**Engineering the Sequestration of Carbon: Challenges and Opportunities**
**Introduction**

Anthropogenic greenhouse gas emissions (GHG) have reached very high levels, causing long-term climate changes and visible in many ways such as rising sea levels, warmer and more acidic oceans, diminished ice coverage, increased global surface temperatures, and multi-dimensional chemical changes that can alter the global equilibrium of the earth systems. This climate shift has started to disturb natural ecosystems and human societies, necessitating significant changes in how we manage and allocate natural resources and our living spaces (IPCC 2007; IEA 2022a).

The escalating vulnerability of our natural and human systems underscores the urgency to control the effects of climate change and to prevent severe and widespread incidents such as heat waves, wildfires, floods, droughts, and cyclones. These events pose a significant risk to the entire ecosystem and obstruct global socioeconomic progress. Consequently, climate change experts suggest the need to restrain the rise in surface temperatures to below 2 °C compared to pre-industrial levels throughout the 21st century (IEA 2021). This can be attributed to CO2 emissions that is increased significantly since the industrial revolution and parallel the growth in power requirements to sustain the demand as well as current lifestyles.

Gas injection at large scale has been practiced in petroleum/subsurface engineering area for more than half century. Many technologies developed during this period. Initially, most of the technologies for various gas injection processes, such as hydrocarbon gases and/or CO2, developed are centralized around the recovery improvement and gas storage. Later on, these technologies are applied for CO2 sequestration successfully at different settings at various countries. When the objective of CO2 injection is not limited to oil recovery processes, the application envelope for CO2 injection includes wider spectrum of options, such as deep saline aquifers and as well as basaltic rocks in addition to depleted hydrocarbon reservoirs and coal seams. Each option/case will have its own complexities, from data requirements to monitoring, especially in the context of reducing the uncertainty for screening, project execution and surveillance. In this talk, we will stress some of the key points and challenges of this global problem & how and how much progress was made in terms of reducing uncertainty for various subsurface options. Every option will require different type of evaluation and as well as dataset to be able to reduce the uncertainty in the analysis.

Significant efforts have been presented in literature to implement carbon capture, utilization, and storage (CCUS) projects, in the context of technological challenges, capacities, and perspectives. We categorize the proposed options into three groups:

1. Currently available technologies; (deployable options today)
2. Near-future technologies; (enabling technologies are getting cheaper – or not – to be coherent with the current technologies for the future)
3. Long-term technologies.

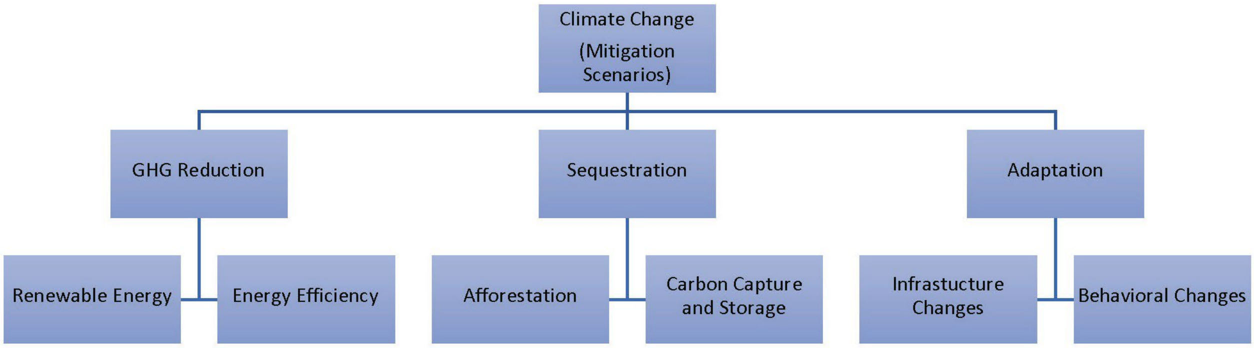
Categories (2) and (3) are discussed in terms of cost and scale-up potential, where both can be an impediment for wide-scale deployment. Many such options are functions of the energy price and local incentives. Therefore, while focusing on the technical aspects, we also discuss some of the enabling factors. Some of the elements of (2) are also related to source-sink matching, yet direct air capture (DAC) is being highlighted as a remedy of this issue while the costs are still an impediment for widespread use (IEA 2022b). In this talk, we examine methods that use CO2 and other gases to improve the recovery of hydrocarbons and simultaneously store concentrated CO2 in the subsurface. Our main conclusion is that the petroleum industry has all of the tools and expertise to implement and adopt CCUS projects and to contribute to the sustainable future from a technological perspective (see, the books towards reducing emissions/CCUS: Livescu-Dindoruk 2025, Dindoruk-Temizel-Ratnakar, 2026, Temizel-Dindoruk-Phirani, 2026). Current and future challenges and opportunities are outlined, along with the essential role for engineers to secure foreseeable robust solutions.

Gas injection at large scale has been practiced in petroleum/subsurface engineering area for more than 50 years. Many technologies developed during this period. Initially, most of the technologies for various gas injection processes, such as hydrocarbon gases and/or CO2, developed are centralized around the recovery improvement and gas storage. Later on, these technologies are applied for CO2 sequestration successfully at different settings at various countries. When the objective of CO2 injection is not limited to oil recovery processes, the application envelope for CO2 injection includes wider spectrum of options, such as deep saline aquifers and as well as basaltic rocks in addition to depleted hydrocarbon reservoirs and coal seams. Each option/case will have its own complexities, from data requirements to monitoring, especially in the context of reducing the uncertainty for screening, project execution and surveillance.

Overall the challenges are due to

1) Data, key data supply
2) Scale-up and guidelines for proper scale-up
3) Software/tools with Multiphysics
4) Surveillance
5) Guidelines

In this talk, we will stress some of the key points and challenges of this global problem how and how much progress were made for various subsurface options.




**Climate change and mitigation scenarios.**

## Conclusions

At the end all of the key points will be distilled into a single key element: Future workforce and their overall competence and understanding. The CO2 capturing and sequestration processes require interdisciplinary engineering skills in not-so-well-defined systems, such as subsurface. In other words, future CCUS engineers will need to bskilled with tools, techniques, and education that can lead to operating large systems with geological uncertainties. In addition to basic engineering skills, the technical crew should be skilled with surveillance, inverse modeling, and reactive and predictive risk mitigation techniques. Such expertise, coupled with the newer technologies in surveillance and data analytics, will and should cater to the needs of future CCUS engineers. Based on all the points highlighted, what is needed for the long term behavior of CCUS/CO2 and implications will be an important task for the future workforce.


## Acknowledgements (Optional)

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