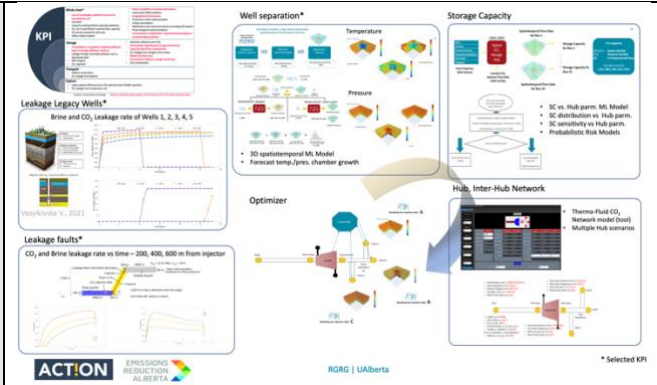


FINAL OUTCOMES REPORT(NON-CONFIDENTIAL)

1.0 PROJECT INFORMATION

1. ERA PROJECT ID #	E0161584
2. CALL / ROUND	Accelerating CCS Technology Round 3 (ACT3)
3. PROJECT TITLE	Advance multitemporal modeling and optimization of CO ₂ transport, utilisation and storage networks– ACTION
4. COMPANY NAME	University of Alberta, Reservoir Geomechanics Research Group [RG] ²
5. PROJECT TYPE (R&D, Development, Demonstration, Implementation)	R&D
6. LOCATION (primary location the project took place by address, land description, or GPS coordinates)	University of Alberta, Edmonton, AB Canada
7. PROJECT START DATE	February 1, 2022
8. PROJECT COMPLETION DATE	April 30, 2025
9. TECHNOLOGY READINESS LEVEL (TRL) AT PROJECT INITIATION	3, 4, and 5
10. TRL AT PROJECT COMPLETION	7 and 8
11. JOBS CREATED	5
12. GHG EMISSIONS REDUCED (Project-level: annual, cumulatively by 2030 and by 2050)	+16 Mtpa by 2030 and 50 Mtpa by 2050
13. TOTAL ERA FUNDING	\$754,416
14. TOTAL PROJECT VALUE	\$1, 886,957
15. ERA PROJECT ADVISOR	Mohammad Chowdhuri
16. SUBMISSION DATE	July 31, 2025
17. KEY PROJECT CONTACT NAME AND EMAIL	Rick Chalaturnyk, rjchalaturnyk@ualberta.ca Gonzalo Zambrano, gonzalo@ualberta.ca
18. QUOTE (why was ERA a pivotal funder for this project? How did ERA funding help advance on the TRL scale? Etc.)	Without ERA’s support, we would not be able to participate in the leading research programs within the ACT initiative. Their contribution enables the synergistic development of emission reduction technologies on a global scale
NOTABLE COMMUNICATIONS	https://x.com/ACTION_ACT3

19. **IMAGE** (please insert or link a photo capturing the technology for ERA publications)



2.0	TABLE OF CONTENTS	
1.0	PROJECT INFORMATION	1
2.0	TABLE OF CONTENTS	3
3.0	LIST OF FIGURES.....	4
4.0	LIST OF TABLES.....	4
5.0	EXECUTIVE SUMMARY	5
6.0	PROJECT DESCRIPTION	7
6.1	INTRODUCTION.....	7
6.2	BACKGROUND OF THE PROJECT	8
6.3	PROJECT OBJECTIVES.....	9
7.0	PROJECT WORK COMPLETED AND OUTCOMES	13
7.1	METHODOLOGY.....	13
7.2	TECHNOLOGY DEVELOPMENT, RESULTS AND ANALYSIS	16
7.2.1	PROXY MODEL DEVELOPMENT	16
7.2.2	IMPLEMENTATION OF MULTI AGENT SYSTEM CCUS.....	18
7.2.3	STRATEGIC DECARBONIZATION CANADIAN CASE.....	20
7.3	PROJECT KEY RESULTS	23
7.4	PROJECT ACHIEVEMENTS	24
8.0	LESSONS LEARNED	25
8.1	CHALLENGES.....	25
8.2	PRACTICAL LEARNINGS.....	25
8.3	ORGANIZATIONAL LEARNINGS.....	25
8.4	HIGHLIGHTS	25
9.0	GHG BENEFITS.....	25
10.0	ENVIRONMENTAL, ECONOMIC, AND SOCIAL IMPACTS	27
10.1	OTHER ENVIRONMENTAL IMPACTS	27
10.2	PROJECTED ECONOMIC IMPACT.....	27
10.3	RESULTED INNOVATION CAPACITY.....	27
10.4	SOCIAL IMPACT	28
11.0	SCIENTIFIC ACHIEVEMENTS.....	28
12.0	OVERALL CONCLUSIONS	29
13.0	LITERATURE REVIEWED	29

3.0 LIST OF FIGURES

Figure 1. Main key developments within ACT!ON - Improved system operability and risk-informed decision-making for CCUS network management	6
Figure 2 CCUS chain from separation to storage/utilization (Tobias da Cruz, et al. 2021)	8
Figure 3 Overall project concept and structure	11
Figure 4 System representation of the proposed Multiagent based optimization tool (ACT!ON Proposal 2022)	14
Figure 5 Multiagent based optimization tool (Xie et al., 2024)	15
Figure 6 Proxy models developed in ACT!ON Project for CO ₂ Capture, Transport, Storage and Utilization	15
Figure 7 Workflow of the modeling and validation process in a typical ML framework. Data and the process are shown side by side (RGRG ERA Milestone 2, 2023)	17
Figure 8 CCUS network planning results for the Teesside area – Derived from ALIGN project (Xie et al., 2024)	19
Figure 9 Daily simulation process of Multi Agent System-CCUS and CO ₂ and information flow (Xie et al., 2024)	19
Figure 10 Teesside CCUS project simulation results: (a) Daily captured emissions of emitters, (b) Daily throughput of pipelines, (c) Daily injection amounts, cumulative amounts and pressures at storage sites (Xie et al., 2024)	20
Figure 11 Alberta Carbon Trunk Line visualization (RGRG ERA Milestone 5, 2025)	21
Figure 12 Alberta CO ₂ Emitters Sources Sectors (https://www.alberta.ca/albertas-greenhouse-gas-emissions-reduction-performance, 2025)	21
Figure 13 Slide bar-based bubble plot visualization of cumulative CO ₂ emission by emitters in Alberta (RGRG ERA Milestone 5, 2025)	22
Figure 14 Alberta storage visualization (RGRG ERA Milestone 5, 2025)	22
Figure 15 Multiperiod network formulation for Alberta scenario (Zhang, 2022)	23
Figure 16. Alberta Plan - Historic GHG Emissions and forecasted by Environment and Climate Change Canada (Government of Alberta, 2023)	26

4.0 LIST OF TABLES

Table 1 Summary of project target metrics and achievements	12
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5.0 EXECUTIVE SUMMARY

The ACT!ON project (Advance Multitemporal Modeling and Optimization of CO₂ Transport, Utilization, and Storage Networks) aimed to develop efficient infrastructure to support regional decarbonization by identifying the most effective ways to connecting CO₂ sources with both geological storage and non-geological utilization pathways, ultimately minimizing the green house gas (GHG) emission from the process. As large-scale deployment of Carbon Capture, Utilization, and Storage (CCUS) becomes critical to achieving long-term climate goals, ACT!ON addressed the urgent need for flexible and resilient CO₂ transport and storage networks that can adapt to varying supply rates and operational conditions, enabling the safe and effective reduction of GHG emissions. This technology aims to reduce GHG emissions (+16 Mtpa by 2030 and 50 Mtpa by 2050 in Alberta) by optimizing the entire CCUS chain, helping stakeholders in planning and designing large-scale flexible CCUS networks and enabling more efficient decarbonization efforts. ACT!ON developed optimization tools will significantly contribute to achieving the Alberta's goal of carbon neutrality by 2050.

As Canada's carbon tax increases and Alberta enforces stricter emissions reductions for major industrial emitters, sectors beyond hydrocarbons are actively exploring carbon capture solutions. ACT!ON's integrated CO₂ supply chain modeling and optimization is critical in this evolving landscape enabling Front-End Engineering Design studies, pilot projects, and market expansion through a system that supports the full value chain: capture, transport, storage, and utilization. ACT!ON's capabilities can be applied across key capture sources such as cement (e.g., Lehigh Cement Plant), chemicals (e.g., Nova Chemicals), oil sands (e.g., SAGD operations), steel (e.g., Stelco/AltaSteel), coal-fired power (e.g., Keephills and Sundance), and emerging direct air capture initiatives in Alberta, BC, and Saskatchewan. On the storage and utilization side, ACT!ON supports enhanced oil recovery (EOR), heavy oil operations in regions like Lloydminster, and novel CO₂ uses such as blue hydrogen, plastics, and advanced concrete production. Additionally, ACT!ON's modeling can integrate and repurpose legacy oil and gas infrastructure, including over 13,000 suspended wells in Alberta and Saskatchewan, and facilitate national CCS network development by connecting existing projects like Aquistore and Weyburn with industrial operations in other provinces.

The key component of ACT!ON is a multitemporal integrated assessment model, capable of simulating short-term (daily operations), medium-term (system evolution), and long-term (climate target alignment) dynamics. This approach helps stakeholders navigate the complex challenges associated with CCUS such as geological constraints, economic variability, regulatory uncertainty, and engineering limitations.

The project integrated modular proxy models that simulate subsurface and engineering processes, including geological flow barriers, geomechanical risks, and well performance. These models formed the building blocks of optimized CCUS networks, linking multiple CO₂ suppliers to various storage sites such as saline aquifers, depleted fields, and EOR operations. The multitemporal modeling capabilities were applied to case studies in the EU, U.S., and Canada, incorporating both pipeline and ship transport systems.

By providing practical design tools and workflows, ACT!ON supports the development of safe, scalable, and future-proof CO₂ infrastructure offering a critical pathway toward meeting regional and global decarbonization goals. Figure 1 presents some of the key developments within ACT!ON.

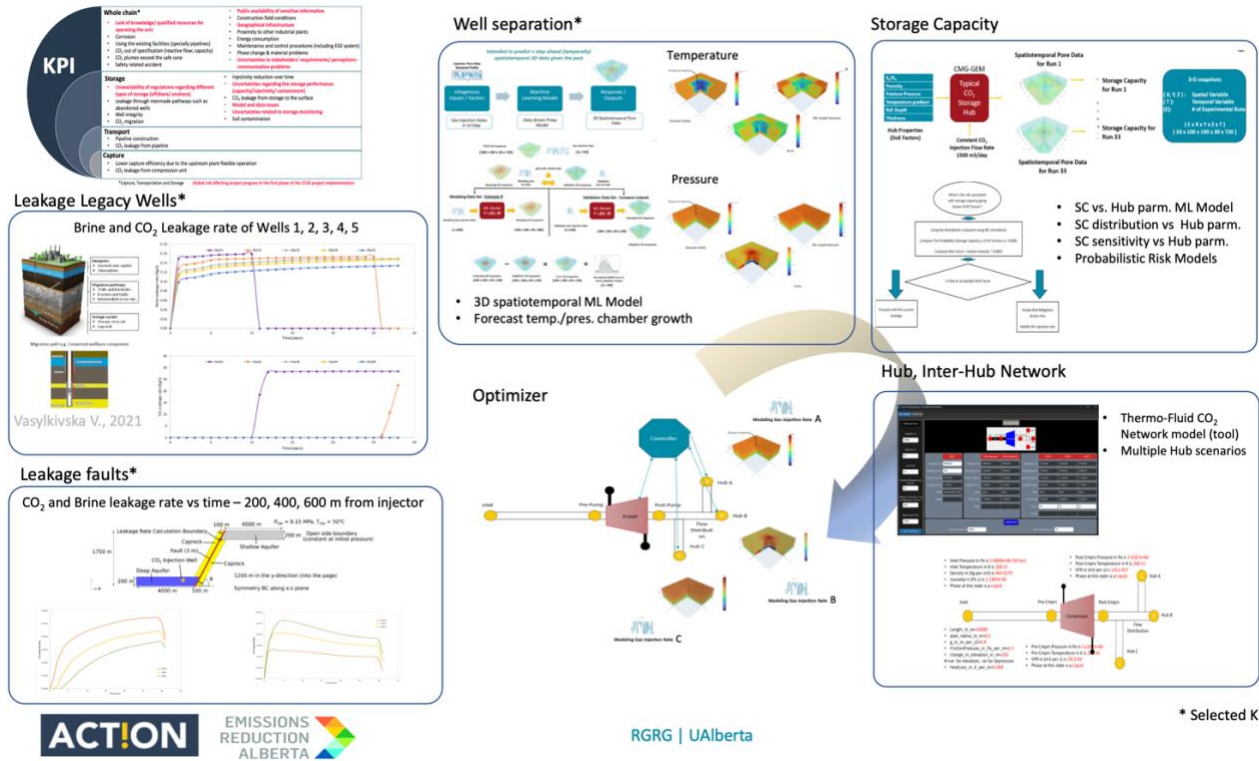


Figure 1. Main key developments within ACTION - Improved system operability and risk-informed decision-making for CCUS network management

6.0 PROJECT DESCRIPTION

6.1 INTRODUCTION

Anthropogenic CO₂ emissions, arising from daily human activities such as power generation, transportation, chemical production, industrial processes, oil and gas production, and agriculture, are significantly contributing to the rising atmospheric levels of carbon dioxide (CO₂). At the same time, the relentless growth in global energy demand poses a challenge to striking a balance between reducing dependence on fossil fuels and increasing the generation of renewable energy. In 2018, the extended reliance on fossil fuels as an energy resource accounted for 68% (or 37.5 GtCO₂) of the total global greenhouse gas (GHG) emissions of 55.3 GtCO₂ (Turgut, 2022). In response to this, several countries joined the Paris Climate Agreement (2016) to reduce the amount of GHGs in the atmosphere. While achieving even 50% market penetration of renewable energy by 2030 is unlikely, underground storage of CO₂ emissions from human activities is considered one of the most effective methods to combat climate change. However, capturing CO₂ at the multi-gigaton scale would require resources and technologies capable of operating cost-effectively on such a large scale, an area where current capabilities are insufficient (RGRG, 2022; Turgut, 2022).

The implementation of carbon dioxide capture, transport, utilization, and storage (CCUS) involves a network of interconnected and complex components, including CO₂ sources (e.g., power plants, cement production), capture plants (e.g., chemical absorption, membrane separation), transportation modes (e.g., pipelines, ships), utilization sites (e.g., construction materials, enhanced oil recovery), and sequestration sites (e.g., saline formation storage). Figure 2 displays the elements involved in the CCUS technology from separation and capture to utilization and storage (Tobias da Cruz, et al. 2021). Consequently, potential investment decisions by stakeholders are influenced by a variety of risks and uncertainties. These include factors such as regulatory frameworks (e.g., climate change policies), market fluctuations (e.g., power and CO₂ prices), the accessible quantity of CO₂, storage site capacity and injectivity potential, and the performance of capture technologies (Hasan et al., 2015; ACT!ON Proposal, 2022).

CCUS is a large-scale technology that faces several challenges, including the need to manage varying CO₂ supply rates from different sources and ensure the availability of flexible transport and storage networks to avoid the high emission costs associated with venting. To support stakeholders in the planning and design of large-scale, flexible CO₂ transport, utilization, and storage networks, it was necessary to research and develop a multitemporal integrated assessment model. This model enables comprehensive reporting on decarbonization efforts while addressing engineering constraints, geological impacts, economic conditions, regulatory frameworks, and their associated uncertainties.

The general objective of this project, ACT!ON (Advance Multitemporal Modeling and Optimization of CO₂ Transport, Utilization, and Storage Networks), is to determine how to develop an efficient infrastructure that connects CO₂ sources with geological storage and non-geological utilization options, as part of regional decarbonization efforts. Achieving this requires an in-depth understanding of the impact of flow phenomena on the design and operation of such infrastructure, ensuring its adaptability and responsiveness to operational variations across distinct components of the chain.

To support large-scale CCUS (Carbon Capture, Utilization, and Storage) deployment, the project integrates these components into comprehensive models that optimize transport and storage networks. These integrated models demonstrate the interactions between different elements, providing critical insights for stakeholders. Modular computationally independent proxy models were developed to represent various subsurface and engineering processes, such as geological flow barriers, geomechanical constraints, and well performance, serving as the foundational building blocks for these integrated models.

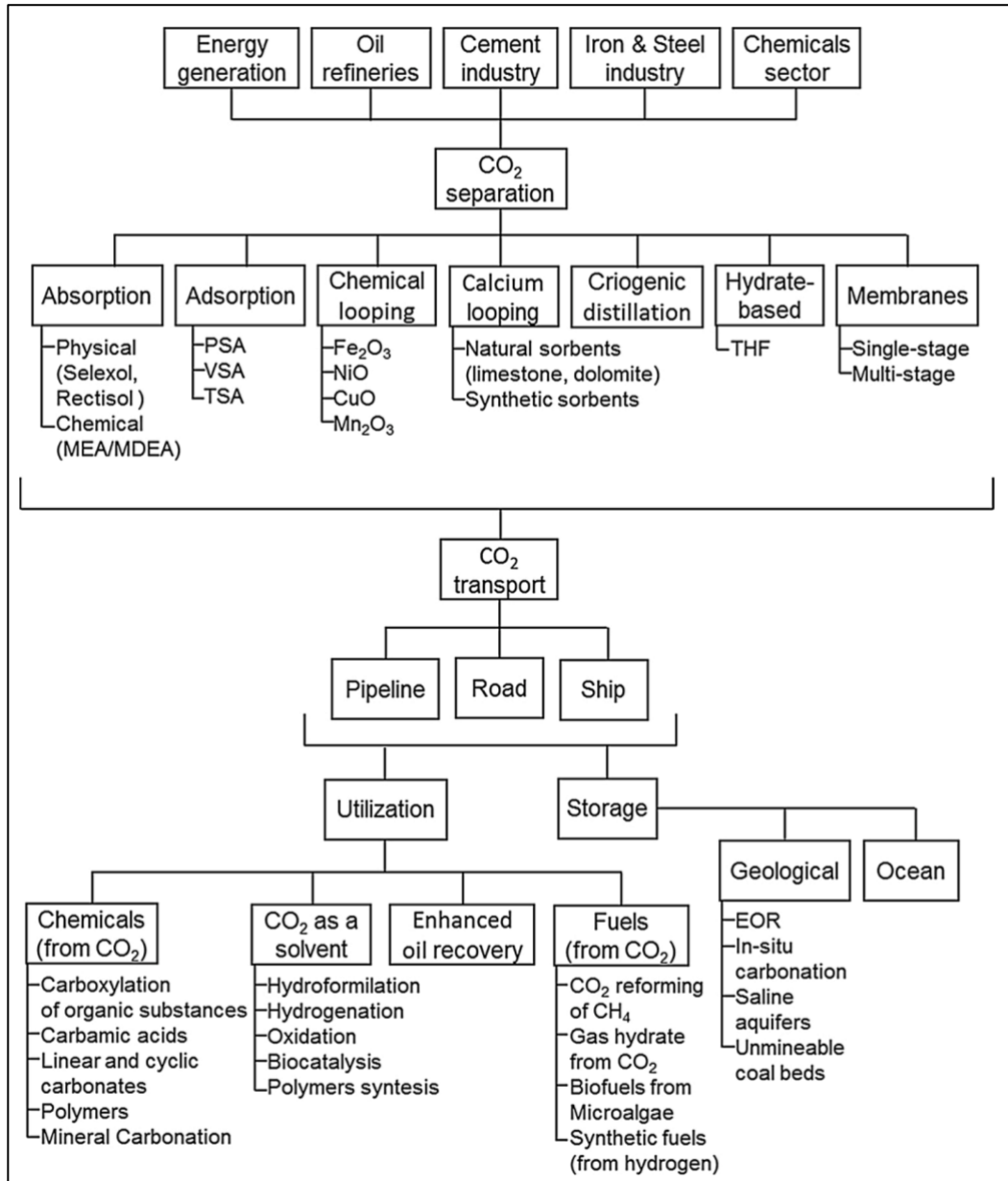


Figure 2 CCUS chain from separation to storage/utilization (Tobias da Cruz, et al. 2021)

6.2 BACKGROUND OF THE PROJECT

Carbon capture, utilization, and storage (CCUS) is a crucial technology for reducing greenhouse gas emissions, especially in sectors reliant on fossil fuels. CO₂ injection for enhanced oil recovery (CO₂-EOR) has been in use since the 1960s, and geological storage projects, such as Sleipner in 1996 (Kongsjorden et al., 1998), have provided valuable insights into large-scale CO₂ sequestration. Over 200 CO₂-EOR projects exist in North America (e.g. Weyburn Canada), contributing to knowledge on injection processes, storage performance, and associated risks (Verma, 2015).

However, CCUS implementation involves several uncertainties and challenges, including regulatory frameworks, fluctuating CO₂ markets, injectivity issues, and subsurface geological complexities. Numerical modeling and simulation tools help optimize CCUS operations by assessing storage site performance, injection rates, and dynamic interactions between CO₂ and geological formations. Injectivity variations have been observed in multiple projects, requiring adaptive models that consider interactions between CO₂, formation water, minerals, and host rock permeability (Carrol et al., 2013; Smith et al., 2013; Hao et al., 2013; Hutcheon et al., 2016).

To optimize CCUS networks, proxy models and machine learning techniques have been developed to improve risk assessment and decision-making. The ACTION project aimed to integrate dynamic risk-based optimization frameworks to enhance CCUS supply chain efficiency. CCUS network models often treat geological storage as a static element, but incorporating dynamic variables such as fluid flow, pressure changes, and reservoir behavior is essential for robust optimization. CO₂ transportation is another critical aspect of CCUS, with pipelines and ships being the primary options. While pipelines are cost-effective for short distances and high volumes, maritime transport offers flexibility for varying CO₂ demand, such as in enhanced oil recovery. Research explored optimal conditions for CO₂ transport, balancing pressure and temperature to ensure safety and efficiency.

ACTION project brought together research institutions and organizations coming from seven different countries integrating the project consortium partnership, these are United Kingdom (IMPERIAL, BP), United States (LANL), Canada (UAlberta, PTRC, CVICTUS, WOLF), Netherlands (TNO, NEPTUNE), France (IFPEN, TOTAL), Romania (GeoEcoMar) and Germany (WD). The consortium partners leveraged their extensive expertise in CO₂ storage research, insights gained from industrial field pilot projects, and validated models. They also explored potential future CCUS network scenarios.

6.3 PROJECT OBJECTIVES

ACTION aimed to develop an integrated, multitemporal assessment model to support the planning and design of large-scale CO₂ transport, utilisation, and storage (CCUS) networks as part of regional decarbonisation efforts. The model accounts for geological, engineering, economic, and regulatory constraints across three time scales (multitemporal): short-term (hours/days) for safe and efficient operations, medium-term (years) for managing dynamic storage capacity and network connections, and long-term (decades) for strategic planning to meet decarbonisation targets.

By integrating geological, engineering, and economic models, the project pursued to optimise network operability, mitigate risks, and improve decision-making for stakeholders. Building on previous research, ACTION uniquely addressed multitemporal network operability and strategic decarbonisation challenges. Key contributions included developing modular proxy models for CO₂ capture, transport, storage, and utilisation; supporting investment decisions for governments and industry through cost assessments and lifecycle evaluations; and demonstrating the approach through case studies across Europe, the US, and Canada, considering various transport methods and network complexities. This initiative will provide essential tools for designing resilient, efficient, and future-proof CCUS infrastructure.

The project was organized in five technical Work Packages (WP) and one for project management and coordination, each aligned with the project's objectives, along with their respective leadership, as illustrated in Figure 3. University of Alberta – Reservoir Geomechanics Research Group (RGRG) led Work Package 3. WPs objectives were as follows:

Work Package 1 - Geological and engineering fast proxy models. This WP was focused on the dynamic behaviour of subsurface storage systems (saline aquifers, depleted gas fields, CO₂-EOR in reservoirs, and deep unmineable coal

seams) for various CO₂ injection scenarios. The main objective of WP1 was to develop fast proxy models to provide relevant dynamic feedback at appropriate temporal scales to surface network configuration scenarios.

Work Package 2 - Transport network operability and multitemporal CCUS model development. The first objective of this work package was to build proxy models to support the design and management of CO₂ transport networks (pipelines and shipping), linking a multitude of CO₂ emitters to CO₂ users and storage reservoirs. This will support planning at the scale of days to weeks. This WP also developed integrated multitemporal model templates for pipeline systems and batch wise transport options to consider the short-term statistical response of the combined proxy models. The focus of WP2 was the development of integrated modelling for capture, transport, utilisation, and storage networks spanning the different temporal scales. It expanded to the long-term planning horizon, including the uncertainty associated with the processes involved within the market, economic and regulatory environment in which the system operates.

Work Package 3 - Storage and network risk dynamics. The objective of WP3 was to characterise the integrated storage and network risk dynamics. This was 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 capacity (CO₂ supply accommodation). It is recognised that it is challenging to quantify risks across full-scale deployment of a CCUS network. Within ACT!ON, risk was considered in the context of system operability only. Project tasks within WP3 were 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, were established based on these risks and used to regulate the proxy models in WP1. In particular, WP3 focused on the relationship between subsurface system risk and network risk at short temporal scales, which has been largely ignored in earlier CCUS supply chain risk and optimisation studies. In addition, techniques were developed providing fast constraints for network optimisation, based on (user-specified) acceptable limits on risk ranking. This WP was led by the University of Alberta.

Work Package 4 - CCUS proxy models development and decarbonization assessment methods. The first objective was to develop proxy models for CO₂ utilisation and conversion technologies that are likely to be part of future CCUS systems. Parameterised for the CCUS network systems in ACT!ON, the proxy models provided conversion and utilisation metrics with a temporal variability, which was used as input in the strategic decarbonisation modelling to carried out in WP5. The second objective was to convert the new process models to Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) models which was 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.

Work Package 5 - Strategic decarbonization scenarios accounting and reporting. WP5 was 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 identified specific development and research needs, centred around developing full-chain CCUS projects. WP5 was dedicated to the tailored implementation of the multitemporal CCUS network modelling tools developed in ACT!ON. The purpose was 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 levels.

Work Package 6 - Project coordination and management. The overall technical coordination of the project was the responsibility of IMPERIAL, who also led dissemination activities with all partners.

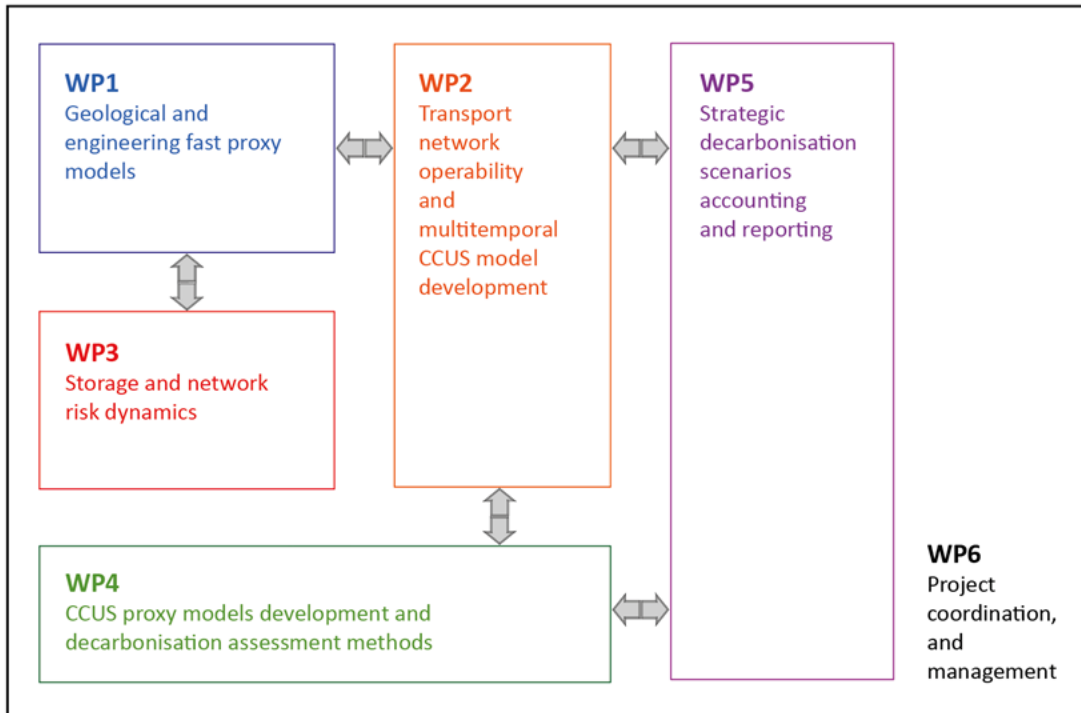


Figure 3 Overall project concept and structure

PERFORMANCE/SUCCESS METRICS IDENTIFIED IN THE CONTRIBUTION AGREEMENT

Table 1 presents the list of metrics targets and achievements within ACT!ON. The high TRLs were achieved through the application of the ACT!ON network simulation tools to case studies that are located throughout Europe, the US and Canada. By addressing the most critical aspects of future network layouts and storage types, these case studies identified key challenges in the development and operation of CCUS networks.

Table 1 Summary of project target metrics and achievements

Success Metric	Project Target	Commercialization Target	Explanation	Project Achievement
Model development of dynamic subsurface risk of CCUS network	Developing new reservoir performance, well, near-wellbore, storage system integrity, capture from industrial sources, conversion, and utilization proxy model tools.	TRL8 fully functional for integration in planned CO ₂ capture, transport, utilisation and storage networks TRL8 pilot demonstration at selected region case studies	Geological and engineering fast proxy models provide dynamic feedback at temporal scales to surface network configuration and strategic decarbonization modeling scenarios	Successfully evolved the dynamic subsurface risk model from independent components to a fully integrated system, enabling its application in planned CCUS projects and regional pilot demonstrations, with proxy models serving as key building blocks for system integration.
Integration of field deployment of large CCUS projects	Development of multiperiod, multimode CCUS value chain model including batch-wise transport options and performance indicators for risk mitigation and control	TRL7 implemented and prepared ready for demonstration at planned CCUS clusters in Europe and Western Canada	Modular workflow designed to evaluate the entire CCUS chain and enable decision/optimization, addressing uncertainties, downtime, and operational constraints	Advanced the integration of large-scale CCUS projects from desk studies to implementation readiness, implemented and prepared for demonstrations across major CCUS clusters, including Porthos and Aramis (Netherlands), Net Zero Teesside, Northern Endurance, East Coast and South Wales clusters (UK), Longship/Northern Lights (Norway), Dunkirk-North Sea (France), Getica (Romania), and the Alberta Carbon Trunk Line (Canada).
LCA and LCC models	Techno-economic and life cycle environmental assessment and cost method	TRL7 pilot demonstration and methodology development	Holistic and cohesive perspective on the environmental (e.g. GHG emissions, solid waste), economic, regulatory, and financial factors influencing CCUS projects, the model aids decision-making for stakeholders at all levels, project developers, policymakers, and investors	Developed and implemented Life Cycle Assessment and Life Cycle Cost models for CCUS planning by converting new process models (e.g., biological and chemical conversions, CO ₂ mineralization) into LCA/LCC frameworks, establishing methodology for pilot demonstrations and achieving high TRLs through ACT!ON network simulation applied to international case studies, identifying key challenges in CCUS network development and operation.

Future CCUS network scenarios under development in ACT countries were analyzed and incorporated into strategic decarbonization scenarios accounting and reporting (WP5) to implement the multitemporal CCUS network modeling tools created in this project. These scenarios enabled the measurement and reporting of GHG emissions reductions at various levels, including operational, regional, national, and international scales.

7.0 PROJECT WORK COMPLETED AND OUTCOMES

7.1 METHODOLOGY

The methodology followed in this project included the following steps:

1. The development of computationally efficient proxy models that accurately represent both static geological reservoir characteristics and dynamic responses for different CO₂ injection scenarios, including saline aquifers, depleted reservoirs, and enhanced oil recovery (EOR) applications. These models were designed to account for factors such as reservoir type, geological flow barriers, storage system integrity (wells, faults, caprock), and injectivity conditions (salt precipitation and CO₂ hydrate formation near the wellbore). The consortium leveraged its extensive expertise in CO₂ storage research, insights from industrial field pilots, and validated models (case histories) to achieve this goal.
2. Implementation of the ACT!ON project developed multitemporal CCUS network modeling tool into future CCUS network scenarios being planned in ACT countries, to evaluate key decarbonization strategies tailored to each region. It aims to establish methods for accounting and reporting greenhouse gas (GHG) emission reductions at operational, cluster, regional, national, and global scales.

The main objective of this project was to develop an integrated, multitemporal assessment model to support the planning and design of large-scale CO₂ transport, utilisation, and storage (CCUS) networks as part of regional decarbonisation efforts. Hence, a decentralized multiagent based optimization tool was developed. Figure 4 shows the system representation and design of the proposed tool, where it is highlighted the general interaction between physical systems, regulation, financial and economics exogenous parameters. This tool is designed to fit for the purpose of the ACT!ON regional studies.

The multi-agent approach simulates how individual agents respond to system changes, including engineering flexibilities, variability, uncertainties, and market fluctuations. The model is structured to account for the specific characteristics of a given system, as well as external parameters, generating outputs that support operational adjustments and decision-making within defined constraints. Ensuring that each agent operates in an optimized state, and the overall system reaches equilibrium. On the other hand, a multi-period stochastic optimization methodology was applied at the individual agent level, allowing each agent to retain full control over its own operations.

Modular proxy models from work packages can be fully integrated into the multi-agent system. Figure 6 displays all the proxy models developed in this project to represent each physical agent scenario for the optimization tool, the proxy models created by University of Alberta - RGRG are highlighted by bold (UofA). The proxy models were created by using machine learning techniques and integrating them with methods like reduced order model (e.g. Proper Orthogonal Decomposition), kriging or neural networks trained on complex numerical simulations (RGRG Milestone 2&3 ERA Report, 2023). These models accounted for the geomechanical and geochemical effects of CO₂ injection and adapt to changing operating conditions over time, offering a more accurate representation of well injectivity and field behavior throughout the storage lifecycle.

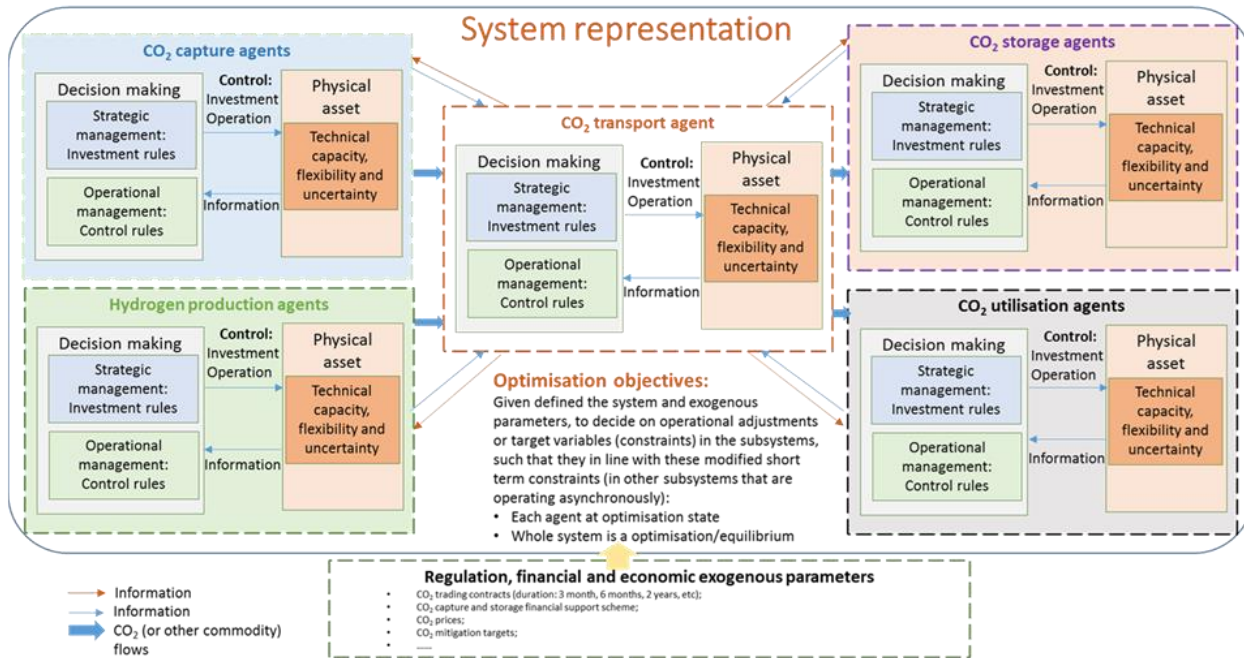


Figure 4 System representation of the proposed Multiagent based optimization tool (ACT!ON Proposal 2022)

This multi-agent simulation framework can also be observed in Figure 5, it is structured into two interconnected layers: a decision layer and a physical layer. In the decision layer, agents act as virtual decision-makers, managing their respective physical assets while accounting for engineering limitations, business strategies, and market dynamics. Meanwhile, the physical agents simulate CO₂ flow based on directives from the decision layer. By utilizing simplified proxy models to represent complex processes like subsurface CO₂ injection, the framework effectively captures short-term variations and uncertainties, providing a more realistic depiction of system behavior (Xie et al., 2024).

The model was built in Python 3.9, using the MESA library for modular agent-based modeling. It integrates network components (sources, sinks, pipelines) as physical agents and creates corresponding decision agents to optimize operations through mathematical optimization. The model operates on a multi-temporal framework with a base time unit of days, balancing short-term operations with long-term profitability and system stability. The framework alternates between decision and physical layers to enhance CCUS network efficiency, incorporating engineering, economic, and policy considerations (Xie et al., 2024).

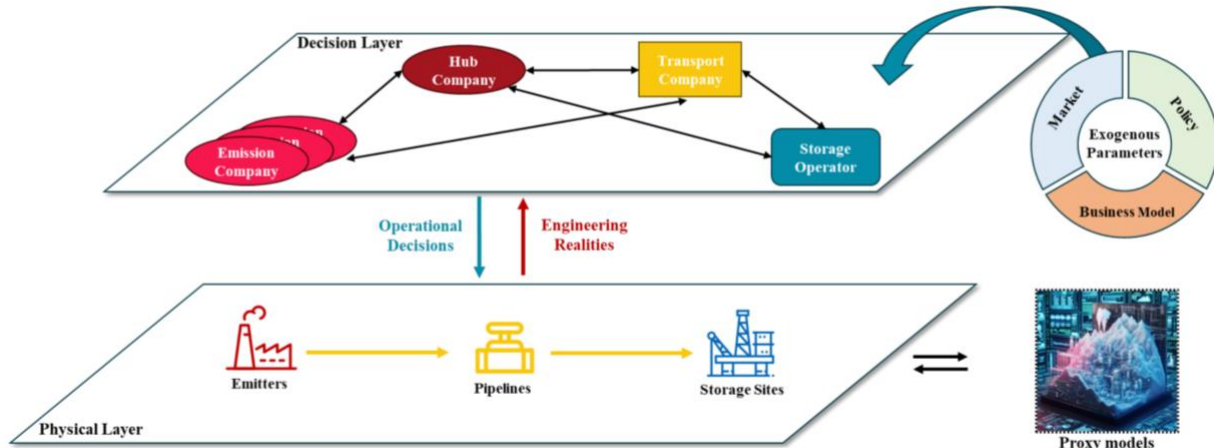


Figure 5 Multiagent based optimization tool (Xie et al., 2024)

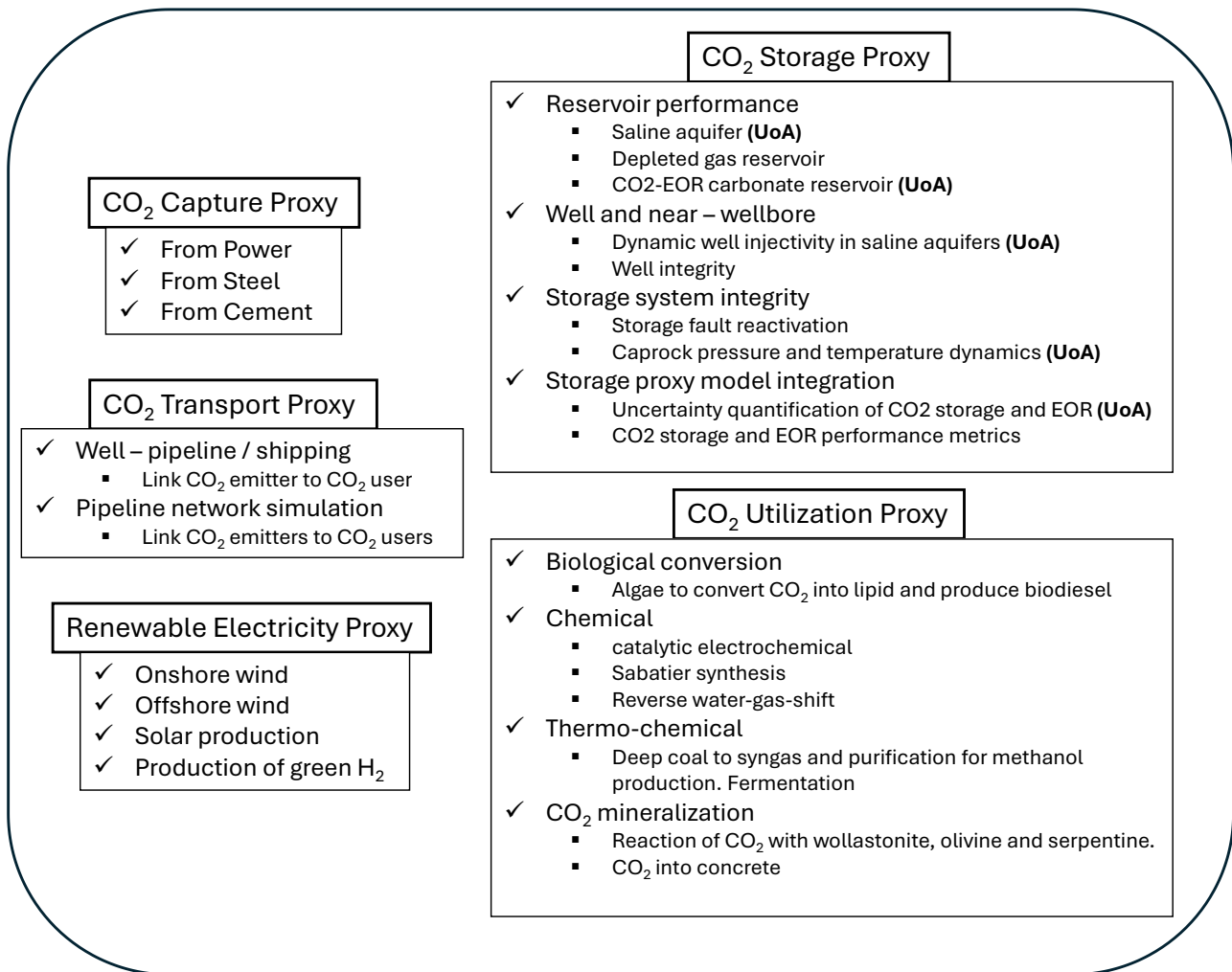


Figure 6 Proxy models developed in ACTION Project for CO₂ Capture, Transport, Storage and Utilization

7.2 TECHNOLOGY DEVELOPMENT, RESULTS AND ANALYSIS

7.2.1 Proxy model development

The creation of proxy models for reservoir performance, well and near-wellbore behavior, and storage system integrity was based on previously validated reservoir models from multiple sites, along with insights gained from long-term research conducted by project partners. These sites included the K12-B gas field in the Dutch North Sea sector, the P-18 depleted gas reservoir also in the Dutch sector, the In Salah CO₂ Storage Site in central Algeria, the Forties and Nelson Cenozoic System in the UK sector of the Central North Sea, the West Paris Basin sandstone aquifers, the Weyburn-Midale CO₂-EOR Site in Saskatchewan, and the Aquistore saline aquifer in Canada (Korre et al., 2022).

CO₂ Storage proxy model

Geological and engineering fast proxy models focused on the dynamic performance of underground storage systems, including saline aquifers, depleted gas fields, and CO₂-EOR reservoirs, across different injection scenarios. The primary goal is to create efficient proxy models that deliver timely dynamic insights, aligning with surface network configuration scenarios at suitable temporal scales. The following proxy models were generated:

- ✓ A Gaussian process-based proxy model for saline aquifers was developed and validated using data from the West Paris Basin sandstone aquifers.
- ✓ An analytical proxy model designed to optimize brine extraction in saline aquifers was demonstrated using the saline formations of the North Sea’s Forties and Nelson fields.
- ✓ An Artificial Neural Network-based proxy model was created using data from the Weyburn-Midale CO₂-EOR reservoir. This model uses an autoregressive approach with external inputs to estimate the amount of stored CO₂ and the rate of fluid production.
- ✓ An analytical proxy model for estimating Joule - Thomson cooling during CO₂ injection in saline aquifers was applied to gas field P18-4, determining the reduced injection rate necessary to prevent hydrate formation.
- ✓ A convolutional neural network-based proxy model for depleted gas reservoirs was implemented using a realistic model inspired by gas fields in the Dutch offshore region.
- ✓ Proxy model that provides a first order estimate of well integrity for the effect of given combinations of bottomhole pressure and temperature on stress.
- ✓ Developed proxy models to ensure the integrity of storage systems when injecting CO₂ into depleted gas reservoirs. The geomechanical workflow aimed to predict the potential risks of fault reactivation at reservoir and caprock depth due to cold CO₂ injection. The stress state and the likelihood of fault reactivation, along with the magnitude of induced events were considered.
- ✓ A proxy model for fault reactivation was developed using the In Salah storage site as a case study. The study examined potential CO₂ leakage through a vertical fault, considering uncertainties in caprock and fault permeability, friction angle, critical slip distance, and geomechanical permeability multiplier. Response surfaces are used to analyze CO₂ and brine mass flux through the fault.
- ✓ The University of Alberta – RGRG utilised the data from the Aquistore site, Saskatchewan to develop control-relevant proxy models from spatial-temporal data of pressure and temperature in the storage formation and caprock during CO₂ storage operations (RGRG ERA Milestone 2&3, 2023). The proxy models were used for risk assessment and uncertainty quantification to contribute establishing the methodology for risk mitigation measures at CO₂ hub and inter-hub levels. Machine learning and reduced order models were employed throughout the uncertainty and probability estimation procedures to increase the computational speed process significantly (RGRG ERA Milestone 4, 2024).

Figure 7 shows the workflow used by the University of Alberta – RGRG, the generated input-output (I/O) data was split into modeling, and validation data sets, usually at a ratio of 80:20. Most of the data was set into modeling, and only a fraction was into validation. Using most of the data to train the ML models made them effectively predict the output (RGRG ERA Milestone 2, 2023). As shown in the Figure 7, the modeling I/O data set trained the ML model (estimated the ML model parameter θ from outputs Y and input U). The validation output data set was used to validate (compared with) the ML model's output estimated for the validation inputs to assess the model adequacy. POD-based spatial-temporal frame estimation results (prediction error) for Temperature and Pressure data are illustrated. The results were very satisfactory (less than 10%) in the first 5 steps of the simulation.

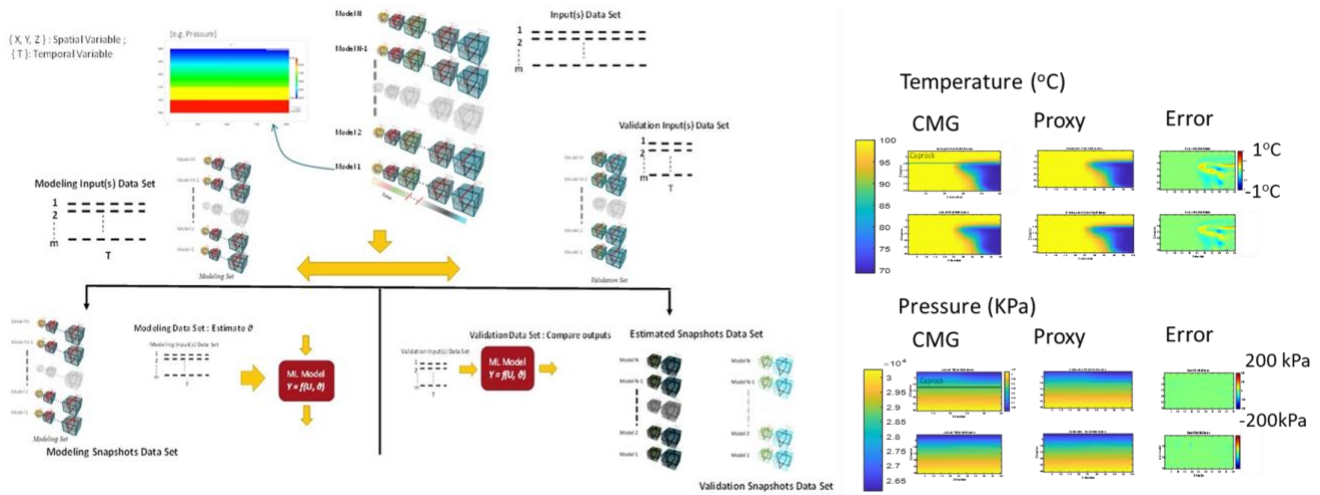


Figure 7 Workflow of the modeling and validation process in a typical ML framework. Data and the process are shown side by side (Ganesh et al., 2023)

CO₂ Transport proxy model

- ✓ Proxy models for pipelines and wells have been developed for integration into a CO₂ transport and storage network model. These models require fluid properties over a wide range of pressures and enthalpies, obtained using Refprop. A one-dimensional solver, incorporating mass, momentum, and energy conservation, calculates output pressures and enthalpies for various flow rates, input pressures, and input enthalpies. The results are compiled into a large dataset for each well and pipeline, allowing the network model to interpolate values and determine pressures and temperatures across the system.
- ✓ A network model was developed to assess pressures, temperatures, and flows in a CO₂ transport and storage system over time. It assumes a single CO₂ source and consists of pipelines connecting hubs, where flow is distributed to wells or additional hubs. The pipelines, wells and reservoirs are represented by proxy models, where pipelines and wells are calculated in steady state, while a transient reservoir model is considered. The network model enables long-term evaluation of CO₂ flow and injection scenarios over months to years with minimal computational cost.

CO₂ Utilization proxy model

Proxy models for CO₂ utilization/conversion technologies were developed as a function of input engineering parameters at appropriate temporal resolution allowing to capture the effect of potential variability in CO₂ supply, predicting CO₂ conversion efficiency and CO₂ utilization rate. This research project examined the southwestern

region of the US covering Utah, Colorado, New Mexico, and Arizona, which presents favorable conditions for non-geological CO₂ utilization technologies, including biological and chemical conversion, as well as CO₂ mineralization (Korre et al., 2022). The explored approaches to develop proxy models ranging from multi-variable regressions fitted to engineering performance data to analytical/semi-analytical solutions to process engineering equations. The developed proxy models are the following:

- ✓ Biological conversion technology by utilizing algae to convert CO₂ into lipids to produce biodiesel was studied. The proxy models focused on processes such as biomass cultivation, lipid extraction, and hydrothermal liquefaction.
- ✓ Chemical conversion technology included catalytic and electrochemical processes to produce intermediate products such as methanol, methane and formic acid, among other chemical products. Models and corresponding proxies for CO₂ methanation, the reverse water-gas shift, and hydrogenation to hydrocarbons via Fischer-Tropsch were prepared.
- ✓ Thermo-chemical conversion models were developed for deep coal resources to syngas and purification for methanol production, providing an approximate relationship over time between key parameters and product flows.
- ✓ Mineralisation technology proxy models were created included the reaction of minerals with CO₂ to produce inert carbonates and injection of CO₂ into concrete materials to produce building materials.

7.2.2 Implementation of Multi Agent System CCUS

The networks analyzed included the Porthos and Aramis capture, transport, utilization, and storage networks in the Netherlands; the Net Zero Teesside (NTZ), Northern Endurance (NEP), and East coast CO₂ clusters, along with the South Wales Industry Cluster in the UK; the Longship/Northern Lights CCS initiative; the Dunkirk-North Sea CCS cluster; the Getica CCS project in Romania; and the Western Canada Region/Alberta Carbon Trunk Line (ACTL) system. These networks incorporated various CO₂ capture, transport, and storage approaches. This final report highlights the case study on the UK's Teesside industrial cluster and the ACTL case in the section of strategic decarbonization Canadian case. The details of the remaining cases can be found in their respective publication.

A case study on the UK's Teesside industrial cluster demonstrated how the Multi Agent System CCUS can improve coordination, ensure safe and efficient operations, and achieve balanced economic outcomes for stakeholders (Xie et al., 2024). The Teesside CCS network layout for 2051-2055 was modeled using Multi Agent System CCUS, which simulates operations on a daily basis (Figure 9 shows daily simulation process). Unlike previous studies that assumed a single CO₂ entry point, this model considers three industrial sources (power and two chemical production facilities) with emissions evenly distributed daily. Storage planning follows contractual annual injection rates, with geological data from the CO₂ Stored database for storage sides (Closures 35 and 36). CO₂ supply rates fluctuate monthly, following a normal distribution with a standard deviation of 0.1 around the mean daily emissions. The framework of the Multi agent optimization tool used in this specific study can be visualized in Figure 5 where all involved entities are shown.

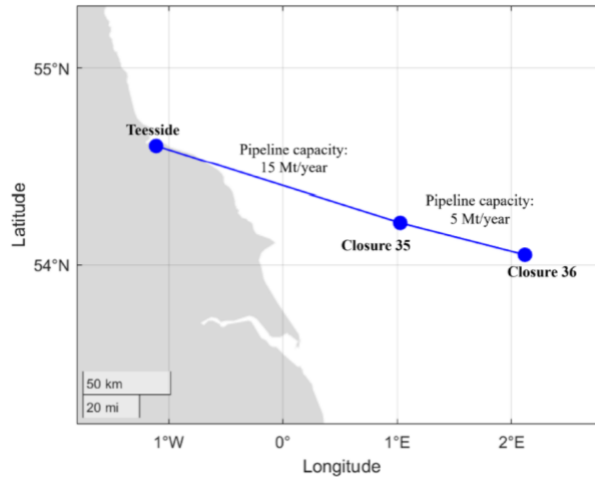


Figure 8 CCUS network planning results for the Teesside area – Derived from ALIGN project (Xie et al., 2024)

The CO₂ storage proxy model for saline aquifers was used in two ways: to simulate pressure variations during injection and to ensure the maximum injection rate avoids excessive pressure buildup at each storage site.

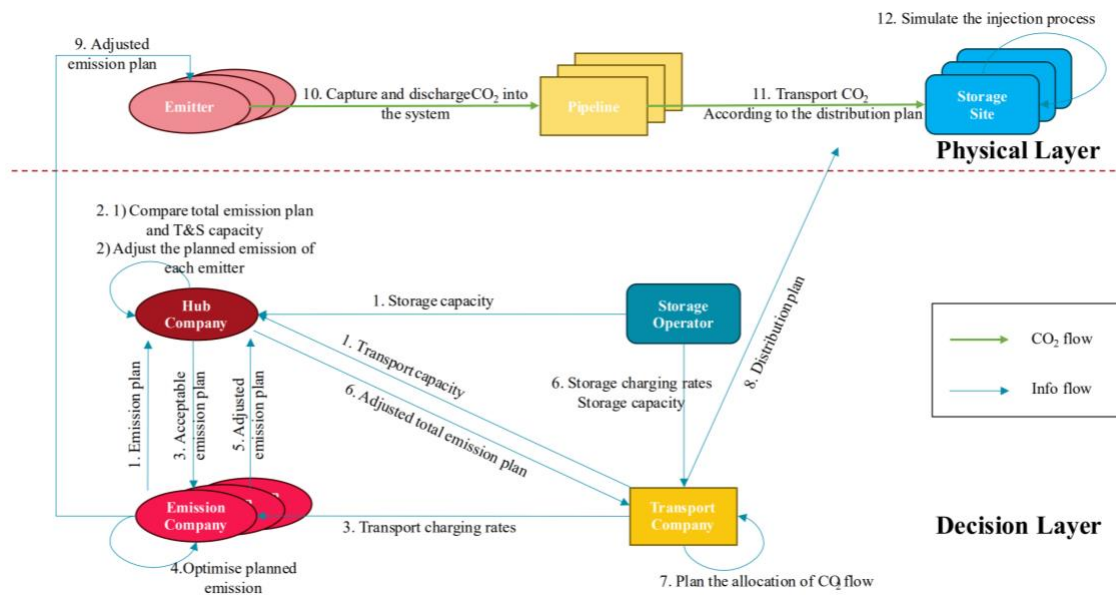


Figure 9 Daily simulation process of Multi Agent System-CCUS and CO₂ and information flow (Xie et al., 2024)

7.2.2.1 Results and analysis

The current implementation focuses on the handling of CO₂ from the onshore terminal (Teesside) to the storage sites within the network (Closures 35 and 36), so it is a CCS network model implementation, Figure 8 displays the CCUS network planning results for the Teesside area. In addition, the results of the Multi agent System CCUS framework implemented to simulate the Teesside case are shown in Figure 10, providing key engineering data on CO₂ emissions, pipeline throughput, and storage site injections. The results show fluctuations in daily CO₂ capture from three emitters due to emission uncertainties, impacting transport and storage (Figure 10 (a)). Pipeline throughput remains within safe design limits despite variations in supply, ensuring stable system operation Figure 10 (b). Storage site

data, including daily and cumulative injections, confirms that injection rates stay within the safe maximum set by the storage proxy model. Well bottom hole and dome pressures are also maintained within safe ranges, demonstrating effective control of operating conditions Figure 10 (c). The MAS-CCUS two-layer structure enables coordinated network operation, ensuring efficiency while mitigating engineering risks.

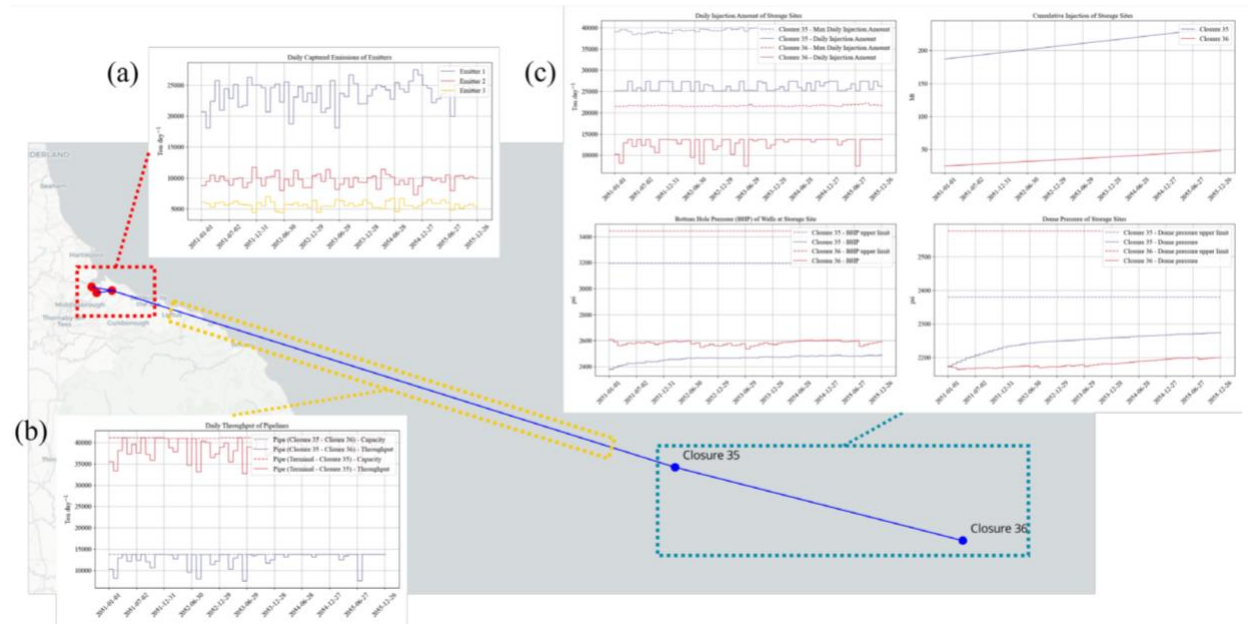


Figure 10 Teesside CCUS project simulation results: (a) Daily captured emissions of emitters, (b) Daily throughput of pipelines, (c) Daily injection amounts, cumulative amounts and pressures at storage sites (Xie et al., 2024)

7.2.3 Strategic decarbonization Canadian case

This project has contributed to the advancement of decarbonisation strategies through CCUS (Carbon Capture, Utilization, and Storage) in six industrial regions across the EU, the UK, Canada (Alberta region), and the US. Each region has specific development and research needs for full-chain CCUS projects.

This report section highlights the work done for the Canadian Alberta region. This study explored Western Canada (Alberta region) CCUS network scenarios linked to incorporating current infrastructure (ACTL pipeline) and future expansions, the Alberta Carbon Trunk Line can be visualized in Figure 11. Industrial stationary CO₂ sources (e.g., cement, chemical plants, refineries) along with Oil and Gas sector emissions were analysed, Figure 12 illustrates Alberta CO₂ Emitters Sources Sectors, where it is noticed that 76% of total emissions are represented by mined oilsands extraction (27%), in-situ oilsands extraction (30%), and fossil fuel electric power generation (19%).

Scenarios illustrating how CO₂ transport and storage (Figure 14 shows Alberta storage sites) needs affect the network were devised and assessed. It examined the feasibility, cost, and efficiency of CO₂ transport and storage networks under three decarbonization scenarios: Optimistic, Moderate, and Pessimistic. Each scenario analyzed varying industrial CO₂ emission levels and compares the effectiveness of integrated versus standalone network configurations. Figure 15 displays the multiperiod network formulation where integrated and individualistic methodologies to connect the sources to the sink are observed. The following section summarizes some findings, more detailed explanation can be found in the report RGRG ERA Milestone 5 (2025).

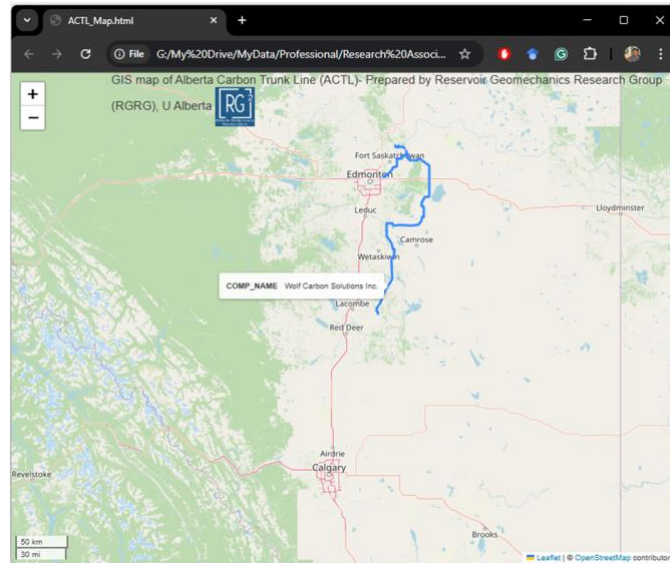


Figure 11 Alberta Carbon Trunk Line visualization (RGRG ERA Milestone 5, 2025)

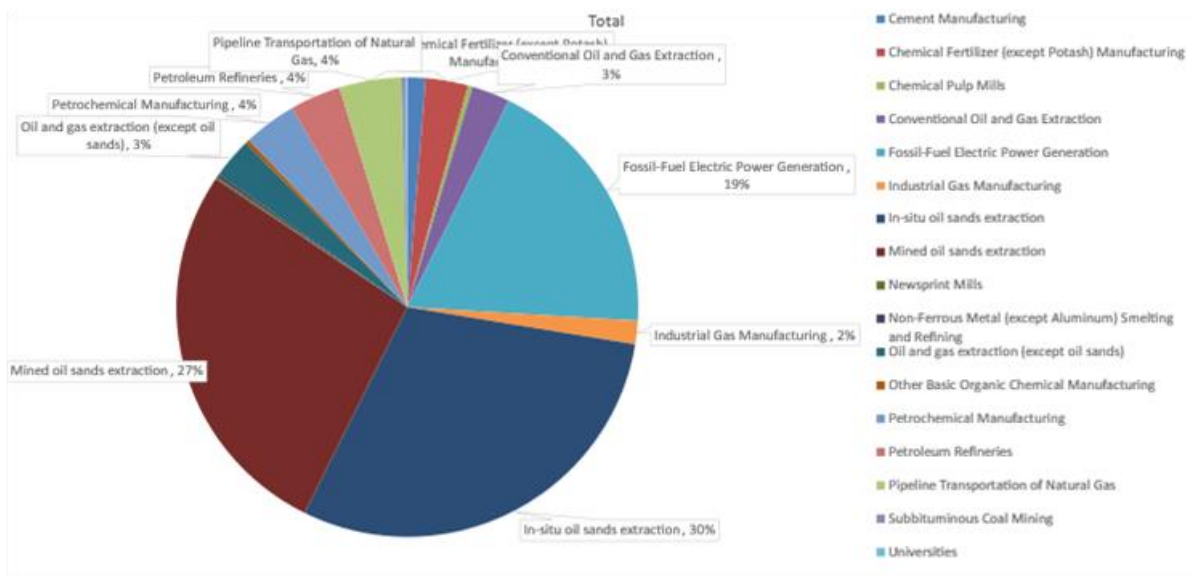


Figure 12 Alberta CO₂ Emitters Sources Sectors (<https://www.alberta.ca/albertas-greenhouse-gas-emissions-reduction-performance>, 2025)

RGRG designed a tool to visualize cumulative emission until 2022 by each emitter, it can be observed in Figure 13.

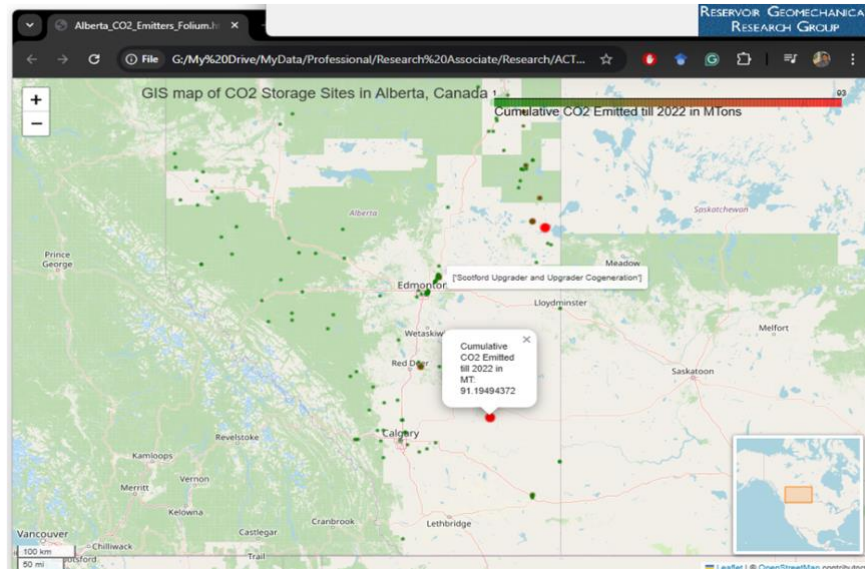


Figure 13 Slide bar-based bubble plot visualization of cumulative CO2 emission by emitters in Alberta (RGRG ERA Milestone 5, 2025)

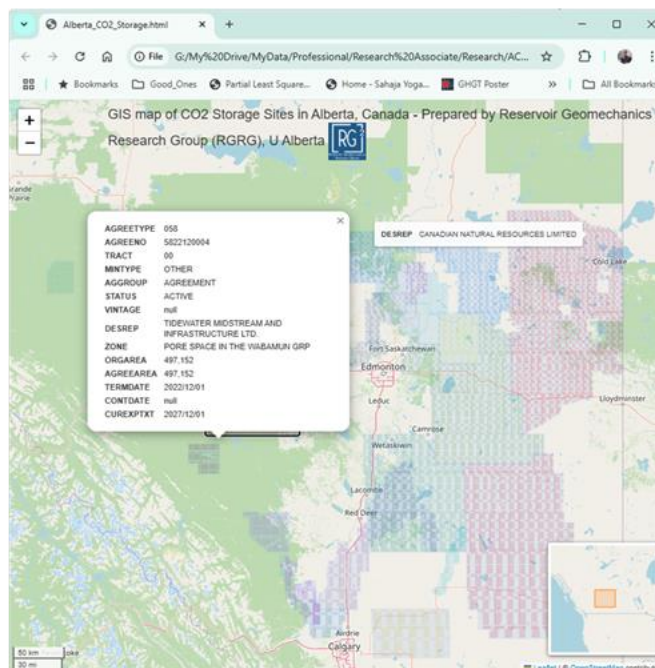


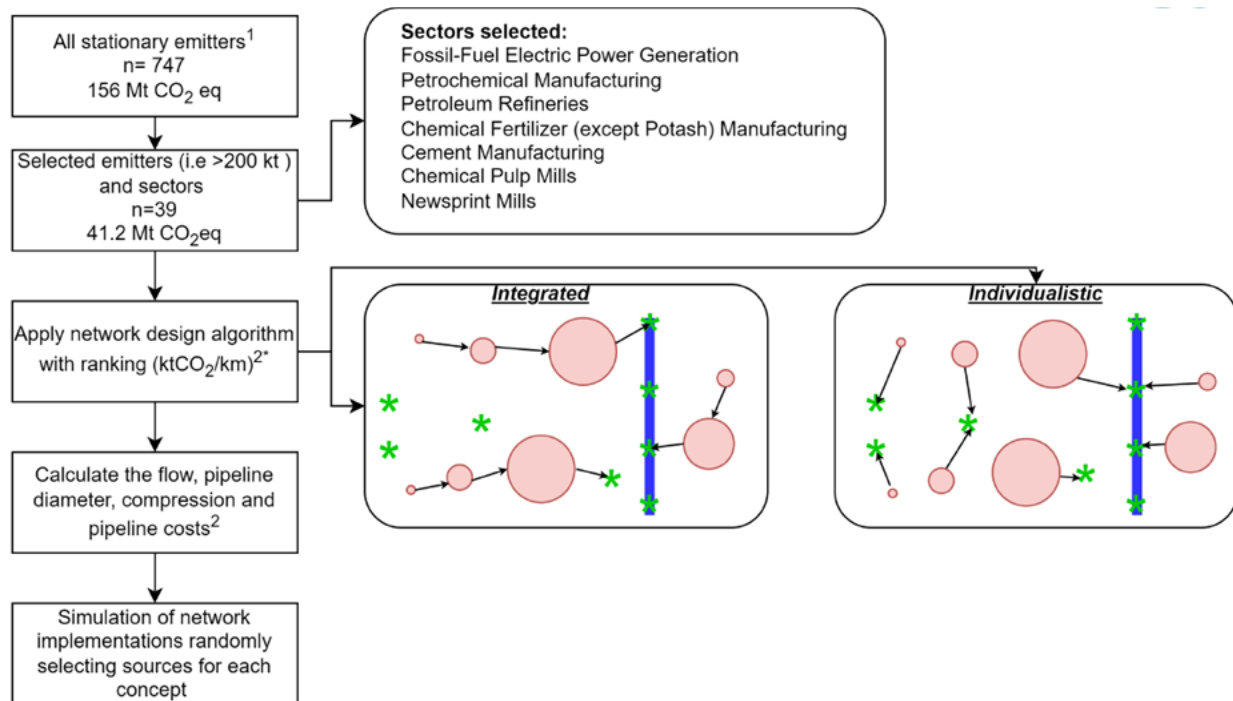
Figure 14 Alberta storage visualization (RGRG ERA Milestone 5, 2025)

7.2.3.1 Results and analysis

The integrated CO₂ transport and storage network was consistently more cost-efficient than an individual approach, showing lower total costs across all scenarios, primarily due to reduced capital expenditures (CAPEX) on pipeline infrastructure. The individualistic approach results in greater infrastructure redundancy, leading to longer pipelines and higher CAPEX (RGRG ERA Milestone 5, 2025).

The pipeline unit cost (M CAD km⁻¹) rises as the decarbonization scenario becomes more pessimistic, reflecting the reduced economies of scale with lower CO₂ storage volumes. On the other hand, total unit costs (CAD t⁻¹ CO₂) slightly

decrease in the moderate scenario but increase in the pessimistic one, indicating the cost impacts of lower network utilization. In terms of infrastructure, pipeline length and storage site availability are crucial to network efficiency, as some emitters can only be effectively connected once the storage site is ready (RGRG ERA Milestone 5, 2025).



1- https://indicators-map.canada.ca/App/CESI_ICDE?keys=AirEmissions_GHG&GoCTemplateCulture=en-CA

2- Zhang, Y. (2022) *Development of an engineering simulation and techno- economic-environmental optimisation framework for industrial decarbonisation*

* modified from

Figure 15 Multiperiod network formulation for Alberta scenario (Zhang, 2022)

7.3 PROJECT KEY RESULTS

- ✓ The geological and engineering fast proxy models resulted in the generation of a catalogue of proxies related to reservoir response (pressure, temperature, fault and well integrity, etc.). These fast (proxy) models for reservoir storage provide information about the behaviour of CO₂ and the status of key risks. For instance, allowing the fast prediction of injectivity that is influenced by several processes enabling effective management strategies (considering uncertainties).
- ✓ A multi Multi-temporal assessment models for CCUS networks were developed, which integrates all elements (sources and their intermittency, transport options and several CO₂ sink (utilization, fields, wells). As a result, the case studies executed will inform national governments to formulate long-term CCUS plans, by clarifying and detailing the long-term needs for storage and transport infrastructure.
- ✓ Various decarbonization pathways including uncertainty were assessed, enabling de-risking of large scale integrated operations inherent complexity of CO₂ utilization and storage options.
- ✓ Storage and network risk dynamics workflows and tools to track risks associated with changes within elements of the network to the whole system. Consequently, the impact of changes at different time scales in part of the chain on the full system can be assessed which are essential to understand design choices for large-scale networks.

- ✓ A portfolio of proxy models of utilization and conversion technologies was created, demonstrating that can be effectively combines in full CCUS networks. Contributing to the strengthens of market for CO₂ based product due to the improvement of efficiencies predictions and its impact on decarbonization.
- ✓ Developed a comprehensive decarbonization accounting and reporting framework for complex networks, enabling stakeholders to assess long-term impacts, including effectiveness, cost, environmental consequences, and potential performance risks, across multiple time scales to support informed policy and decision making.

7.4 PROJECT ACHIEVEMENTS

- ✓ Provided important set of tools for industry stakeholders constituted by a portfolio of proxy models innovative workflow and validated methodologies including reservoir performance, well, near-wellbore, storage system integrity, well-pipeline, CO₂ capture and utilization, Figure 6 shows the applied detail scenario.
- ✓ Developed a pipeline network simulation tool connecting CO₂ emitter with CO₂ users.
- ✓ Delivered functional process engineering models for CO₂ conversion and utilization options.
- ✓ Delivered Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Consequential Lyfe Cycle Assessment models (CLCA) for several utilization and conversion technologies.
- ✓ Developed and implemented a source and sink matching and multimode transport network tool.
- ✓ Developed and implemented a multi agent system modeling of CCUS system tool.
- ✓ Generated an interactive visualization tool for CO₂ emitters in Alberta.

8.0 LESSONS LEARNED

8.1 CHALLENGES

During the first 14 months of the project, ACT!ON faced several challenges, including minor delays in proxy model development and deliverables in WP1, additionally, staffing issues at one of the partners, and a delay in signing the consortium agreement. However, these issues were effectively managed, with a new leadership appointed to WP1. The overall impact on the project timeline was minimal, and adjustments were made in the updated Gantt chart to reduce disruptions to other tasks.

8.2 PRACTICAL LEARNINGS

One key takeaway from the ACT!ON project is the immense value of strong collaboration across multiple partners and countries. With all partners actively engaged in various work packages and tasks, we have seen firsthand how broad participation enhances knowledge sharing and collective problem-solving. Regular meetings, attended by representatives from all organizations, have reinforced the importance of inclusive discussions, as every partner has valuable insights to contribute. Additionally, the involvement of universities and research institutes from seven different countries has significantly enriched the project, bringing in diverse academic expertise that supports industry efforts in decarbonization while also increasing international visibility for all contributors.

8.3 ORGANIZATIONAL LEARNINGS

ACT!ON project embraced innovation, interdisciplinary collaboration, and real-world application in CCUS technologies. University of Alberta research group (RGRG) strengthened knowledge in CCUS full chain processes and gain valuable international exposure by participating actively in all WPs throughout the project lifecycle. The University of Alberta plays a significant role in advancing the development and implementation of Carbon Capture, Utilization, and Storage (CCUS). It supports this effort by promoting research, fostering collaboration among stakeholders, and facilitating policies that encourage adoption. This includes driving technological innovations, building essential infrastructure, and shaping regulatory frameworks to accelerate the widespread deployment of CCUS solutions.

8.4 HIGHLIGHTS

The ACT!ON project strengthened expertise of talented, purpose driven individuals within its partner organizations to drive the advancement and global commercialization of CCS, CCU, and CCUS technologies. By working collaboratively and fostering the growth of early career researchers and academics, the project aimed to contribute its knowledge and skills to addressing climate change in key industrial sectors ultimately striving to make a meaningful, positive impact on the world.

9.0 GHG BENEFITS

The majority of Alberta’s emissions come from its industrial sectors, necessitating a unique strategy compared to other parts of Canada. Achieving the province’s goal of carbon neutrality by 2050 (see Figure 16) will rely heavily on the development and implementation of innovative technologies within these industries. Alberta is taking a systems level approach to map out practical emission reduction pathways, assess sector-specific opportunities, evaluate related costs and technologies, estimate timelines, and determine the policies and programs needed to drive further progress (Government of Alberta, 2023).

The CCUS Optimization tools developed in ACT!ON project will significantly contribute achieving net-zero emissions, especially in hard-to-decarbonize sectors. This involves improving CO₂ capture rates (up to 99%), reducing costs through innovation and scale, and finding economic uses for captured carbon (e.g., fuels, chemicals, building materials). Integrating CCUS with renewables such as biomass with CCS, and advancing direct air capture technologies also contribute to carbon removal. Effective policies, industry collaboration, and secure long-term storage (e.g., in geological formations) are essential. CCUS optimization workflows enable significantly reduce emissions from power generation, heavy industry, and hydrogen production.

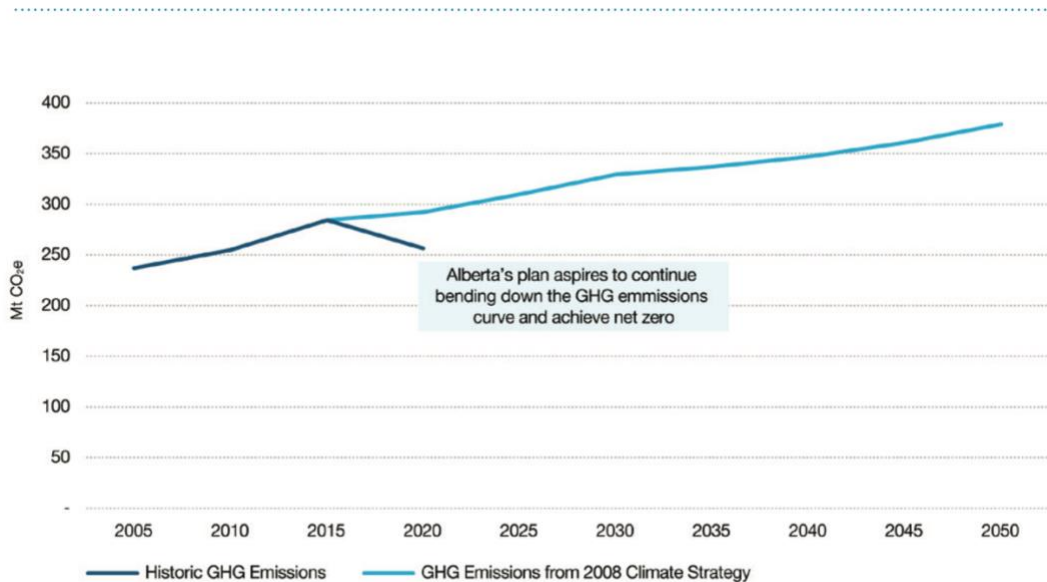


Figure 16. Alberta Plan - Historic GHG Emissions and forecasted by Environment and Climate Change Canada (Government of Alberta, 2023)

Alberta and Saskatchewan are leading in carbon capture and storage (CCS) research and industrial development. Alberta projects like the Quest Project, Alberta Carbon Trunk Line, and Lehigh Hanson Cement study could benefit from ACT!ON’s modeling and optimization tools. ACT!ON also supports emerging blue and green hydrogen initiatives by enhancing the CCUS value chain, project like Cvicvus converting biomass to hydrogen and taking CO₂ out of the carbon cycle can be optimized by ACT!ON. Through collaboration with PTRC, Saskatchewan facilities such as Boundary Dam, Aquistore, and Weyburn-Midale can use ACT!ON’s tools to improve CO₂ capture and storage efficiency (RGRG ERA Milestone 5, 2025).

The growing opportunities for CO₂ capture, transport, utilization, and storage can be most effective when integrated into a cohesive system across various industries. This integration helps broaden market access, improve cost-efficiency and technological progress, and streamline regulatory compliance. The ACT!ON project aims to enable this integration by uniting the diverse and sometimes conflicting interests within the CCUS sector into a comprehensive modeling framework that supports the industry's growth and long-term success.

It’s important to emphasize once more that ACT!ON is not a specific mitigation or storage technology. Rather, it is a network-based initiative that combines a multitemporal integrated assessment model with advanced data management tools. Its purpose is to support the integration of both current and emerging technologies into existing infrastructure across oil and gas, various industrial sectors, pipelines, geological storage, network risk systems, and CO₂ utilization sites. Without these efficiencies and Artificial Intelligence-driven capabilities, regulators and governments will face significant challenges in collecting accurate data and demonstrating the effectiveness and efficiency of CCS and CCUS operations.

10.0 ENVIRONMENTAL, ECONOMIC, AND SOCIAL IMPACTS

10.1 OTHER ENVIRONMENTAL IMPACTS

Decarbonisation accounting and reporting for complex networks including environmental consequences assessment at different time scales allows stakeholders to understand the impact (decarbonisation effectiveness, cost and economics, environmental and potential unexpected performance and maintenance along the chain) of choices over the long-term and inform policy instruments. Relevant environmental metrics describing the potential consequences of networks implementation on decarbonisation efforts can be produced.

By optimizing CCUS, the ACT!ON project aimed to enable the transition to a low-carbon economy, particularly in carbon intensive sectors where alternative decarbonization options are limited. In addition, CCUS can play a crucial role in supporting the integration of variable renewable energy sources, such as wind and solar, by offering a reliable method of offsetting emissions during periods when renewable energy generation is insufficient. This dual approach strengthens efforts toward deep decarbonization while enhancing the stability and resilience of the energy system.

10.2 PROJECTED ECONOMIC IMPACT

Classical economic analysis generally takes into account capital, operating and financial costs of an investment project in a region. Related to the capability of an investment to produce valuable products or services, the profitability of the investment is generally calculated. In case of CCUS projects, the main “product” of the investment is the reduction of CO₂ emissions. The profitability of the investment is then calculated related to its capability to avoid CO₂ penalties. The impact of a CO₂ reduction investment would not only be estimated comparing total costs to total CO₂ reductions (in terms of \$/t CO₂ avoided for example) but would also compare CCUS investment costs with CO₂ penalty costs (that is without CCUS investment).

The ACT!ON project focused on assessing the economic feasibility and regulatory landscape for the large-scale implementation of CCS, CCU, and CCUS globally. These factors, alongside technological advancements achieved through modeling tools and decarbonization assessment methods for industrial clusters, aimed to significantly reduce greenhouse gas emissions and establish a foundation for a low-carbon economy in the EU, Canada, and the US.

Additionally, ACT!ON developed methodologies and tools for integrated cost estimation of CCS/CCU/CCUS networks, addressing a widely recognized challenge. The project incorporated uncertainty and risk assessments across capture, transport, utilization, and storage technologies while considering economic and market fluctuations as part of an integrated system. The outcomes equipped industry leaders and policymakers with the necessary insights to drive decarbonization strategies forward.

Furthermore, ACT!ON evaluated the full life-cycle environmental benefits and costs of various decarbonization scenarios, ensuring that CCS/CCU/CCUS systems are designed with necessary constraints and flexibility. This will help optimize and fairly distribute social, environmental, economic, and political benefits across the entire carbon management value chain.

10.3 RESULTED INNOVATION CAPACITY

The ACT!ON project introduced innovations at multiple levels. First, it developed an integrated network simulator that operates across various time resolutions and incorporates injection constraints from reservoirs and wells to assess the potential of a depleted field for inclusion in a future CCS network. Second, the network model can reliably simulate reservoir responses to CO₂ injection using reduced-order proxy models, incorporating critical processes in

pipelines, wells, and reservoirs, as well as uncertainties, allowing for a stochastic approach. This model supports operators in optimizing well operations and ensuring proper field functioning.

10.4 SOCIAL IMPACT

Numerous researchers have conducted surveys, interviews, and studies to examine public perceptions and preferences regarding energy technologies, either individually or in comparison with others. Understanding these perceptions is crucial for minimizing risks associated with the commercial deployment of CO₂ injection. Negative public sentiment toward proposed industrial and energy projects in local communities can lead to their premature cancellation. Public engagement becomes most tangible when specific projects are planned for particular locations. Most existing studies on public perception focus on the social contexts of the EU and North America, where public attitudes and involvement have both driven innovation and hindered the rollout of low-carbon energy technologies.

The social impact of the ACT!ON project can be categorized in a range of environmental, economic, and social benefits. Environmentally, it helps reduce greenhouse gas emissions, improves air quality, and supports the integration of renewable energy by stabilizing energy supply. Economically, the project creates jobs in sectors such as engineering, construction, and operations, promotes regional economic development, and fosters technological innovation in carbon capture and storage (CCUS). Socially, it enhances energy security by reducing dependence on imports, increases public awareness and engagement in climate efforts, and can deliver local community benefits through development agreements.

11.0 SCIENTIFIC ACHIEVEMENTS

This is a list of some publications generated during the project period:

- A. Korre, S. Durucan, F. Neele, S. Hurter, R. Pawar, R. Chalaturnyk, G. Zambrano, Estublier A., Coussy P., S. Anghel, D. MacLean, W. Sturgess, O. Burachok, F. Devaux, R. Arts, J. Pearson, T. Espie, D. Fujii ACT!ON ERA-NET ACT project: Advanced multitemporal modelling and optimisation of CO₂ transport, utilisation and storage networks. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022.
- A.T. van Nimwegen, R.J.P. van der Linden, S.P.C. Belfroid, R. Octaviano, F.P. Neele. A network model for transport and storage of CO₂. Abstract submitted to 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022.
- Rangriz Shokri, A., Ganesh, A., Zambrano, G., Chalaturnyk, R.J. (2022) Building Reservoir Performance Proxy Models in Saline Aquifer using the Boundary Dam CCS Project, ACT!ON-Emission Reduction Alberta 2nd Steering Committee Meeting, Virtual, November 30.
- A. Korre, S. Durucan, F. Neele, S. Hurter, R. Pawar, R. Chalaturnyk, G. Zambrano, Estublier A., Coussy P., S. Anghel, D. MacLean, W. Sturgess, O. Burachok, F. Devaux, R. Arts, J. Pearson, T. Espie, D. Fujii. Advanced multitemporal modelling and optimisation of CO₂ transport, utilisation and storage networks. SHARP consortium meeting. Oxford 13th June 2023.
- D. Fraga, A. Korre, Z. Nie, S. Durucan (2023) Multi-period, multi-objective optimisation of the Northern Lights and Stella Maris carbon capture and storage chains. TCCS-12, Trondheim, 13th June 2023.
- P. Sharan and R. Pawar 2023. CO₂ Utilization via Concrete Curing, The 47th International Technical Conference on Clean Energy, July 23 to 27, 2023, Clearwater, Florida, USA.
- Sharan, P. et al. CO₂ Utilization via Concrete Curing and potential application in intermountain West USA”, submitted to International Journal of Energy for a Clean Environment.

- Korre et al., 2022. ACT!ON ERA-NET ACT project: Advanced multitemporal modelling and optimisation of CO2 transport, utilisation and storage networks. 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, 23rd -27th October 2022, Lyon, France.
- Ganesh, A., Rangriz Shokri, A., Peralta Gil, Y., Zambrano, G., Chalaturnyk, R. J., & Nickel, E. (2024). Application of Machine Learning Tools for Uncertainty Quantification of Storage Capacity in Geological Co2 Storage Sites. Available at SSRN 5020365.
- Peralta, Y., Ganesh, A., Zambrano, G., Chalaturnyk, R., & Shokri, A. R. (2024, November). Development of Fast Predictive Models for CO2 Enhanced Oil Recovery and Storage in Mature Oil Fields. In Abu Dhabi International Petroleum Exhibition and Conference (p. D011S001R001). SPE.
- Ganesh, A., Shokri, A. R., Peralta, Y., Zambrano, G., Chalaturnyk, R., & Nickel, E. (2024, March). A System Identification Approach for Spatiotemporal Prediction of CO2 Storage Operation in Deep Saline Aquifers. In SPE Canadian Energy Technology Conference (p. D011S015R001). SPE.
- Ganesh, A., Shokri, A. R., Peralta, Y., Zambrano, G., Chalaturnyk, R., & Nickel, E. (2023, October). A Risk-Based Proxy Modeling Approach to Assess the Performance of CO2 Storage in Deep Saline Aquifers. In First EAGE Workshop on Hydrogen & CCS in LATAM (Vol. 2023, No. 1, pp. 1-4). European Association of Geoscientists & Engineers.
- Fraga D. et al. Multi-period, multi-objective optimisation of the Northern Lights and Stella Maris carbon capture and storage chains. Carbon Capture Science & Technology. Volume 11, June 2024, 100190.
- Korre et al., 2025. Process modelling and greenhouse gas emissions accounting of alternative designs of natural gas based hydrogen and ammonia production. Proceedings of the 17th Greenhouse Gas Control Technologies Conference (GHGT-17) 20-24 October 2024.

12.0 OVERALL CONCLUSIONS

- This project highlighted the need for strategic planning in CCUS deployment, recommending an integrated network approach to optimize cost efficiency and infrastructure utilization. Future research should include more detailed parameters for capture costs, dynamic storage capacity, and factors like regulatory policies, land use restrictions for routing, and operational feasibility, ensuring the proposed decarbonization strategies evolve toward successful implementation.
- This project made a substantial contribution on designing an optimal CCUS networks that considers costs of capture, compression, transportation, utilisation and geological storage and simultaneously selects and optimises CO₂ sources, capture materials, capture technologies, and utilisation and storage sites, integrating with utilisation.
- The tools developed will support network operators, who will be responsible for optimum network functionality under variable supply rates, as well as future storage operators by providing an estimate of the performance and value of their reservoir as a future part of an offshore or onshore CCUS network. They will also clarify to the government the required network investments over the coming decades.

13.0 LITERATURE REVIEWED

- Hasan, M; First, E.L.; Boukouvala, F.; Floudas, C.A. A multi-scale framework for CO2 capture, utilization, and sequestration: CCUS and CCU. Comput. Chem. Eng. 2015; 81, 2–21. doi: 10.1016/j.compchemeng.2015.04.034
- Project No 79 - ACT!ON. Full Proposal, 2022. Advanced multitemporal modelling and optimisation of CO2 Transport, utilisation and stOrage Networks– ACT!ON.
- Turgut M. Gür. Carbon Dioxide Emissions, Capture, Storage and Utilization: Review of Materials, Processes and Technologies. Progress in Energy and Combustion Science 89 (2022) 100965.

- Tobias da Cruz et al. Life cycle assessment of carbon capture and storage/utilization: From current state to future research directions and opportunities. *International Journal of Greenhouse Gas Control* Volume 108, June 2021, 103309.
- RGRG – University of Alberta. Risk-based key performance indicators. *Advanced Multitemporal Modelling and Optimization of CO₂ Transport, Utilization and Storage Networks – ERA (E0161584)*, 2022.
- Kongsjorden et al., 1998. Saline aquifer storage of carbon dioxide in the Sleipner project. *Waste Management*, Volume 17, Issues 5–6, 1998, Pages 303-308. [https://doi.org/10.1016/S0956-053X\(97\)10037-X](https://doi.org/10.1016/S0956-053X(97)10037-X).
- Verma, M.K. Fundamentals of carbon dioxide-enhanced oil recovery (CO₂-EOR)—A supporting document of the assessment methodology for hydrocarbon recovery using CO₂-EOR associated with carbon sequestration: U.S. Geological Survey Open-File Report 2015–1071, 19 p., <https://dx.doi.org/10.3133/ofr20151071>.
- Carroll, S.; Hao, Y.; Smith, M.; Sholokhova, Y. Development of scaling parameters to describe CO₂-rock interactions within Weyburn-Midale flow units *Int. J. Greenh. Gas Cont.*, 16 (2013), pp. S185-S195, 10.1016/j.ijggc.2012.026.
- Smith, M.; Sholokhova, Y.; Hao, Y.; Carroll, S. CO₂-induced dissolution of low permeability carbonates. Part I: Characterization and experiments, *Advances in Water Resources*, Volume 62, Part C, 2013, Pages 370-387, ISSN 0309-1708, <https://doi.org/10.1016/j.advwatres.2013.09.008>.
- Hao, Y.; Smith, M.; Sholokhova, Y.; Carroll, S. CO₂-induced dissolution of low permeability carbonates. Part II: Numerical modeling of experiments, *Advances in Water Resources*, Volume 62, Part C, 2013, Pages 388-408, ISSN 0309-1708, <https://doi.org/10.1016/j.advwatres.2013.09.009>.
- Hutcheon, I.; Shevalier, M.; Durocher, K.; Bloch, J.; Johnson, G.; Nightingale, M.; Mayer, B. Interaction ACTIONS of CO₂ with formation waters, oil and minerals and CO₂ storage at the Weyburn IEA EOR site, Saskatchewan, Canada, *International Journal of Greenhouse Gas Control*, Volume 53, 2016, Pages 354-370, ISSN 1750-5836, <https://doi.org/10.1016/j.ijggc.2016.08.004>.
- Korre et al., 2022. ACTION ERA-NET ACT project: Advanced multitemporal modelling and optimisation of CO₂ transport, utilisation and storage networks. 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, 23rd -27th October 2022, Lyon, France.
- Ganesh, A., Rangriz Shokri, A., Peralta Gil, Y., Zambrano, G., Chalaturnyk, R. J., & Nickel, E. (2024). Application of Machine Learning Tools for Uncertainty Quantification of Storage Capacity in Geological Co₂ Storage Sites. Available at SSRN 5020365.
- Peralta, Y., Ganesh, A., Zambrano, G., Chalaturnyk, R., & Shokri, A. R. (2024, November). Development of Fast Predictive Models for CO₂ Enhanced Oil Recovery and Storage in Mature Oil Fields. In Abu Dhabi International Petroleum Exhibition and Conference (p. D011S001R001). SPE.
- Ganesh, A., Shokri, A. R., Peralta, Y., Zambrano, G., Chalaturnyk, R., & Nickel, E. (2024, March). A System Identification Approach for Spatiotemporal Prediction of CO₂ Storage Operation in Deep Saline Aquifers. In SPE Canadian Energy Technology Conference (p. D011S015R001). SPE.
- Ganesh, A., Shokri, A. R., Peralta, Y., Zambrano, G., Chalaturnyk, R., & Nickel, E. (2023, October). A Risk-Based Proxy Modeling Approach to Assess the Performance of CO₂ Storage in Deep Saline Aquifers. In First EAGE Workshop on Hydrogen & CCS in LATAM (Vol. 2023, No. 1, pp. 1-4). European Association of Geoscientists & Engineers.
- RangrizShokri A., Chalaturnyk R. (2019). Non-Isothermal injectivity considerations for effective geological storage of CO₂ at the Aquistore site, Saskatchewan, Canada. SPE-196118-MS.
- RGRG ERA Milestone 1, 2022. Risk – based key performance indicators. ACTION Project ERA (E0161584).
- RGRG ERA Milestone 2, 2023. Development of storage system integrity proxy models. ACTION Project ERA (E0161584).
- RGRG ERA Milestone 3, 2023. Machine Learning Model for Multi-Temporal Dynamic Risk Assessment. ACTION Project ERA (E0161584).

- RGRG ERA Milestone 4, 2024 Report on the methodology to establish risk mitigation measures at CO2 hub and inter-hub level. ACT!ON Project ERA (E0161584). RGRG ERA Milestone 5, 2025. Alberta Canada strategic decarbonization opportunity. ACT!ON Project ERA (E0161584).
- RGRG FPP ACT3 – University of Alberta, 2021. Full Project Proposal (FPP) Supplemental Information. Accelerating CCS Technologies (ACT) 3rd Call.
- Alberta CO2 Emitters Sources Sectors (<https://www.alberta.ca/albertas-greenhouse-gas-emissions-reduction-performance>).
- Zhang, 2022. Development of an engineering simulation and technoeconomic-environmental optimisation framework for industrial decarbonisation. PhD thesis submitted to Imperial College London.
- Government of Alberta, 2023. Alberta emissions reduction and energy development plan. ISBN 978-1-4601-5713-8.