Accelerating results in carbon storage studies using an integrated and automated approach

Aurore Plougoulen[1]* presents an advanced technology and workflow for carbon storage that provides an efficient approach to generating 3D models of the storage complex at all stages of the project.

Abstract

Geological storage of carbon dioxide (CO_2) is considered an enabler of different business models aligned with decarbonization of the energy market. Partnerships are forming worldwide to develop large-scale carbon capture, utilization and storage (CCUS) projects: 2021 was a record year for project pipeline growth for these types of projects. This growth will result in an increasing need for subsurface technologies that can unlock fast time-to-results throughout all the steps of the project, from site selection to storage monitoring.

At an early stage of a carbon storage project, a thorough verification of the technical and economic viability of the project is critical. The high degree of geological uncertainties in the case of storage in under-explored saline aquifers can make this step challenging. As the project progresses, fast assimilation of monitoring data to prove conformance and update predictions of the storage complex performance is key.

An advanced technology from AspenTech can serve as a catalyst for efficient carbon storage studies. It tightly integrates static and dynamic domains and offers the propagation of uncertainties, from seismic characterization through to geological modelling and simulation. Using results from a large set of models increases predictability of the subsurface and enables more efficient analysis of uncertainty in predicted storage capacity and containment. This fully automated workflow can be run at will with new data, drastically reducing the time needed by carbon storage teams to update the model and the predictions as monitoring data is acquired.

Introduction

As part of the net zero pathway, oil and gas, petrochemical and power generation companies are committing to ambitious and broad carbon mitigation. Carbon Capture Utilization and Storage (CCUS) is set to play a key role in reducing emissions from the hardest-to-abate industry sectors. Its ability to prevent carbon dioxide emissions at source and permanently store the captured CO_2 in the subsurface makes it an essential part of the solution. Partnerships are forming worldwide to develop large-scale CCUS projects. However, the IPCC (Intergovernmental Panel on Climate Change) has recently highlighted in its 2022 report that the number of carbon capture projects in the pipeline for 2030 is significantly below where it needs to be to reach net zero emissions (Figure 1). If the world is to come close to achieving net zero, the total mass of CO_2 captured will need to increase by a factor of 40 just in the next eight years. Closing the gap will require a dramatic switch that will enable the rapid design, development and implementation of carbon capture and storage projects.

In that context, there is a sense of urgency regarding the exploration and development of large-scale geological storage to meet these targets and enable decarbonization of the energy market. Digital technology is a critical enabler for accelerating time-to-results throughout all the steps of carbon storage projects, from site selection to post-closure.

This paper presents an advanced technology and workflow for carbon storage. The objective is to provide an efficient approach to generating 3D models of the storage complex at all stages of the project. The integrated and automated workflow presented in this article combines geological modelling and flow

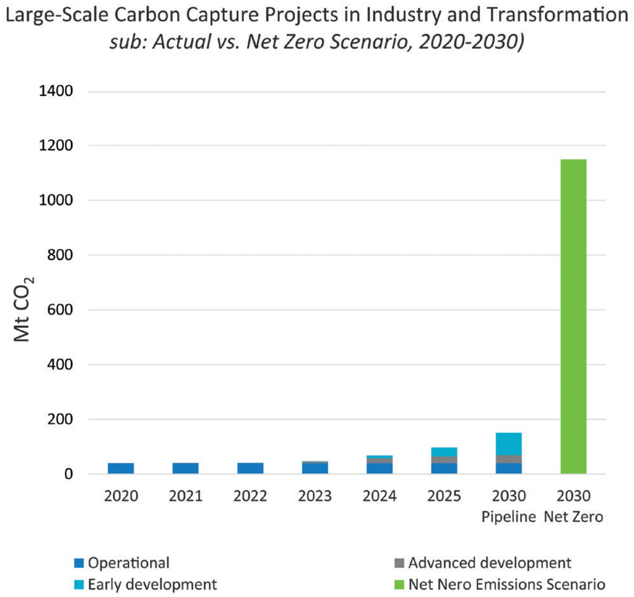

Figure 1 Actual carbon capture projects currently in the pipeline for 2030 vs. number needed to achieve net zero (Source: IEA).

[1] AspenTech Subsurface Science & Engineering
* Corresponding author, E-mail: aurore.plougoulen@aspentech.com
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simulation that can be used to confirm the technical and economic feasibility of the candidate storage site, identify opportunities for reducing costs and optimizing injection, and demonstrate regulatory conformance. The end goal is to accelerate the time to subsurface modelling and simulation results to assist in the rapid design, development and implementation of carbon capture and storage projects.

Carbon storage regulatory framework and specificities

The life cycle of a CO_2 storage complex project can be divided into four main steps: exploration, operation, closure and long-term stewardship or post-closure (Figure 2).

Carbon storage projects begin with exploration, site selection and geological characterization of the storage complex to confirm its suitability for permanent storage of CO_2. At this stage, a thorough feasibility study must be performed to evaluate the technical and economic viability of the project.

The IEA (International Energy Agency) has defined a carbon capture and storage regulatory framework that establishes an approval system for storage site development, including appropriate characterization and site selection processes. The IEA technical guidance is similar to the EU CCS Directive regarding carbon storage and includes:

- Subsurface data collection
- Creation of a 3D static geological earth model
- Characterization of the dynamic response to the injection and storage of carbon in order to estimate storage capacity and CO_2 behavior and fate
- A sensitivity analysis achieved by varying key parameters involved in the performance assessment; the IEA report advises compiling multiple simulations to gain a good understanding of the key factors controlling risks
- Risk assessment based on the performance assessment and sensitivity analysis
- Definition of the proposed modes of operation
- Establishment of a monitoring plan

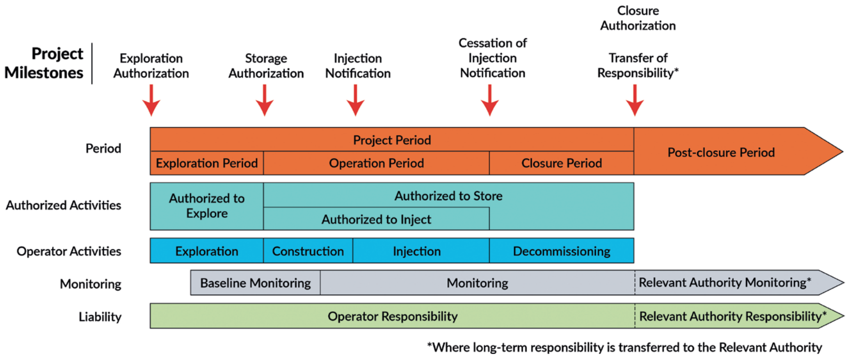
The IEA technical guidance is very similar to what is currently done in the oil and gas industry in the exploration, appraisal and development stages of a field. This means that the oil and gas industry brings many years of technologically advanced software solutions to the carbon storage market. However, these solutions must be adapted to tackle the specific challenges of carbon storage studies.

The life cycle of carbon storage projects is longer than that of oil and gas exploration and production projects, in that operators need to ensure that the carbon will be safely and permanently stored. According to the IEA, the long-term responsibility for stored CO_2 could reside with the host government after a period of operator responsibility once injection ceases. However, the operator will be required to demonstrate confidence in the behaviour of the CO_2 plume and ensure that there is no significant risk of future leakage before transfer of responsibility. This means that, from the feasibility stage to closure, operators need to evaluate the predicted dynamic behaviour of the storage complex over a long period of time, extending years after cessation of the injection.

Today, most operational CCS projects are associated with storage in depleted fields. Depleted fields represent low hanging fruit, as the existing infrastructure can be repurposed to transport and store carbon dioxide. In such cases, large amounts of subsurface data are available, simplifying geological characterization and limiting the degree of uncertainty regarding the storage complex.

However, it is saline aquifers, with their wide geographic extension, that represent the largest storage capacity opportunity. If the quantity of CO_2 to be captured and stored is to be multiplied by 40 by 2030, saline aquifer storage will need to increase. Feasibility studies for saline aquifer storage may be more challenging than depleted fields, as these aquifers are often under-explored. It means that geoscience teams will need a digital solution that allows them to consider a high number of uncertainties in their sensitivity analysis. Moreover, when storing CO_2 in a saline aquifer, the CO_2 plume can extend over a large areal scale. This requires the construction of large-scale 3D geological models to accurately predict the CO_2 fate and the subsurface response to carbon storage.

At the operational stage of a carbon storage project, the operator is required to begin monitoring the storage complex and injection facilities to ensure safe and secure permanent storage of CO_2. Monitoring is essential to assess whether injected CO_2 is behaving as expected, whether any migration or leakage is occurring, and whether any identified leakage is damaging the environment or human health (governmental regulations). Monitoring practices and requirements will continue to evolve as greater practical experience is gained in the coming years. However, the current regulatory framework mentions the need to collect and interpret monitoring data, with the observed results being compared to predicted behaviour. Calibration of the 3D models to the monitoring data must be



*Where long-term responsibility is transferred to the Relevant Authority

Figure 2 The life cycle of a CCS project as presented in the IEA regulatory model framework.

repeated on a regular basis across the life of a storage project to provide updated predictions. If significant differences are observed between the previous performance assessment and the observed behaviour, the monitoring plan might need to be adapted. In that context, it appears that there is a need for digital technology that will enable fast-tracking of the integration of monitoring data in 3D models and updating storage performance predictions, in order to reduce the time spent demonstrating regulatory conformance.

An integrated and automated digital technology

This paper reviews the application of the AspenTech Big Loop technology to a case of carbon storage in a saline aquifer.

While this technology has been used in a variety of oil and gas assets, from exploration to production (Abd-Allah et al. 2017), the workflow appears today to be even more relevant to carbon storage studies. Its evergreen and collaborative aspect and its ability to provide a quantitative assessment of uncertainty answer the challenges of carbon storage projects: long project duration, a high degree of uncertainty in the case of storage in saline aquifers, and the need to regularly integrate storage monitoring information into 3D models.

The presented solution is an application-agnostic ecosystem for creating automated, reproducible and auditable workflows that help to propagate uncertainties and capture their dependencies, resulting in reliable probabilistic predictions. The workflow includes tools to generate an ensemble of models, as advised by the IEA regulatory framework, by orchestrating multiple software applications (Figure 3) to create a wide-ranging cross-domain workflow. This enables the entire workflow to be run in batches many times over, generating multiple geologically consistent 3D models.

In this paper, the workflow orchestrates geological modelling and flow simulation applications to generate 3D models that integrate the existing static and dynamic uncertainties in the storage complex. Static and dynamic modelling parameters with uncertainties are changed in each realization to sample the uncertainty space. As a result, a sample of realizations is generated; the realizations cover the range of possible models rather than restricting the uncertainty analysis to low/medium/high representative models. Each model represents a probable configuration of the geological storage based on the specified uncertainties. Percentiles at different times can be derived from the ensemble members and used for any simulation output, such as pressure or total CO_2 injected; a range of values, each with its measure of confidence, can then be calculated. The use of ensembles improves understanding of the storage complex and helps answer questions such as: What is the P10, P50, P90 effective storage capacity? What is the P50 total mass of injected CO_2 in 5, 10 and 15 years? How reliable is my P50 case through time? What is the risk of reservoir pressure reaching fracture pressure?

In this application, the link between the geomodelling workflow and the reservoir simulator is controlled by a sophisticated shared uncertainty analysis tool, so that all asset members can contribute in the same time frame and as part of the same workflow. Uncertainties from the different disciplines are preserved and propagated through the stages of the modelling process. A common understanding of the storage complex is increased through multi-disciplinary collaboration and results in the generation of consistent models. The team can confidently present to decision makers an understanding of the storage capacity, containment and injectivity with their associated uncertainties, and guide future data acquisition.

To aid the storage operation planning process, an embedded optimization method accounts for geological uncertainty. The optimization workflow is based on an ensemble of models that capture the uncertainty as described above (Bordas et al, 2020). The goal is to find values for a set of control parameters that maximize an objective function. The objective function can be as simple as the total mass of CO_2 injected, through to a comprehensive estimate of the net present value of the carbon storage project. The control parameters are defined by the operation strategy. Controls can include targets for injection rates, location of the injection well(s) or drill time of the new well. Such a workflow allows operators to optimize injection and drilling plans to ensure the economic success of the project.

At the operational stage, when monitoring data is acquired and the operator is required to demonstrate regulatory conformance on a regular basis, the existing workflow is able to run the existing automated static and dynamic workflows and integrate new data into the models. The models are calibrated to the observed data, and input parameter likelihoods are constrained by observed data of any type: static, dynamic, spatial and time dependent. The assisted history-matching process can be proxy-based or ensemble smoother-based, depending on user preferences and on whether or not 4D seismic data is integrated (Taha et al, 2019). With both methods, the result is a ready-to-analyse flow model of the storage complex calibrated to multiple geophysical, geological and dynamic data, ensuring consistency with underlying geology. This enables a drastic reduction in the time needed to update the models and provide new predictions of future storage performance to decision makers and regulators.

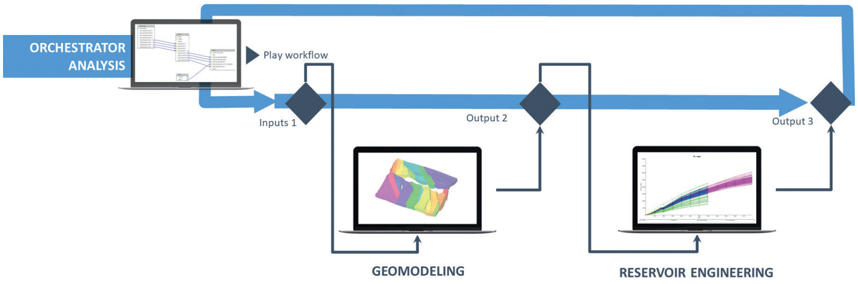


Figure 3 AspenTech automated and integrated subsurface workflow principle. The modelling tasks are played automatically in sequence. The workflow, inputs and outputs are controlled by the workflow orchestrator.

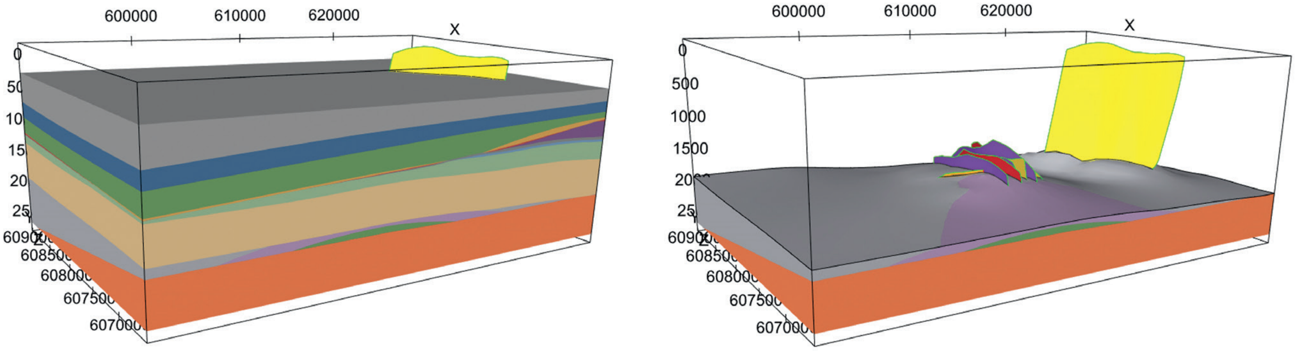


Figure 4 The structural model includes the whole column of rock from seabed to layers at 2500 m depth (a). The targeted faulted anticline is also shown (b).

Preliminary results of an application to a carbon storage case

The results shown in this section relate to a synthetic case based on the structure of an existing offshore Netherlands reservoir.

In this case, the targeted saline aquifer is in a faulted antiform. A shaly caprock and the anticline form a structural trap to store CO_2. Several faults cross the storage formation and end in the caprock. However, a major fault crosses the entire stratigraphic column in the east.

A structural model including the over-burden and under-burden is built using seismic interpretation (Figure 4). A high-resolution 3D geological grid is also created and used to support the modelling of facies and petrophysical properties based on logs from one well and on geological knowledge of the area. A flow model is derived from the same structural model and properties are upscaled from the geologic model. All the processes described above are controlled by a workflow manager that enables process automation and updates. In this case, uncertainties are considered on the horizon depth and fault locations, facies modelling parameters, porosity and permeability modelling parameters.

The modelling application is connected to a flow simulator to simulate the subsurface dynamic response to carbon injection and storage. The compositional flow model is simulated over a period of 100 years. During the first 30 years, CO_2 is injected from a well located on the west flank of the anticline (Figure 5) at an average injection target rate of 2Kt of CO_2 per day with a limit on the well bottom hole pressure that prevents the fracture pressure value being exceeded. CO_2 is injected at the base of the reservoir unit and is expected to spread toward the centre of the structure. Uncertainties are considered on the fault transmissibilities and rock compressibilities.

Several realizations of the entire static and dynamic workflow are run with different values of the parameters that have been defined as uncertainties. In this preliminary analysis, the focus of the sensitivity analysis is to understand the impact of the uncertainties on increased reservoir pressure over time, the total mass of CO_2 that can be injected over the 30 years, and the extension of the CO_2 plume.

The ensemble of models is analysed using dedicated post-processing tools designed to make the display more accessible to geoscientists and engineers and enable them to easily extract meaningful information from the ensemble models. The interactive dashboard enables the team to post-process a large number of simulations (Figure 6) as a coherent ensemble to gain a good

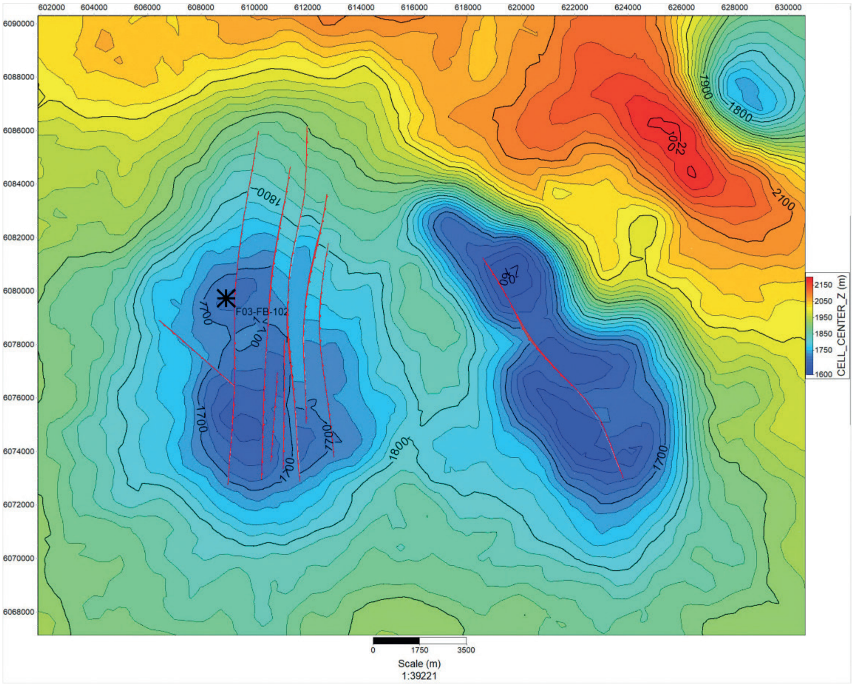


Figure 5 Map of the faulted top of the storage reservoir with contours indicating the burying depth (m). The injection well location is marked with a black star.

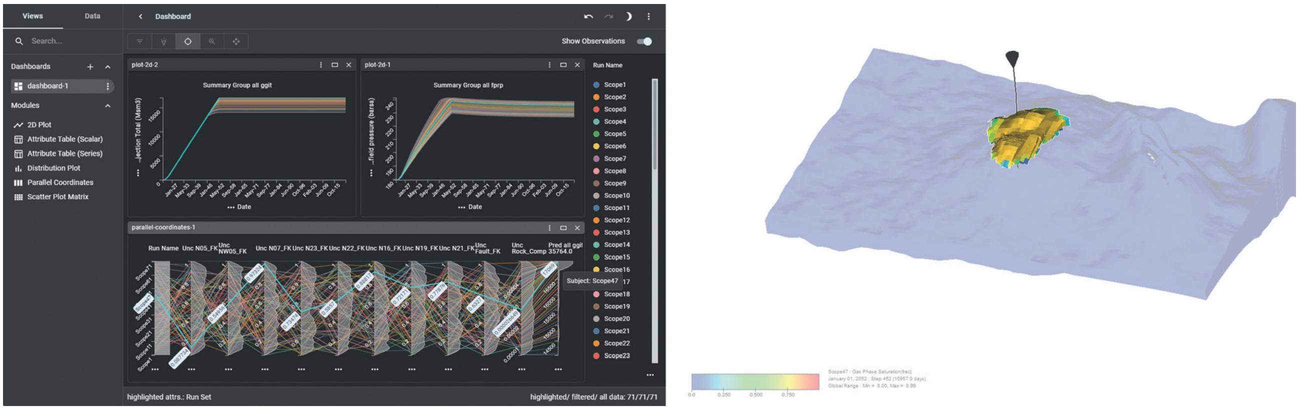


Figure 6 Left: Interactive dashboard to post-process the ensemble of models generated. Total CO2 injected, field pressure, and range and values of uncertainties are displayed in the dashboard. Right: 3D view of the dynamic model corresponding to the highlighted simulation (blue) on the left.

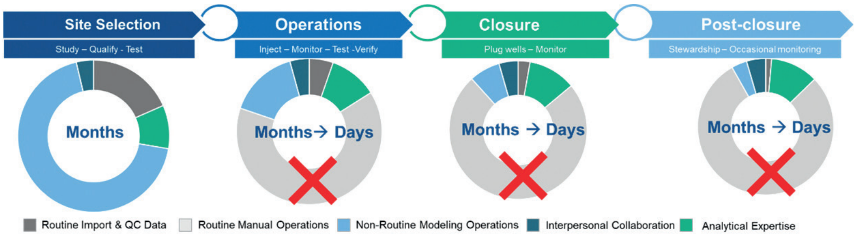


Figure 7 Optimized reservoir modeling cycle time.

understanding of the storage complex and to clearly communicate to management, partners and regulators about the impact of uncertainties. It appears that with the existing degree of uncertainties on the structure, rock property modelling parameters, fault transmissibility and rock compressibility, the total mass of CO_2 that can be injected varies between 25 and 31 Mt and the maximum pressure increase in the storage reservoir varies between 45 and 58 bar. In all the models generated, the CO_2 does not leak to the second anticline structure in the east where a major fault is crossing the entire stratigraphic column. At this stage, the containment of the CO_2 is validated but it will need to be confirmed in an additional step using geomechanical simulations.

The results presented in this paper for the case described above focus on an overview of the initial sensitivity analysis. Now that the automated and integrated workflow has been set up it is ready to be leveraged at any time throughout the life of the carbon storage project. Starting with the ensemble of models generated, the optimal injection well location and operation modes can be evaluated. Once the injection begins, the team will be able to reuse the existing workflow to integrate monitoring data and update the models. A tremendous amount of time will be saved by eliminating the need to perform a series of routine manual modelling operations (Figure 7).

Conclusion

An automated scalable workflow from geomodelling to reservoir engineering is strategic in carbon storage studies. The advanced workflow presented in this article can help carbon storage project stakeholders to accelerate time-to-results, from site selection to post-closure, while meeting regulatory requirements.

The workflow provides a collaborative ecosystem for G&G disciplines and reservoir engineers. It reduces the risk of losing information throughout the process of building and updating 3D models of the storage complex. The technology enables the generation of an ensemble of models to capture and propagate geological uncertainties through the different stages of the modelling process, and predict the storage complex dynamic response with more confidence.

Moreover, the presented workflow answers the need for a digital technology for projects that extend over a long period of time. Indeed, the auditable and automated nature of the technology enables new team members to be recruited quickly. Models can easily be updated with the latest storage complex information in a short period of time. It results in updated predictions of the storage performance, based on calibrated 3D models, that can be provided to decision makers and regulators at any time.

The featured workflow framework is open and can be extended. More applications can be connected, such as a flow assurance and optimization software to model the storage of CO_2 from surface to subsurface. The workflow is open enough to allow organizations to build their own workflow framework, which can be replicated and customized for any of its storage assets.

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