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# ACTiON ERA-NET ACT project: Advanced multitemporal modelling and optimisation of $CO_2$ transport, utilisation and storage networks

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## Abstract

ACTiON (Advanced multitemporal modelling and optimisation of $CO_2$ Transport, Utilisation and stOrage Networks) is a project from the ACT3 programme with its main objective to establish how an efficient infrastructure, connecting $CO_2$ sources with $CO_2$ geological storage and non-geological utilisation options, can be developed as part of regional decarbonisation efforts. To achieve this, ACTiON aims to research and develop a multi-temporal integrated assessment model that will support stakeholders in the planning and design of large-scale, flexible $CO_2$ transport, utilisation and storage networks, and enable reporting on decarbonisation efforts. Besides addressing geological and engineering constraints, the project will also address the impact of economic conditions and regulatory environment, as well as the unavoidable uncertainties in defining them.

*Keywords:* $CO_2$ transport, $CO_2$ storage, $CO_2$ infrastructure development; risk assessment, strategic decarbonisation

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## 1. Introduction

The main objective of ACTiON is to establish how an efficient infrastructure, connecting $CO_2$ sources with $CO_2$ geological storage and non-geological utilisation options, can be developed as part of regional decarbonisation efforts. To achieve this objective, ACTiON aims to research and develop a multitemporal integrated assessment model that will support stakeholders in the planning and design of large-scale, flexible $CO_2$ transport, utilisation and storage networks, and enable reporting on decarbonisation efforts. The work carried out addresses geological and engineering constraints, the impact of economic conditions and regulatory environment, as well as the unavoidable uncertainties in defining them.

The term ‘multitemporal’ refers to three different time scales:

- short term (hours/days): required for safe and efficient network operability and to enable efficient $CO_2$ utilisation options function;
- medium term (years/several years): related to dynamic storage capacity and the function of large-scale transport and storage network, connecting $CO_2$ supply to multiple storage and utilisation sites;
- long term (several decades): horizon planning to meet decarbonisation targets.

The rationale behind these aims is that large-scale implementation of CCUS requires the availability and flexible utilisation of a transport and storage network that can handle varying $CO_2$ supply rates from different sources. Such a network must provide flexibility in available transport, storage and utilisation capacity to be able to handle the supply of captured $CO_2$, avoiding potential high emission costs of venting.

Moreover, a thorough understanding of the impact of both steady-state and transient flow phenomena on its design and operation is essential to de-risk the integrated operation by building in flexibility and resilience in response to operational changes in different parts of the chain.

Specifically, from the network operator’s viewpoint, seeking to utilise the most cost-efficient sites, the overall cost of storing or the benefit of utilising a contracted amount of $CO_2$ is relevant and needs to be considered in a dynamic, time dependent framework that respects complex engineering, economic and regulatory constraints. At a higher level, the strategic decarbonisation point of view, it is important to be able to determine decarbonisation performance at operation and cluster level (annual resolution, multiyear, planning horizon) that may be used to verify $CO_2$ credits, use this for $CO_2$ accounting and reporting and have the means to devise stage-gates and communicate progress towards the longer term decarbonisation agenda of the industry operators and regional clusters, many of which have ambitious 2050 targets. All stakeholders, industry and regulators, need clear insights regarding the impact of uncertainties of subsurface characteristics, engineering systems and processes, economic developments, as well as potential unexpected changes in $CO_2$ supply affecting the deployment and costs of CCUS, to be able to make timely and robust investment and operational decisions.

Until today, such assessments have been considered separately within a site-specific evaluation framework for individual storage sites, and a few utilisation options, implementing detailed geological site characterisation, engineering design and modelling studies, also including uncertainty considerations, as part of many national and international research projects. More recent efforts (e.g. ERANet ACT ALIGN CCUS and ELEGANCY projects and the SimCCS tool developed in the US) have focused on source – sink matching in the long-term planning horizon, considering distances and the means of transport (lorries, shipping, pipelines) in relation to costs. However, none of these programmes have considered in an integrated framework, the network operability issues, the multitemporal dimension and the strategic decarbonisation aspects of the challenges that need to be addressed for the successful deployment of large-scale CCS networks.

In ACTiON, we aim to demonstrate the interplay between such issues by combining them into integrated component models for optimisation of capture, transport, utilisation and storage networks to support stakeholders in large scale CCUS deployment. Complex subsurface and engineering features and processes, such as geological flow barriers, geomechanical constraints and well performance, will be implemented as modular computationally independent proxy models to provide the building blocks for integrated models. Similar resolution proxy models will be developed for capture, conversion and utilisation options to provide fine scale temporal resolution for expected and required $CO_2$ supply, energy, other important resources to be consumed and produced (e.g. biomass, $H_2$, syngas, chemicals).

ACTiON is considering networks that link multiple suppliers of $CO_2$ to multiple injection wells and storage locations. Including depleted fields, saline aquifers and EOR in the study, ACTiON aims to provide the building blocks and workflows for network developers, as basis for efficient design and safe operations. The multitemporal modelling tool that will be produced will support national governments, by clarifying the required network investments over the coming decades. In addition, may prove useful in an assessment of the value of specific assets (e.g., platforms or depleted fields) as a future $CO_2$ infrastructure. Such information will be invaluable when decisions around abandonment or safekeeping are to be made. With the life cycle assessment and life cycle costing work to be conducted at unit process resolution, it will be possible to derive marginal abatement curves for decarbonisation, and decarbonisation trajectories, which are very valuable for industry when they devise stage gates in their decarbonisation efforts.

The multitemporal modelling capabilities to be developed will be applied to a number of case studies, that cover the approaches to CCUS network development in different EU Member States, the US and Canada. Pipeline and ship transport will be included, as will be networks of different complexity aiming to support the development of fit-for-purpose, future-proof $CO_2$ transport, utilisation and storage networks..

## 2. Project structure

The project is structured under five research work packages and a project coordination and management work package Fig 1.

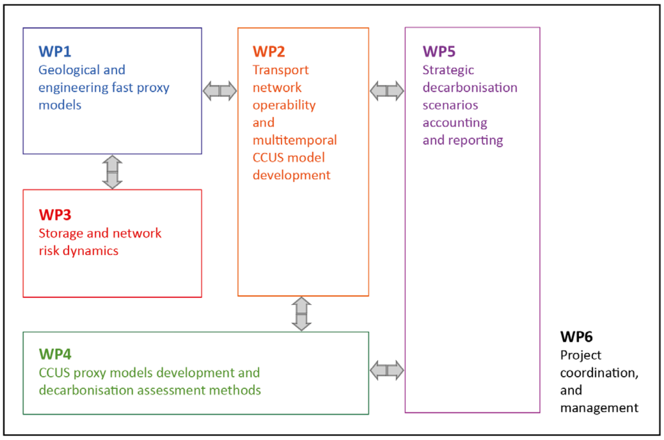


Fig. 1. Overal project concept and structure.

WP1, geological and engineering fast proxy models, will focus on the dynamic behaviour of subsurface storage systems (saline aquifers, depleted gas fields and $CO_2$-EOR in reservoirs) for various $CO_2$ injection scenarios. The main objective is to develop fast proxy models to provide relevant dynamic feedback at appropriate temporal scales to surface network configuration scenarios. WP2, transport network operability and multitemporal CCUS model development, will build proxy models to support the design and management of $CO_2$ transport networks (pipelines and shipping) linking a multitude of $CO_2$ emitters to $CO_2$ users and storage reservoirs. This will support planning at the scale of days to weeks. This WP will also develop integrated multitemporal model templates for pipeline systems and batchwise transport options to consider the short-term statistical response of the combined proxy models. The focus of the work is the development of an integrated model for capture, transport, utilisation and storage networks spanning the different temporal scales and expanding to the long-term planning horizon including the uncertainty that is associated with the processes involved within the market, economic and regulatory environment the system operates.

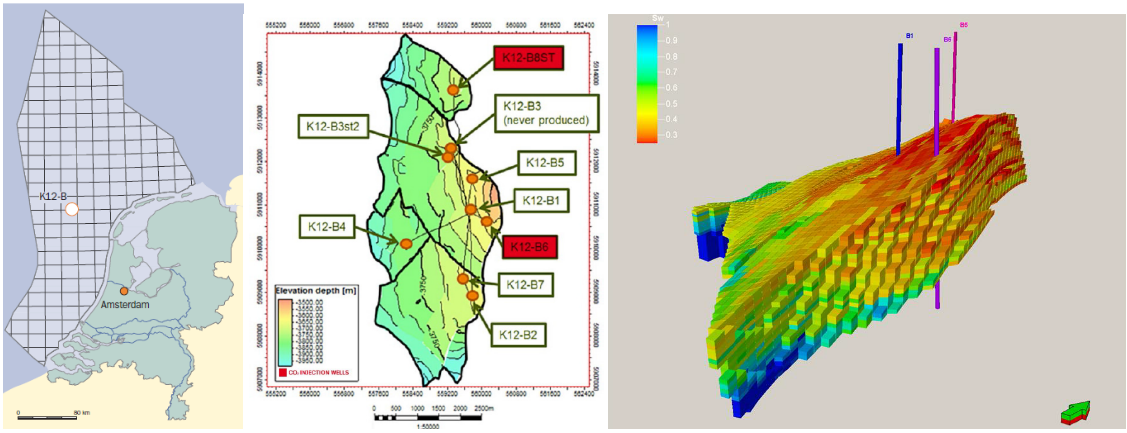
WP3, storage and network risk dynamics, will aim to characterise the integrated storage and network risk dynamics. This will be achieved through the implementation of modelling and through risk assessments at hub and inter-hub level, addressing the inherent geological variability and uncertainties associated with the subsurface and its response to temporally variable demands on storage capacity. Project tasks within WP3 are structured to enable to track the risks associated with the dynamic changes in the network and subsurface storage systems. Performance indicators, acting as system controls or constraints, will be established based on these risks and used to regulate the proxy models in WP1. WP4, CCUS proxy models development and decarbonisation assessment methods, will develop proxy models for $CO_2$ utilisation and conversion technologies that are likely to be part of future CCUS systems. Parameterised for the CCUS network systems in ACTiON, the proxy models will provide conversion and utilisation metrics with a temporal variability, which will be used as input in the strategic decarbonisation modelling to be carried out in WP5. The second objective is to convert the new process models to Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) models which will be used for the decarbonisation accounting and reporting in WP5. Finally, the consequential LCA (C-LCA) methodology will be tailored for implementation in environmental consequences assessment.

WP5, strategic decarbonisation scenarios accounting and reporting is dedicated to advancing the strategic decarbonisation of CCUS in six industrial regions across EU member states, the UK, the US and Canada/Alberta Region. Each of the regions has identified specific development and research needs, centred around developing full-chain CCUS projects. WP5 is dedicated to the tailored implementation of the multitemporal CCUS network modelling tools developed in ACTiON with the purpose to assess strategic decarbonisation scenarios relevant for each region and to provide the means for GHG emissions reductions accounting and reporting at operation, cluster/regional, national and international level.

## 3. Case histories and future CCUS network scenarios

One of the main objectives of ACTiON is to develop computationally efficient proxy models that capture static geological reservoir characteristics and dynamic reservoir responses for various $CO_2$ injection scenarios such as saline aquifers, depleted reservoirs and EOR applications. These models are being configured to capture storage reservoir type, geological flow barriers, storage system integrity (well, fault, caprock), and injectivity conditions (salt precipitation, $CO_2$ hydrate in near wellbore). In doing so, the consortium partners will draw upon their substantive research experience in $CO_2$ storage research, field case histories developed through work with industrial field pilots, and models developed and validated.

Previously validated reservoir models of a number of sites and the experience gained from long-term research by the project partners will be used in the development of reservoir performance, well/near wellbore and storage system integrity proxy models. These include: the K12-B gas field located in the Dutch sector of the North Sea (Fig. 2), the P-18 depleted gas reservoir in the Dutch Sector; In Salah $CO_2$ Storage Site in the central region of Algeria; the Forties and Nelson Cenozoic System in the UK Sector of the Central North Sea (Fig. 3); the West Paris Basin sandstone aquifers (Fig. 4); the Weyburn-Midale $CO_2$-EOR Site, Saskatchewan (Fig. 5); the Aquistore saline aquifer, Canada (Fig. 6).



(a) (b) (c)

Fig. 2. (a) Location of the K12-B gas field, (b) Compartment structure of the K12-B gas field with the CO2 injection wells in compartments K12-B8ST and K12-B6ST highlighted in red, (c) Dynamic reservoir model of the centre compartment of K12-B, indicating water saturation [1].

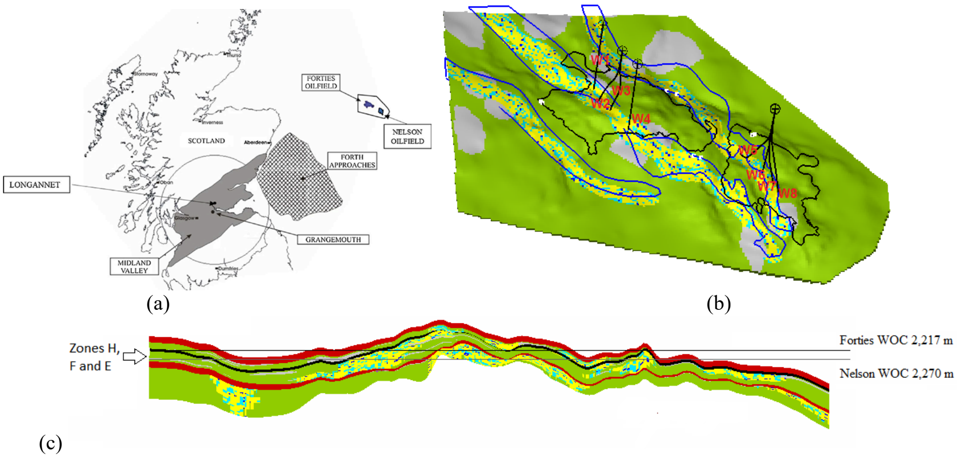


Fig. 3. (a) The geographic location of Forties and Nelson oil fields in the Central North Sea. (b) Facies map used in geological modelling, injection wells indicated by W1 to W4 in Forties and W5 to W8 in Nelson, and flow line polygons indicated by blue lines. (c) Cross sectional view of the Forties Field structural closure and facies distribution. [2-4].

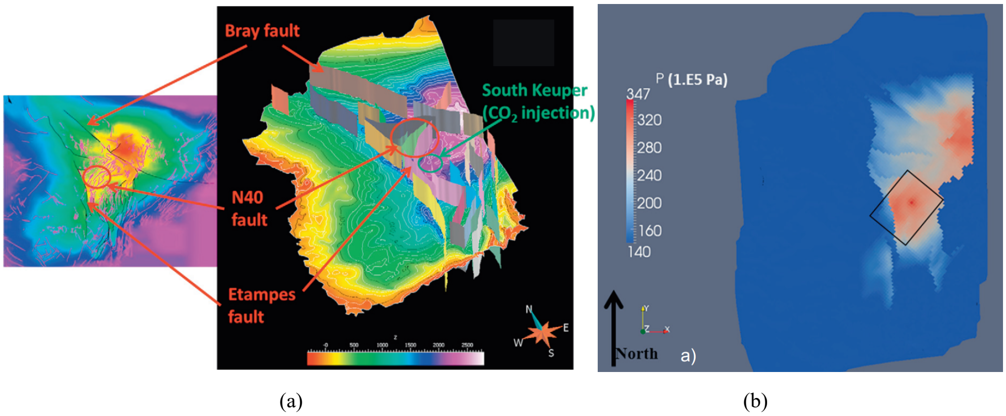


Fig. 4. Structural map showing faults and the Triassic top layer of the Paris Basin, (b) Basin scale simulated pressure map in 50 years [5]).

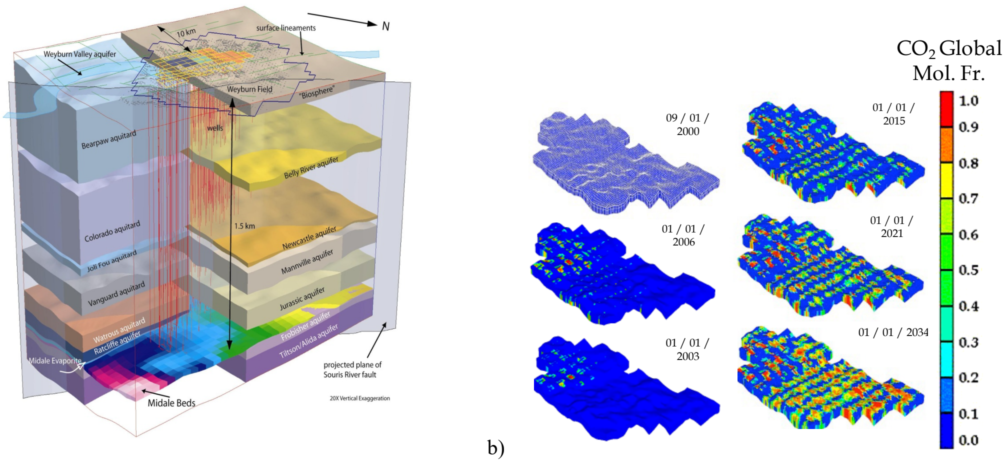
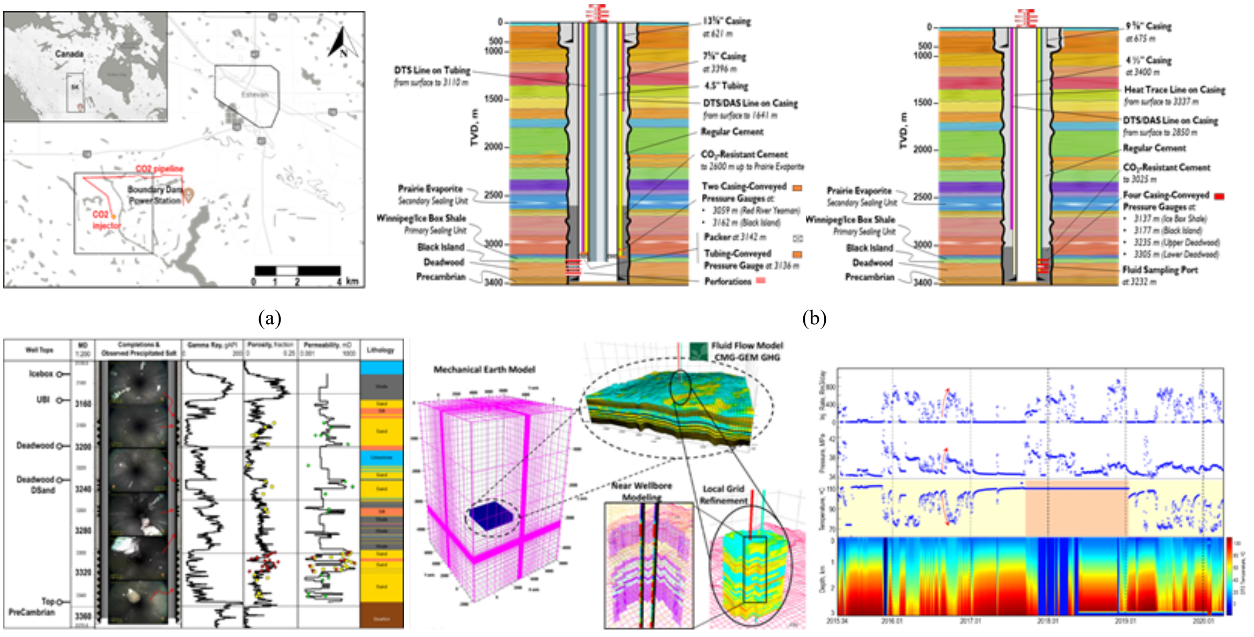


Fig. 5. Geological units of Weyburn-Midale $CO_2$ geological storage case study; and c) 75 Pattern reservoir simulation from Weyburn-Midale Monitoring and Storage Project [6]).



(a) (b)

(c) (d) (e)

Fig. 6. (a) Map of the Aquistore storage site with the locations of the Boundary Dam Power Station, CO2 pipeline and CO2 injection well, schematic of (b) the injection and observation wells, and some of the monitoring components installed, (c) overview of the aquifer petrophysical properties. (d) Representation of 3D mechanical earth model, the full geological model in CMG-GEM, and local grid refinements for the near-wellbore region (e) 5 years of the Aquistore injection history [7-9]).

Future CCUS network scenarios currently being planned in the ACT countries will be explored and used in WP5 to implement the multitemporal CCUS network modelling tools developed in ACTiON and provide the means for GHG emissions reductions accounting and reporting at operation, cluster/regional, national and international level. These include the Porthos and Aramis capture, transport, utilization and storage networks in the Netherlands, the Net Zero Teesside (NTZ) and Northern Endurance (NEP) and East $CO_2$ast clusters and the South Wales Industry Cluster in the UK, Longship/Northern Lights CCS case study, the Dunkirk-North Sea CCS cluster, Getica CCS in Romania, the Western Canada Region/Alberta Carbon Trunk Line (ACTL) system all of which include different CO2 capture, transport and storage options; and the Southwest region of US including the four states of Utah, Colorado, New Mexico and Arizona favourable for non-geological $CO_2$ utilisation technologies, including biological conversion, chemical conversion and $CO_2$ mineralisation.

In all regions, efforts aiming to advance strategic decarbonisation are centred around developing full-chain CCUS projects. Learnings from the strategic decarbonisation scenarios accounting and reporting to be carried out in ACTiON will be presented in an industry and government stakeholders' workshop to gain wider views and amplify the communication of the project results. A publishable report that will be open access will report on the outcomes and conclusions of the workshop.

## 4. CCUS network modelling methods

Current $CO_2$ or CCS network models approach network operation or network development with a relatively simple representation of the processes involved in the flow of $CO_2$ through pipelines and wells and in the injection into the subsurface reservoirs. Results from such models, and examples are found in the reports from the recent ERA-NET ACT ALIGN-CCUS project [10-13] and provide useful information about the size and scale of CCS networks that will be needed for CCUS to play its role as a GHG emissions reduction measure, as well as about the timeline of investments to realise these networks.

Several of the currently ongoing activities in Europe - to construct the first elements of what will likely become a large-scale, internationally connected CCUS network - are considering using depleted fields for storage. These fields are often at low or even very low pressure after production, which has significant impact on the injection procedures. Earlier work [14] sketches the implications for network design and network operation: the choice between injecting the $CO_2$ in liquid or gas phase strongly affects feasible injection rates and, hence, aspects such as the number of injection wells and the timing of activities related to network expansion. Such aspects are currently not included in current CCUS network models. Reservoir properties the operability (the 'operational window') of wells in depleted fields is also, among other factors, determined. In cases of injection of $CO_2$ in liquid phase, wells can have significant minimum flow rates, limiting flexibility and operational freedom of the network operator. Such well behaviour is a key element of an assessment of the operational 'risk state' of a network. Operators that are considering the use of depleted fields for $CO_2$ storage recognise the need for a network model that is capable of simulating relatively complex systems, with many reservoirs, wells, platforms (offshore) or sites (onshore), taking into account as closely as possible relevant processes throughout the system to support storage site selection and network concept choice. Such network tools do not exist yet and are being build in ACTiON.

For natural gas pipelines, nodal analysis based on pressure drop is enough to evaluate system performance. However, $CO_2$ injection in depleted fields causes the conditions downstream of the choke to be often in two-phase flow regime causing flashing across the valve and the pressure and temperature across the valve to be discontinuous. Heat transfer in the well and choke needs to be considered because well head temperature is key to processes that cause large fluctuations of fluid properties in the well and near wellbore reservoir area that affect injectivity. For $CO_2$ -rich compositions, classic descriptions of pressure-temperature do not work well, therefore a Pressure-Enthalpy formulation is necessary. To be able to analyse a large number of storage scenarios - as would be needed to assess the response of a network operator to changes in the supply of $CO_2$, pipeline flow, well flow, and reservoir inflow - simulations must be evaluated fast, requiring the development of proxy models that replace detailed, first-principles simulators such as OLGA (for $CO_2$ flow through pipes) or GEM ($CO_2$ flow in reservoirs).

Carbon capture, use and storage implementation involves a complex chain of elements; namely, power generation or industrial processes, $CO_2$ capture, $CO_2$ transportation and $CO_2$ storage. Therefore, investment decisions by potential stakeholders are subject to a wide range of risks and uncertainties. Therefore, it is highly desirable to develop an investment decision framework, in which these uncertainties and engineering flexibilities are appraised, optimised and factored into the investment decisions, so that investors or regulators can confidently identify CCUS investment options (including incentives) which may trigger CCUS project implementation.

In recent years, CCS network design methods have become more sophisticated with multi-period network optimisation models based on mixed-integer linear programming algorithm. The real options framework presented in authors' previous work seamlessly integrates the real options methodology and the multi-period optimisation solution, with the real options value generated based on stochastic multi-period optimisation. The ACTiON team has illustrated its functionality through four case studies set in the Netherlands around the Rotterdam cluster, UK (Teesside and Grangemouth), and Norway (Grenland and Northern Lights cluster). Moreover, the ACTiON project team has considered options of transporting $CO_2$ by vessels. Offloading at an onshore terminal and transporting by pipeline to the offshore storage site is often identified as the preferred solution. When comparing the costs of pipelines and vessels, investment cost (CAPEX) is the main cost driver for pipelines, while for ships, the cost drivers are operational. Cost estimation methods combined with Aspen simulations have also shown that for shorter distances combined with large volumes, pipeline transport is less costly, while for longer distances and smaller volumes, ships are favourable. The use of maritime vessels for $CO_2$ transport can also be more suitable for enhanced oil recovery activities, whereby the $CO_2$ demand is limited or uncertain, and investment in a pipeline entails too much risk. Despite these benefits, the optimum conditions in which $CO_2$ should be transported by ship are debated. The Norwegian feasibility study and other authors suggested medium pressure conditions as optimal. These conditions are a proven technology and used for commercial $CO_2$ transport. Other recent studies , however, favour lower pressure. Thus, a key technological challenge is to determine which conditions for CO2 transport on a ship/vessel are preferable for offshore offloading, namely medium pressure, ~15 bar at -25˚C to -28˚C or low pressure, near the triple point at ~7 bar and -50˚C.

A Multi-Agent System (MAS) based optimisation approach is introduced for the very first time in the context of CCUS in the ACTiON project and is being used to devise the multitemporal multiagent network model. MAS can be defined as a loosely coupled network of heterogeneous, autonomous, and intelligent problem solvers (also called agents) that interact to solve common problems that are outside the individual competencies or knowledge of each of them. The characteristics of a MAS are that: (a) each agent has imperfect information or capabilities for solving the problem and, therefore, has a limited and partial perspective; (b) each agent acts based on a set of rules, reacting upon factors coming from outside; (c) there is no global control; (d) data are decentralised; and (e) computation is asynchronous. Multi-agent systems are ideal for problems that require multiple problem solving methods, multiple perspectives and/or multiple problem solving entities. In recent years, MAS has been employed to modelling energy system investment, energy system transition, energy system fuel switching etc. No literature has applied MAS on CCS network optimization and the aim is to introduce the first results in the second year of the ACTiON project.

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## References

[1] Vandeweijer V., Hofstee C., Graven H., 2018. 13 Years of Safe CO2 Injection At K12-B. Proc. Fifth CO2 Geological Storage Workshop, EAGE, 21-23 November, Utrecht, The Netherlands.

[2] Santibanez-Borda E, Govindan R, Elahi N, Korre A, Durucan Set al., Maximising the dynamic CO2 storage capacity through the optimisation of CO2 injection and brine production rates, 2019, International Journal of Greenhouse Gas Control, Vol: 80, Pages: 76-95, ISSN: 1750-5836.

[3] Babaei M, Pan I, Korre A, Shi J-Q, Govindan R, Durucan S, Quinn M., $CO_2$ storage well rate optimisation in the Forties sandstone of the Forties and Nelson reservoirs using evolutionary algorithms and upscaled geological models, International Journal of Greenhouse Gas Control, 2016, Vol:50, ISSN:1750-5836, Pages:1-13.

[4] Babaei M, Govindan R, Korre A, Shi J-Q, Durucan S, Quinn M. Calculation of pressure- and migration-constrained dynamic CO2 storage capacity of the North Sea Forties and Nelson dome structures. International Journal of Greenhouse Gas Control. 2016; Vol:53:127-40.

[5] Estublier A., Fornel A., Brosse E., Houel P., Lecomte J-C., Delmas J., Vincké O., 2017. Simulation of a potential $CO_2$ storage in the West Paris Basin: Site characterization and assessment of the long-term hydrodynamical and geochemical impacts induced by the $CO_2$ injection, Oil & Gas Science and Technology – Rev. IFP Energies Nouvelles, 72, 22.

[6] IEA Greenhouse Gas R&D Programme (2012) Best Practices for Validating $CO_2$ Geological Storage: Observations and Guidance from the IEAGHG Weyburn-Midale $CO_2$ Monitoring Project, Geoscience Publishing, 353 pages.

[7] Rostron, B., White, D. Hawkes, C., Chalaturnyk, R.J. (2014) Characterization of the Aquistore $CO_2$ project storage site, Saskatchewan, Canada, Energy Procedia, 63: 2977-2984. https://doi.org/10.1016/j.egypro.2014.11.320.

[8] White, D., Hawkes, C., Rostron, B., 2016. Geological characterization of the Aquistore $CO_2$ storage site from 3D seismic data. Int. J. Greenh. Gas Control 54 (1), 330–344. https://doi.org/10.1016/j.ijggc.2016.10.001.

[9] Roach, L.A.N., White, D.J., 2018. Evolution of a deep $CO_2$ plume from time-lapse seismic imaging at the Aquistore storage site, Saskatchewan, Canada. Int. J. Greenh. Gas Control 74, 79-86. https://doi.org/10.1016/j.ijggc.2018.04.025.

[10] Shchipanov A., Kollbotn L., Berenblyum R. Pressure Transient Analysis in $CO_2$ Storage Projects: from Reservoir Characterization to Injection Performance Forecast // 77th EAGE Conference & Exhibition, June 1-4, 2015, Madrid, Spain.

[11] Fraga D.M., Korre A., Nie Z., Durucan S. Multi-period cost optimisation of multi-mode carbon capture and storage chains. GHGT-15, March 2015.

[12] Skagestad R. , Fraga D.M., Eldrup N.H.,Haugen H.A., Korre A., Nie Z., Durucan S., Design of a Multi-user Intermediate Storage Facility in the Grenland Region of Norway. GHGT-15, March 2015.

[13] Nie Z., Korre A., Durucan S., Fraga D.M., Mikunda T., Neele F., $CO_2$ pipeline transport and storage network cost modelling and multi-period multi-scenario stochastic optimisation. GHGT-15, March 2015

[14] Belfroid, S., Koenen, M., Kreft, E., Huijskes, T., Neele, F., CCS in Depleted Gas Fields in the North Sea: Network Analysis, GHGT-15, Abu Dhabi, 2021.

[15] Middleton, R.S., M.J. Kuby, R. Wei, et al., 2012, A dynamic model for optimally phasing in CO2 capture and storage infrastructure. Environmental Modelling & Software, Volume 37:p.193-205.

[16] Elahi, N., 2015, Multi-period whole system optimisation of an integrated carbon dioxide capture, transportation and storage supply chain. 2015, Imperial College London. p 192.