Recommendations for the Technical Governance Framework to Build a Resilient Carbon Storage Portfolio in Saudi Arabia

Introduction

As the Kingdom of Saudi Arabia strives to achieve net-zero by 2060, a critical component of the vision is about developing a robust carbon storage exploration program capable of supporting large-scale CCS projects in future. Among several initiatives, the carbon storage exploration is aimed to identify and develop a resilient portfolio of mega-scale carbon sinks within the diverse geological landscape of the Kingdom. The primary objective is to assure availability of long-term geologic storage options across all regions that can effectively minimize the need for cross-country transport of industrially emitted CO_2. By generating a balanced and healthy portfolio of carbon storage, we aim to address emission challenges faced by different industrial hubs, paving a strategic path-way towards decarbonization.

More than 50 perspective sinks have been identified all over the kingdom covering up to 100,000 sq km. that may potentially store several gigatons of industrial carbon dioxide over decades, adequate to achieve the net-zero ambition. These prospective sinks consist of carbon storage complexes from different geological ages and tectono-stratigraphic settings associated with varied exploratory risk profiles. While the key carbon storage elements for evaluation remain same for all the opportunities, the geological complexity of each of them are different. In order to develop and mature a healthy exploration portfolio of carbon storage, it is essential that the identified sinks are evaluated using a standardized technical governance process. Here, we present the 4-stage carbon storage prospect maturation workflow that is established for exploration governance framework that spans from screening through feasibility check and detailed technical evaluation to the final recommendation of a drill-ready prospect (figure 1). This governance structure also ensures cross-functional collaboration and negates the possibility of any operational conflict with ongoing hydrocarbon exploration and development. Considering the cost sensitivity of the carbon storage projects, a 3-dimensional technical evaluation approach is adopted for early assessment of uncertainties that can effectively guide the exploration program.

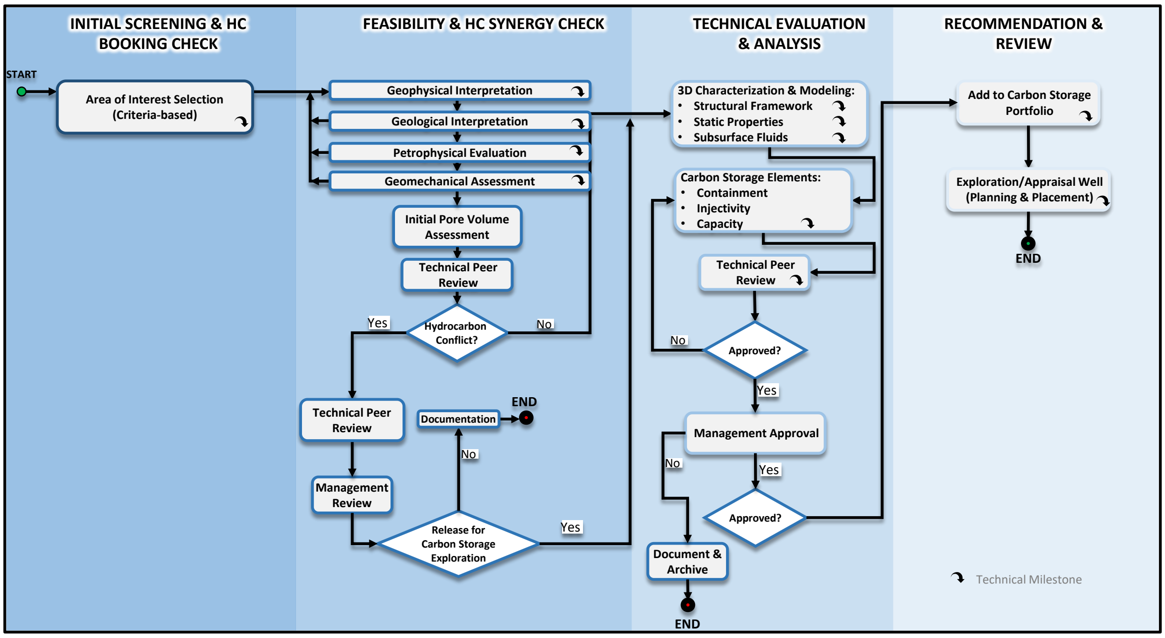

Figure 1: *The 4-stage carbon storage exploration workflow*

Initial Screening and Hydrocarbon Booking check

Screening of potential geological sinks for carbon storage is conducted at a sub-basinal scale, considering proximity to emission sources, land usage and areas of hydrocarbon interest. Initial geological parameters, such as stratigraphic zones of interest within favorable depth windows for carbon storage and aquifer salinity, are evaluated to identify suitable sinks. Following this, a regional synthesis is performed in collaboration with exploration teams to gain a deeper understanding of the tectonic setting, depositional environment, and stratigraphic framework. Once integrated, these serve as a key input for defining the potential carbon storage complex. A typical storage consists of at least a primary aquifer-seal pair and a regional seal to ensure long-term containment of stored CO_2. The presence of additional aquifer-sink pairs can further improve the risk profile of the opportunity as it matures. Geological sweet-spots are identified based on the initial regional synthesis, and prioritized for further evaluation, with preference given to those with closer proximity to CO_2 sources, minimal overlap with hydrocarbon operations, fewer legacy wells, lower structural complexities and more reliable seals. An overview of the screening workflow, including a go-no-go criterion for screening as illustrated in figure 2.

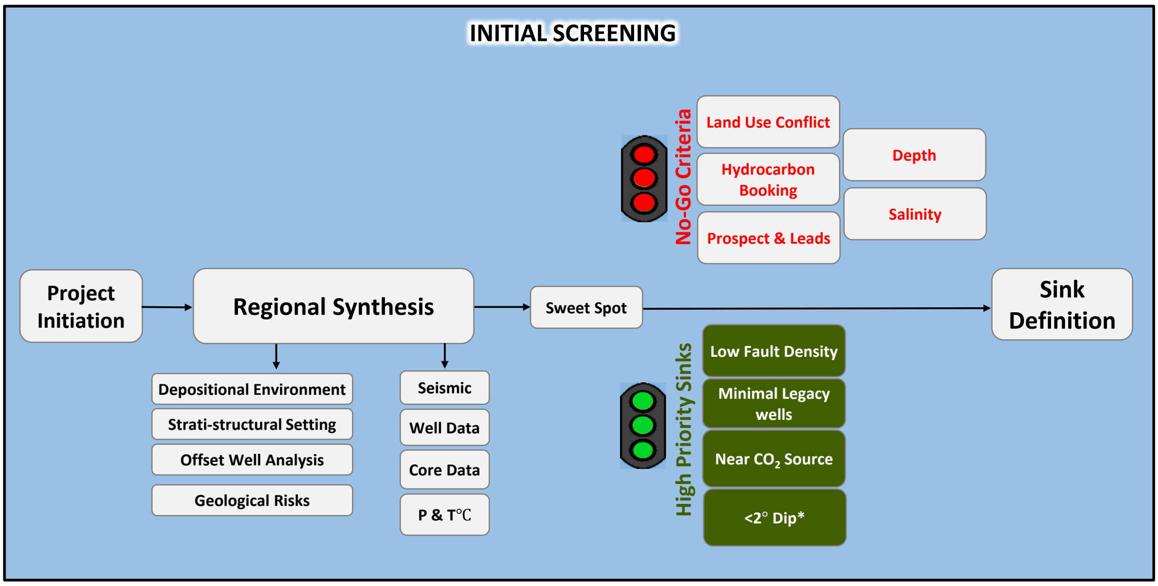

Figure 2: *Go-no Go criteria for screening carbon storage sinks*

Feasibility and Hydrocarbon Synergy Check

The feasibility study phase in carbon storage shares similarities with hydrocarbon prospecting, where key geological features are meticulously mapped to define the prospect boundary. In this phase, the essential elements of the carbon storage complex, including the primary and secondary aquifer-seal pairs and the regional seal, are deterministically mapped on seismic data to define the spatial extent of the prospect. Well data are interpreted for formation tops further evaluated to derive petrophysical parameters that are used to calibrate seismic inversion, stratigraphic analysis and geomechanical studies. The primary objective of this stage is to accurately delineate the carbon storage prospect and prepare the area of interest for a detailed technical evaluation. The geomechanical integrity of the carbon storage complex are also assessed at this stage. It includes, rock strength analysis for the aquifers to help calibrating injection rates and pressure. The faults and seals are also evaluated for their continuity and ability to hold pressure of the injected CO2, thereby ensuring long-term containment.

An overview of the domain-specific studies conducted during the feasibility stage is illustrated in Figure 3, providing a comprehensive framework for assessing the technical feasibility of the carbon storage prospect. Another critical aspect of the prospecting phase is to confirm hydrocarbon synergy. Prospecting efforts are primarily targeted around open or confined aquifers; however also attempts to synergize with hydrocarbon prospects at other stratigraphic units, making a stronger case for exploration drilling.

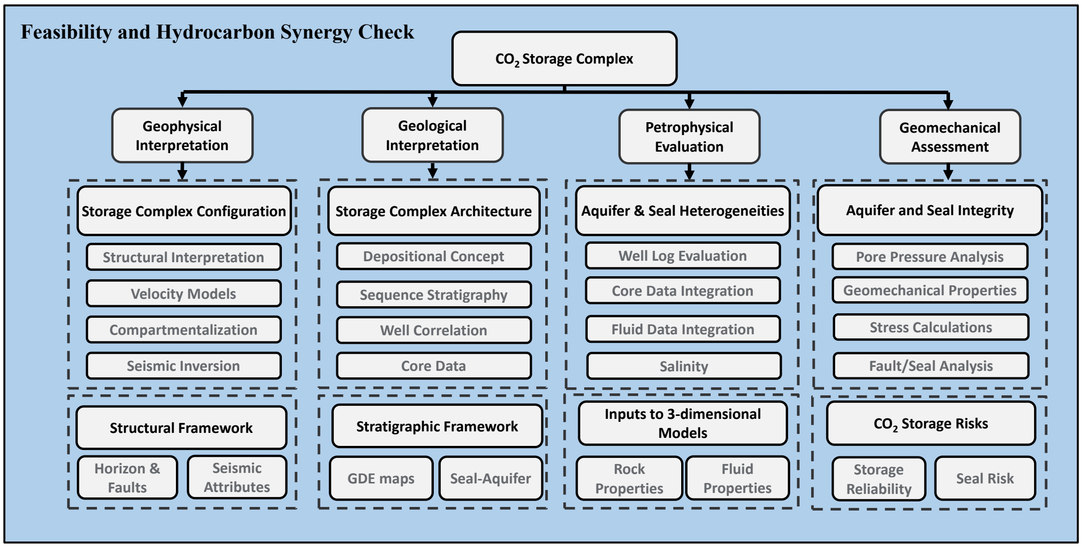

Figure 3: *Different geological studies for carbon storage feasibility assessment*

Technical Evaluation and Analysis

The technical evaluation of carbon storage prospects involves integration of all available data for 3-dimensional characterization of the subsurface, resulting in geological model scenarios and subsequent flow simulations. The simulation models forecast probable migration pattern and extent of the CO_2 plume once injected, providing a detailed view of the storage mechanism. While, reservoir characterization studies are more suited for development stage in conventional hydrocarbon maturation cycle, its application in carbon storage exploration enables the creation of prospect-scale geological models and flow prediction. This approach enhances the understanding of the aquifer and seal properties, facilitates the integration of offset data, enables early decision-making and optimization of future data acquisition strategies. The technical evaluation helps reducing the uncertainty of key carbon storage elements - capacity, injectivity, and containment; there by enabling quantitative evaluation of the storage potential and area of reference. Also, an initial development concept can be prepared using the study results, providing a basis for future project planning. The subsurface models are also leveraged to develop a cost-effective monitoring strategy, utilizing the most suitable technologies for the project. Figure 4 provides an overview of the technical evaluation and analysis framework, highlighting the integrated approach used to evaluate carbon storage prospects.

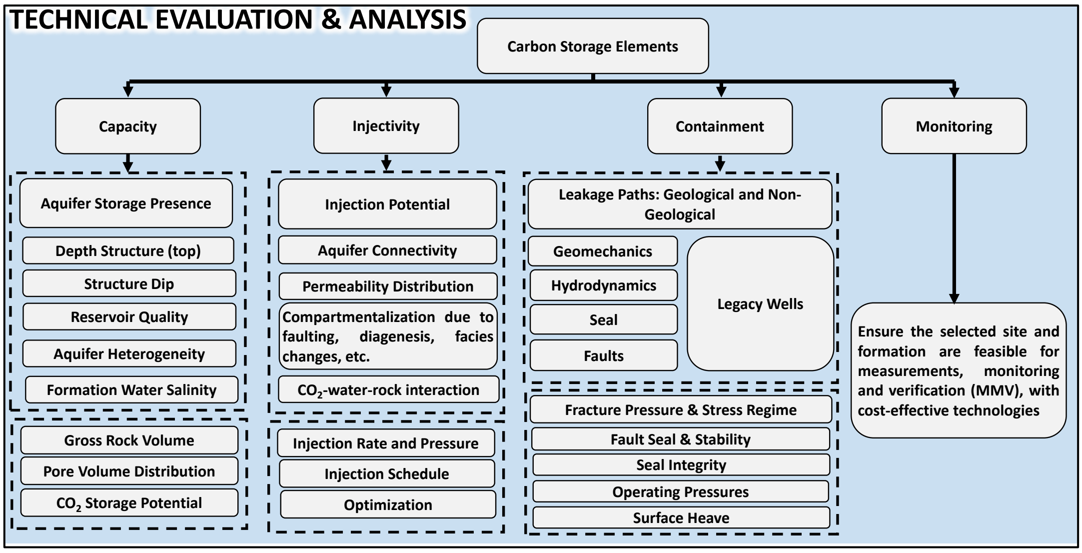

Figure 4: *Key geologic and engineering parameters for technical evaluation of the carbon storage elements*

Recommendations and Review

Upon completion of the technical evaluation of the storage complex, an initial development concept is refined and matured based on the study outcomes. The calculated carbon storage potential for the prospect is thoroughly documented, and exploration/appraisal well planning is initiated. The well location and data acquisition plan are carefully determined by the prospective areas identified within the area of reference, as derived from the geological model and flow simulation results. The key subsurface uncertainties identified during the technical evaluation, drive the scope of data acquisition, ensuring that the most critical information is collected to mitigate risks and optimize the development plan. This marks the culmination of the technical assessment of the carbon storage complex, where the mapped prospect is advanced to a drill-ready condition. Figure 5 provides an overview of this stage, highlighting the key activities and milestones involved.

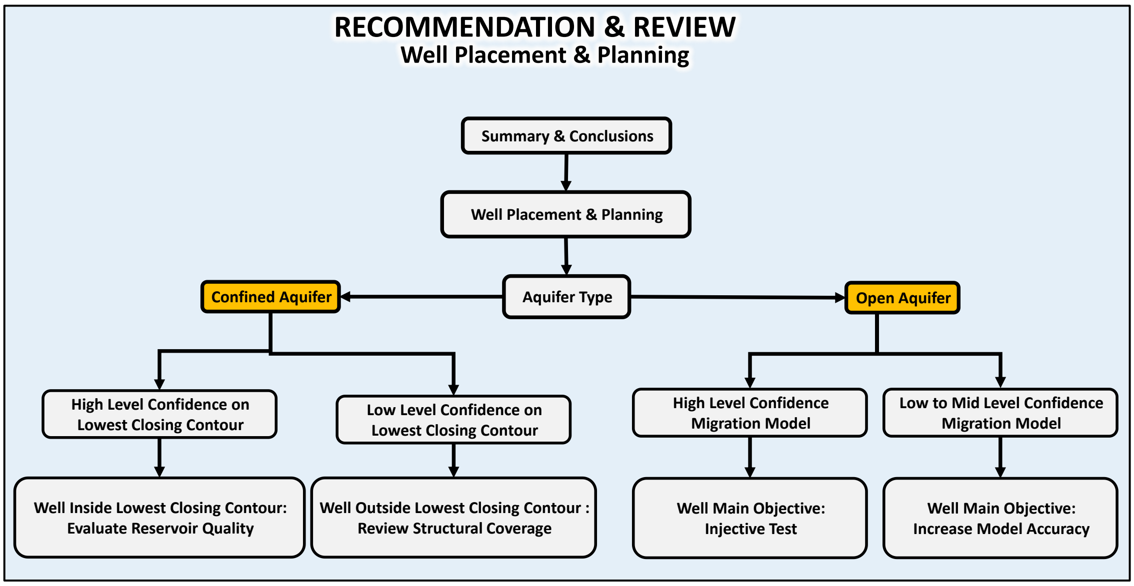

Figure 5: *Key geologic and engineering parameters to evaluate the carbon storage elements*

The actual drilling of an exploration/appraisal well and the development of the carbon storage complex are subsequent steps that are subject to operational planning, budgeting, and approvals. Additionally, the project's viability is contingent upon its linkage to a carbon capture project in the region, ensuring an integrated proposition for carbon capture and carbon storage.

Conclusion

The evaluation of a carbon storage complex relies heavily on integration of geological interpretation, geomechanical assessment, subsurface characterization, and flow simulation. While carbon storage studies share similarities with hydrocarbon exploration methodologies, they require a unique approach due to distinct concepts and desired outcomes. The characterization of saline aquifers, in particular, poses significant challenges due to the large areas of interest and limited data availability. Nevertheless, by analyzing geological processes and subsurface parameters, the risks related to storage capacity, injectivity, and containment can be effectively mitigated. A standardized governance framework equipped with robust quality assurance mechanisms, provides a unified approach to evaluate carbon storage prospects. This facilitates benchmarking and prioritization of exploration options based on risk-reward criteria. As the demand of carbon capture and storage continues to evolve, future enhancements to this governance framework, such as automated quality assurance and developing AI-driven source-to-sink mapping techniques, will play a crucial role to accelerate the maturation of carbon storage exploration portfolios, ultimately driving the transition to a low-carbon economy.