Probabilistic risk assessment for CO_2 Storage: From pilot to commercial scale

Introduction

The PilotSTRATEGY project is a European collaborative effort focused on evaluating the feasibility of underground CO_2 storage in several deep saline aquifers (Bordenave et al., 2023; Bordenave & Wallendorff, 2023). The project covers the mandatory technical studies to comply with legal documents required for the installation of demonstrators or pilot sites. It addresses both technical and socio-economic aspects applied to different chosen study areas. This abstract is specifically dedicated to the quantitative risk assessment conducted during this project and applied to the Paris basin. The study identifies and evaluates 17 risk events classified under three categories: safety risks (e.g. leakage through pre-existing wells, caprock integrity failure, interference with other subsurface uses), performance risks (e.g. lateral plume extent, storage capacity, injectivity), and project risks. These risk events were ranked through a first-round evaluation process and divided into two priority levels. Priority 1 (P1) risks, esteemed as most critical, treated through detailed probabilistic analysis using influence diagrams and Monte-Carlo risk models. Priority 2 (P2) risks were assessed through simple qualitative methods based on expert judgment and estimates usually based on simpler models(Le Guenan et al., 2024).

Method

The risk assessment began with the systematic identification of 17 risk events. For each P1 risk event, influence diagrams were constructed to map the relationships between input uncertainties and risk outcomes, then followed by the development of a probabilistic workflow to treat the P1 risk assessment. The toolkit integrates a range of 2016 dynamic reservoir simulations conducted to provide a representative sampling of uncertainty. Twenty uncertain parameters were varied across the dynamic simulation ensemble, including reservoir permeability-porosity relationships, rock/flow properties, injection rates, and the activity status of a nearby water disposal well (Alavoine et al., 2024). In fact, a fertilizer manufacturing plant has been discharging pre-treated industrial effluents into the Dogger aquifer (the targeted reservoir) within the area of interest(Mathurin et al., 2023). Regarding porosity, since the original porosity realizations and their statistical distributions could not be recovered, the simulations are based on three representative scenarios: a pessimistic estimate (P10), a central estimate (P50), and an optimistic estimate (P90)(Christ et al., 2024). This results in 672 realizations per porosity scenario. The probability distributions assigned to the 20 uncertain parameters are either based on experimental plug samples estimates, or on expert assumptions and analogue-based distributions when direct measurements or site-specific data are lacking.
Two injection scenarios were modeled. The pilot scenario assumed an injection of 100 kt of CO_2 over 4 months, followed by 1000 years of post-injection monitoring. The industrial (commercial) scenario assumed a continuous injection rate of 300 kt/year for 30 years, also followed by 1000 years of monitoring. The pilot scenario was evaluated first to determine its suitability for risk analysis. Results showed negligible impact under all simulated conditions, confirming that risk evaluation at this scale is not possible (see Figure 1). Therefore, the industrial scenario was selected as the basis for detailed quantitative risk assessment.
The conducted simulations are consequently propagated through risk models, and the outputs are expressed as loss distribution curve, providing key percentiles (P10, P50, and P90) that translates the range of potential consequences. Sensitivity analysis methods were applied to rank the importance of input parameters, in order to quantify the contribution of each uncertain input to the variance in the risk output.

Results and conclusions

As predicted during the first-round evaluation, the pilot-scale scenario presents very little risk. The probabilistic risk model was unable to generate undesired risk scenarios. The limited injection volume and short operational period result into a CO_2 plume spatially confined and does not approach any pre-existing wells and does not exceed the seismic survey area (see Figure 1 left). While this confirms that pilot-scale operations present negligible safety risks, it also indicates that the pilot scenario cannot serve for testing the risk models. However, the pilot phase remains important from a model calibration perspective: the data that could be collected from a pilot injection will provide valuable measurements to validate and refine the reservoir models and reduce the assumptions currently used.

On the other hand, the industrial-scale scenario produces different results. The numerical simulations demonstrate that, under current model assumptions, the CO_2 plume can reach nearby wells and might extend beyond the boundary of the 3D seismic survey area (see Figure 1 right). These results are important for both safety risk management and the design of the monitoring program. However, it is expected that the extent and probability of plume migration will be refined as the models are updated with pilot data and additional information.

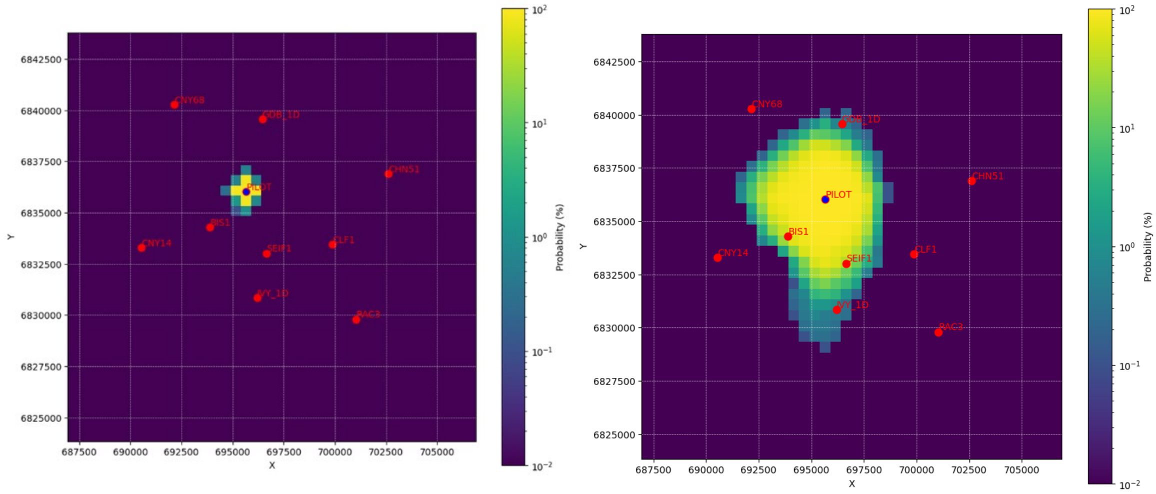

Figure 1 *Probability of CO_2 gas occurrence per grid cell across all realizations over the simulation period. Left: pilot injection scenario; right: commercial injection scenario. Red dots indicate pre-existing wells in the area; the blue dot represents the CO_2 injection well.*

The analysis of the pre-existing well data was conducted for wells that are potentially in contact with the plume. This analysis revealed that the IVY1 well has documented missing plugs, and the BIS1 well exhibits variable cement quality across its intervals. The most identified probable safety risk is leakage through the BIS1 well into the Lusitanian aquifer. However, the analysis also indicates that a direct pathway for CO_2 to reach the surface through BIS1 is unlikely, as the well contains at least six plugs in addition to cement and casing barriers. For SEIF1, which is still an active well, a proper integrity evaluation can and should be conducted.

Regarding potential interactions with other subsurface uses, the assessment is limited to the overpressure effects and the lateral extent of the plume, as no additional data is available at the boundaries of the model. The study site is surrounded by several petroleum concessions, yet the only indicator at this stage is the pressure perturbation propagating toward the model limits.

Concerning injectivity and storage capacity, the model results further confirm that the modeling assumptions adopted in this study tend toward conservative estimates. As for caprock integrity and induced seismicity, the current simulation results do not raise any significant concerns.

Conclusions

The quantitative risk assessment conducted within this study provides a comprehensive probabilistic workflow for evaluating CO_2 storage risks across pilot and industrial scales. Pilot-scale injection presents negligible risk. Whereas the industrial-scale injection presents few risk scenarios that require further investigation. The most probable risk event is CO_2 migration through BIS1 into the Lusitanian aquifer, although direct surface leakage remains very unlikely.
The risk assessment workflow presented here must be updated when new data becomes available. Then the models should be recalibrated, and the risk outputs reassessed. The updated risk assessment should progressively inform the definition of the storage permit perimeter, considering the new plume extent predictions and the development and implementation of remediation plans for pre-existing wells.

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