitigation technologies do not seem to represent a major cost item for CO_2 capture plants. Depending on the solvent costs and emission level considered, they can even lower the cost of CO_2 capture. Importantly to notice, emission mitigation technologies will lower the environmental impact of CO_2 capture, and may be necessary, particularly in cases in which the total nitrogen emissions (amines, ammonia, NOx, etc.) are strictly regulated. Furthermore, it should be noted that any decrease in solvent losses (due to controlled emissions and/or degradation) will also lead to a decrease in the environmental impact of the CO_2 capture process and should therefore be considered also from this perspective.

2.2. WP2: Removing technical barriers to large-scale CO_2 transport

The three overall objectives of WP2 were:

- Develop optimum handling strategies of both low- and medium-pressure CO_2 on vessels in a transportation network, and in offshore offloading systems including required equipment types.
- Investigate use of different solutions including Floating Production, Storage and Offloading units (FPSOs) and/or subsea solutions and identify new chain configurations.
- Suggest optimum combinations between transport solutions and offshore offloading solutions, and establish a benchmark for alternative transport strategies, including cost considerations.

Work Package 2 on CO_2 transport is a natural link in the value chain between capture at one end and storage of CO_2 at the other end. CO_2 transport consists of preparation for transport (conditioning, liquefaction) by ship or pipeline, eventually a hub onshore where CO_2 is offloaded and temporarily stored and then pumps to transport the CO_2 through a pipeline to an injection site (offshore). The Work Package has had a special focus on transport by ships, although including also pipelines when necessary, such as regarding network modelling.

WP2 has demonstrated that low pressure ship transport of CO_2 may be just as (or even more) attractive than the medium pressure transport option, which is the proven technology today. Cost-wise these two options are quite similar. The cheapest injection option seems to be direct injection from a ship. When injecting, the low temperature in combination with the relatively high pressure poses challenges to materials and the integrity of the well. This is a potential risk, which must be contained at the receiving end of the chain. Another risk factor is presence of impurities in the CO_2 stream. Impurities, even in low concentrations, may cause corrosion. Most preferably this risk should be contained at the CO_2 delivery end (capture end) of the value chain. The work in WP2 has extensively relied on techno-economic assessments and this is also an integral part of the model that has been developed for CCS portfolio assessment and network optimization.

2.3. WP3: Large-scale storage networks

The objectives for WP3 were to investigate:

- A methodology to present a standardized tool to communicate the readiness of a prospective site for operational storage;
- A portfolio of selected storage sites that have been characterized sufficiently to progress strategic storage resources for the leading ALIGN-CCUS industrial clusters and most likely to form the backbone of CCUS in north-west Europe;
- An audit of North Sea transport and injection infrastructure that provides least-cost options for storage network development.

A framework of CO_2 Storage Readiness Levels (SRLs) was presented and applied to North Sea sites. The levels are based on the practice and experience of CO_2 storage site appraisal, regulatory permitting and CCS project planning in the UK and The Netherlands, and storage operations in Norway, since the 1990s. Application of the framework communicates what has been achieved and what remains to be completed before a site can become operational. The framework has been applied to more than 700 prospective sites offshore the UK, The Netherlands and Norway. Application of the framework to sites in the European CO_2 storage atlas has been proposed, to integrate regions of northern and southern Europe.

'Next sites' were selected and investigated for four North Sea industrial CCUS clusters, each beyond current industry plans for CCUS, sufficient for annual storage of tens of million tonnes CO_2. Research activities were tailored to be specific to national needs. Selection and simulation of storage site operations for the UK Teesside and Grangemouth clusters was informed by CO_2 supply profiles plotted from industry plans, in collaboration with the ELEGANCY and Acorn projects. Selection of storage sites for the Norwegian Grenland cluster, beyond the plans for the full-scale Northern Lights industry project, was informed by a timeline of CO_2 supply from Scandinavian and northern European sources. Three saline aquifer sites and also the potential capacity of the Troll Field, once depleted, were modelled and injection simulated to provide potential storage capacity of tens to thousands of million tonnes CO_2 in the Horda Platform area. Strategic assessment of depleting gas fields, stepping out from the permitted P18-4 site, informed the mapping of alternative networks for transport and storage of CO_2 from Rotterdam and Amsterdam, The Netherlands.

The objectives of the transport and infrastructure development research were to: consider, apply and rank published criteria for the re-use of offshore oil and gas infrastructure for CO_2 transport and storage; identify oil and gas infrastructure suitable for re-use for each ALIGN-CCUS cluster; provide an overview of current legal situation and recommend amendments to legal regimes governing decommissioning of re-usable offshore assets. The objectives were addressed by developing a methodology based on published criteria and their effectiveness for screening and ease of access to the technical information required. The methodology was applied to available technical infrastructure information for the ‘next sites’ storage options identified for the UK, The Netherlands and Norwegian ALIGN industrial clusters. Legal considerations for re-use within international, European and national laws of the UK, The Netherlands, and Norway were reviewed, and discussed with relevant stakeholders at three national workshops. Three legislative scenarios have been identified to enable infrastructure re-use for CCS; while oil and gas production operations is still in operation; CO_2 storage commences directly after production ceases; CO_2 storage takes place several years after production has ceased.

2.4. WP4: CCUS as an element for large-scale energy storage and conversion

For the first time a full CCU chain to produce the eFuel dimethyl ether (DME) from captured CO_2 and electrolytically produced H_2 was demonstrated in ALIGN-CCUS. In addition to the development, construction and operation of the Power-to-DME plant, the demonstration comprised also the successful use of DME as a fuel for peak and back-up power generation and of OME (polyoxymethylene dimethyl ethers, which can be produced from DME) as a fuel for passenger cars. Both objectives, to present the potential of CCU regarding climate protection and to

Fig. 3: The ALIGN-CCUS full chain CCU demonstrator at Niederaussem

demonstrate its benefit and socio-economic value as an element for large-scale energy storage and sector coupling, have been achieved. The ALIGN-CCUS demonstrator was erected next to the CO_2-capture plant and in the immediate vicinity of the CO_2 filling plant, so that the CO_2 which is captured from the flue gas of the 1000 MW power plant unit could be used for the demonstrator (solvent in use was CESAR1) as can be seen in Fig. 3.

The Power-to-DME demonstrator comprises RWE's CO_2 capture and liquefaction plants and a CO_2 storage tank, the alkaline electrolyser from Asahi Kasei (65 kW_{el} for the production of up to 26 kg H_2/d),, Mitsubishi Power Europe's units for CO_2 conditioning, gas compression and the DME synthesis (up to 50 kg raw DME/d), including a catalytic combustion unit from FZ Jülich for purge gas treatment and the gas supply system and tanks for storage of raw DME and waste water.

The first step for the engineering of the innovative direct synthesis of DME was the development and supply of a bi-functional catalyst by Mitsubishi Power. It took one year to complete the mechanical work and commissioning after installation. During the commissioning, an operation time of more than 200 hours was reached with more than 80 start-ups and shutdowns. Since DME is gaseous under atmospheric conditions and has a lower heating value compared to diesel, changes need to be made in the fuel supply system of the peak-power generator. Because DME combustion has very low soot emissions, the Soot-NOx conflict is eliminated and the EGR rate can be risen without emitting more soot and therefore the NOX emissions can be reduced significantly. The maximum power of 250 kW of the engine operated with diesel was also reached with DME. It is expected that the engine can run continuously on DME at this load level, similar to diesel operation. Emission measurements for DME showed much lower particle mass and particle count, as well as lower CO and hydrocarbon emissions than diesel.

The physical and chemical properties of OME deviate considerably from those of conventional diesel fuel, thus necessitating engine modifications for the passenger car. The results from the engine tests with DME and OME have demonstrated that CCU is more than only climate protection.

A cradle-to-grave Life Cycle Assessment (LCA) has taken into account all life cycle phases of the two investigated use cases (peak-power generation, passenger car), their emissions and material flows in and out of the system, starting from the natural resources and raw materials and ending with the end of life of the plants and hardware and wastes. Potential recycling and interdependencies with other products have been also taken into account. The LCA shows that global warming potential (GWP) of back-up and peak-power production could be significantly reduced compared to diesel fuelled engines or natural gas fired turbines. Prerequisite is that the stored energy comes from a source with low CO_2 footprint such as wind power. Using only today's grid electricity would increase the emissions instead. Transport using OME as fuel and replacing diesel is not viable in comparison with electric cars or conventional diesel fueled cars regarding the GWP. However, DME produced from CO_2 of a lignite fired power plant and hydrogen with low CO_2 footprint would result in a GWP in the same range as an electric car supplied with wind power.

2.5. WP5: Targeted CCUS activities in industrial clusters

The work in WP5 has advanced the development of CCUS in six industrial regions across five European countries. The findings of the work will support national and regional governments in future decision-making for industrial decarbonisation strategies within the targeted regions. It has also drawn together synergies from each case studies to inform a more generic approach to cluster developments in Europe. Beyond the work in each individual cluster region (Tasks 5.1 to 5.5), Task 5.6 has taken a more overarching approach and utilised the research conducted in ALIGN-CCUS to develop more European wide advice documents regarding the business case for hubs and cluster developments.

WP5 overall has provided clarity on the future steps for hubs and cluster within the six industrial regions studied. The results of the research conducted in ALIGN-CCUS into these clusters has also allowed for modelling of embryonic CO_2 cluster infrastructure to be undertaken. Greater clarity can now be provided on the expected investment requirements and benefits for public and private actors of hub and cluster developments for CCUS.

Work on the UK Teesside and Grangemouth cluster has focused on the cost-reduction potential beyond the initial planned projects. This will inform the long-term decarbonisation plans for CCUS which are currently being developed by the UK government. ALIGN-CCUS has accelerated the 'next steps' to achieve capture and storage at tens of million tonnes CO_2 per year by: simulating multi-site storage options; assessing liabilities and recommending business models; and modelling cost-effective networks for transport and storage and CCS project business models. CO_2 storage capacity and operations were modelled for the next sites to provide a growing and mature UK CCS industry to 2100. Barriers to investment for CCUS component industries (costs, liabilities, and risk sharing) were also identified and recommended business models for public and private risk allocation and sharing for Teesside and Grangemouth were provided including cost-effective & flexible options, constrained by geology and geography, to inform choice of business model.

Regarding the Port of Rotterdam, the feasibility of developing a large-scale centralized natural gas decarbonisation facility with CO_2 capture and storage was assessed. The role of hydrogen production in potential decarbonization scenarios was reviewed and alongside potential production technologies. This allowed for the outline of planning requirements and transport routes and locations to be reviewed. Following the identification of potential hydrogen production scenarios, infrastructure requirements in the port to allow for hydrogen use and a central decarbonization facilitiy were identified.

An assessment of possible CCU pathways in North-Rhine Westphalia, Germany, has also been undertaken. A database of over 110 CO_2 sources has been developed along with the forecasting of DME demand until 2050. Modelling has been conducted to optimise DME plant location, CO_2 source selection and potential network development. This has allowed for an investigation into the impact between developing a centralised on decentralised DME production facility. Major costs have been identified and their impact investigated, e.g. the type of capture technology and electricity supply requirements. Intermediate storage and the associated costs impacts have also been assessed. This work has been conducted in collaboration with WP4 and the information collected from the demonstrator has been further developed.

The design of a multi-user intermediate storage site in the Grenland region of Norway was investigated. Three sources are located in close proximity in this region (Norcem, Yara and EGE) and ALIGN-CCUS has conducted a pre-feasibility investigation into the concept of a joint interim CO_2 storage site in Herøya Industripark near Porsgrunn. The effect that different full-chain approaches will have on the storage site design requirements have been assessed alongside a cost assessment of the full CCS chain with an intermediate multi-user storage facility.

Source and sink matching was conducted for the Oltenia Region in Romania. As part of this work major emitters in the region have been identified and data has been collected regarding their annual CO_2 emission volumes. Alongside this, utilization and storage options in the region (both on and offshore) have been reviewed. All this data allowed for an inventory to be produced on the identification of sources and sinks. Following this initial source and sink identification CCUS pathways were identified and potential transport options reviewed. This was then investigated in more detail regarding potential transport links, with all options reviewed including by rail, road, pipeline and ship.

ALIGN-CCUS also bring brought all these case studies together and identified synergies between their findings. Following interviews with the researchers involved in each country's case study, learnings were developed regarding how commercial models can be developed to support CCUS hub and cluster development. A toolkit for action has been developed based on the overall learnings that can be taken for this hubs and cluster research as a whole. This toolkit can be applied to any industrial region embarking on a decarbonisation pathway. It is publicly available and designed to be used by governments and policy developers. This work can help identify existing advantages as well as conditions and requirements necessary to successfully provide access to the infrastructures and technologies required for successful CCUS development. Although each of the industrial clusters has identified specific development and research needs, they are all centered around developing full-chain CCUS projects and have allowed for learnings to be defined relevant to all future CCUS hub and cluster developments

2.6. WP6: Implementing CCUS in Society

The overall objectives of WP6 involved the reduction of non-technical risk for CCUS implementation by:

- Assessing public and stakeholder perception about CCUS, specifically towards industrial CCUS and CO_2 utilisation projects;
- Developing theory-based, evidence-based communication and compensation strategies that instigate trust and have a positive effect on societal acceptance of CCUS.

Overall, the WP6 results obtained provide insights in narratives and arguments used in the media, relevant stakeholders and their perceptions, and determinants of public opinion – this will help in making site selection decisions and developing effective public engagement strategies. Moreover, the WP6 research provides a set of lessons and knowledge gaps for community engagement and compensation in the context of CCS. These findings can provide a useful tool for researchers in this field looking to close knowledge gaps as well as stakeholders (e.g., project developers; authorities; community engagement managers) wanting to understand how to effectively make use of community engagement and community compensation in the CCS context.

Public opinion of industrial CCUS and relevant underlying explanatory variables have been examined by means of an informed polling survey conducted among citizens in the UK and the Netherlands (N = 1961). The information provided in the survey was drafted and revised by very helpful feedback obtained through an expert consultation round with ALIGN-CCUS partners and external experts.

The results of the survey show that citizens in the UK and the Netherlands have moderate awareness and limited knowledge about industrial CCS. After receiving extensive information about the topic, citizens' opinions about industrial CCS on average were found to be neutral to slightly positive. Awareness and knowledge were found to be somewhat higher in the UK than in the Netherlands, and opinions about industrial CCS were found to be somewhat more positive in the UK than in the Netherlands.

Community engagement and community compensation are important instruments to build trust relationships and foster public support for planned and future industrial CC(U)S projects. The main aim of this part of the work was to identify and understand success factors and pitfalls in community engagement and community compensation for CCS projects and to identify and close relevant knowledge gaps. A three-step approach was used to reach this aim, using a mixed-methods approach. The results of the studies show substantial overlap in relative preferences for community compensation measures among citizens in the Netherlands, the UK, and Romania, but also relevant differences between countries when it comes to CCS acceptability and the evaluation of compensation measures.

In Work Package 6 it was also investigated how to change the conversation about CCUS in Europe. Stakeholder perceptions of CCUS in Germany and Romania were examined by means of desk research and 32 semi-structured interviews conducted in Germany and Romania. The results show that in Germany, the stakeholders interviewed support CCU, especially for heavy industries, but are negative towards CCS. In Romania, by contrast, the stakeholders interviewed support both CCU and CCS, but CCS was considered more feasible and important for coal-fired power plants. In both countries the stakeholder interviewed expressed concern about the high cost of implementation of CCS and unclear political support. Stakeholders in both countries further indicated that CCUS acceptance-building measures among the public are important.

Furthermore, a literature review, media analyses (in Germany, the Netherlands, and Romania) and website analyses (in Germany, the Netherlands, the UK, and Romania) were conducted to identify current and past conversation about CCUS in society. The results of the media and website analyses show that coverage levels and type of discourse differ between the four countries. The results also show that similar arguments are used for and against CCS. For example, proponents state that CCS is a sustainable and proven technology, whereas opponents present CCS as not sustainable and unproven. This potentially makes it difficult for the public to form an opinion about an already complex subject. In this study, also four potential CCS messages were tested, and found that what was key for the focus group participants was that messages are clear, accessible, and appeal to citizens' personal interests.

3. Project impact of ALIGN-CCUS in the participating countries

Already before the end of ALIGN-CCUS, the (intermediate) results were used in follow up projects in the participating counties, showing that the project really met the ACT goal of accelerating the implementation of CCUS in Europe and globally. Now that the results of the project are accessible for the wider audience, the project impact will be further increased. In the next paragraphs, the impact in the participating countries in ALIGN-CCUS is given.

3.1. The Netherlands

In the Netherlands, CCUS is focused on the Waste to Energy (W2E) sector and the storage activities around the North Sea area.

The WtE sector is investing a lot into CO_2 capture. With AVR having the first full scale CO_2 capture project running in Europe and Twence linking up with Aker Solutions to build a full-scale plant, the sector is in the frontline of implementing CO_2 capture in Europe. Also HVC has a capture pilot plant and is looking at scaling up. Many others have expressed their interest in capturing CO_2. In the Netherlands there is quite a unique situation that the greenhouses have a demand for CO_2 to increase plant growth. Multiple projects are supplying CO2 to the greenhouses which prevents that greenhouses make their own CO_2 by burning fossil fuels.

Also, for CO_2 storage there are projects being developed in the Netherlands. The two most important being: Porthos (https://www.porthosco2.nl/) and Athos (https://www. athosccus.nl). Porthos is preparing a project to transport CO_2 from industry in the Port of Rotterdam and store this in empty gas fields beneath the North Sea. Porthos stands for Port of Rotterdam CO_2 Transport Hub and Offshore Storage. The Athos project aims to develop a public CO_2-distribution network in the North Sea Canal area, enabling the capture and transport of CO_2, for usage or to be stored in empty gas fields under the North Sea. Athos is an abbreviation for Amsterdam-IJmuiden CO_2 Transport Hub & Offshore Storage. Companies in the respective clusters can use the network to store their captured CO_2.

In ALIGN-CCUS important work was done to support the development of these two projects. Recently, the European Commission has nominated Porthos and Athos for a subsidy of respectively 102 and about 15 million euro for further development.

The Dutch initiative VOLTACHEM (https://www.voltachem.com/) is developing technologies to utilise CO_2 for the production of renewable fuels and chemicals like formic acid. A consortium led by TNO has recently won a H2020 project named TAKE OFF, with the aim to develop synthetic fuels for the aviation industry. Some of the project partners now active in WP4 of ALIGN-CCUS have an important role in that project.

3.2. Norway

The Norwegian partners have been involved in all WPs except for WP4, which is symptomatic for the focus in Norway being more towards CCS than CCU solutions. However, it may change in the future as utilization may become an alternative or combined with storage to make it more attractive for economic reasons. Nevertheless, the work has been very important in many respects and will hopefully get a longer-term impact through near term utilisation of the results. For the research institutes from Norway the knowledge gained in dynamic operation and online measurements (WP1) is mostly taken further in follow up projects like LAUNCH (ACT), NCCS and REALISE (H2020) as well as in a new project initiative aimed at being funded by ACT3 (lead by SINTEF). Important lessons learned were in the CO_2 transport (WP2). The findings have been further followed up through the CO2LOS II project ending in 2020, and to be taken further in a CO2LOS III project that is under preparation. The results have also been used as input for an ACT3 application with TNO as lead. Regarding Storage, the Norwegian partners in ALIGN-CCUS have outlined and discussed possibilities for a large CO_2 storage hub in the region around the Northern Lights storage site. This Horda Platform CO_2 storage hub could likely serve a significant fraction of the storage needs for Scandinavia and Northern Europe. The concept is already being further developed in ongoing work in NCCS. Acquired knowledge from the

ALIGN-CCUS project has already been used in the ACT2 REX-CO2 project and a proposal with wide industry support, recently submitted to the ACT3 call. For the Longship project, the approach taken in ALIGN-CCUS has proven useful. Locally the cluster, in cooperation with SINTEF, is developing a project application to CLIMIT for how to capture and transport all the CO_2 in the region from a common hub. The tool Bellona has developed in ALIGN-CCUS to follow when evaluating individual pathways to deploying CCUS is expected to play an important part in Bellona's future engagement on developing CCU and CCS projects across Europe. A first instance for application is likely to be the 'Building momentum for the long-term CCS deployment in the CEE region' project, financed through the EEA Norway Grants. Also, the research conducted in WP6 has provided valuable information about the perceived role and necessity for CCUS. As such, it will provide valuable background for the development of the messaging intended for those same stakeholders in the future. For IFE the ALIGN-CCUS findings initiated more testing in the KDC III project and are presently used in the design and construction of a new ECCSEL infrastructure for testing, amongst other, ship transport conditions. For TCM the knowledge and competence gained through ALIGN-CCUS is the cornerstone in their advisory activities. Building on the knowledge gained from the ALIGN-CCUS project, TCM aims to test different flue gas sources and under operating conditions that are of value for the industry in order to reach their climate goals. Some projects have already performed specific tests at TCM to answer industry specific questions. The USN Raman solvent monitoring tool was demonstrated for 540 operating hours at pilot scale operation conducted by the Pilot-scale Advanced CO_2 Capture Technology (PACT) facilities, UK, in ALIGN-CCUS. The USN Raman tool was upgraded for determination of CO_2 loading, amine strength and monitoring of oxidative degradation products (heat stable salts). This upgrade was successful despite the rapid and progressive solvent colour change of MEA (from transparent to dark brown). Both NORCEM and Yara will utilize the results from ALIGN-CCUS in further work with CCS and a hub in Grenland for collecting captured CO_2 from many of the industrial plants in the Grenland area may be realized through future projects.

3.3. Germany

Especially the demonstration of the technical feasibility of the full CCU chain and the results of ALIGN-CCUS attracted a lot of attention at German stakeholders. Especially the delivered facts about the potential of synthetic fuels - which are produced from CO_2 - 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.

The industrial partners of ALIGN-CCUS are strongly involved in further projects on Power-to-X technologies and in the field of synthetic fuels. 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. All partners are involved in follow up-projects of ALIGN-CCUS, like the EU-funded project TAKE-OFF on jet fuel production (using the ALIGN-CCUS demonstrator) and national funded projects on the use of the synthetic fuel DME in fuel blends (DMEplusX) and concept studies for large-scale Power-to-X plants.

3.4. United Kingdom

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 reformation of hydrogen and CCS in the UK during the ALIGN-CCUS project. ALIGN-CCUS proposed 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 CO_2 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 CO_2 storage by the Net Zero Teesside Project via TVCA and the H21 North of England Project from Equinor. Project results have been presented, at stakeholder request, to the Climate Change Committee and Oil and Gas Authority.

The Storage Readiness Levels terminology is already in informal use, as noted at the CO_2 storage plenary presentation by industry at the Mission Innovation meeting June 2019 in Trondheim. A journal paper presented from the finalised ALIGN-CCUS deliverable was submitted to International Journal of Greenhouse Gas Control. Revision of the submission in response to reviewer's comments is approaching completion. An abstract on the finalised SRLs framework was submitted and accepted for oral presentation at the GHGT-15 conference in March 2021.

Early research findings on the investigation of the suitability of offshore infrastructure, development of a methodology for screening for use and recommendations on data types and availability were submitted to Oil and Gas Authority in September 2019. There has been stakeholder interest from industry (Net Zero Teesside) and regulator (The Crown Estate) in the modelling of 'next stores' for the UK ALIGN-CCUS clusters, and further strategic modelling to assess CO_2 storage for the Teesside and Humberside industrial clusters included in research proposals. 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 CO_2 injection. Equinor joined the ALIGN-CCUS project as a supporting partner in 2019 specifically to contribute to and access the findings of the CO_2 storage assessment for Teesside to inform their work for H21 North of England.

Emerging findings from the business case and sharing of risks and liabilities considered in the ALIGN-CCUS UK case studies were submitted to BEIS in their consultation on CCUS business models in September 2019. The finalised results have been of interest and presented to industry, National Grid, and presented to the Cabinet Office in 2020.

3.5. Romania

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 making a priority from the 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 skeptical with regard to the future perspectives of CCUS in Romania.

However, the experimental survey findings among citizens in Romania proved that the Romanian respondents presented a higher level of acceptability for CCUS implementation in comparison with the respondents from other countries. Also, the focus group results showed that the implementation of CCUS projects could be accepted by publics if clear and honest information is delivered in a proactive manner.

Acknowledgements

ACT ALIGN-CCUS Project No 271501

This project has received funding from RVO (NL), FZJ/PtJ (DE), Gassnova (NO), UEFISCDI (RO), BEIS (UK) and is co-funded by the European Commission under the Horizon 2020 programme ACT, Grant Agreement No 691712. More information can be found on: www.alignccus.eu