The Role of Subsurface Engineering in the Net-zero Energy Transition

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Abstract. Subsurface energy systems have historically focused on extraction of hydrocarbons through mining (coal) or drilling and pumping (oil and gas). These extractive industries have led to myriad environmental damages at the land surface as well as large greenhouse gas emissions that are driving climate change. Future energy-related usage of the subsurface is likely to involve large-scale fluid injection rather than extraction, with much of the injection occurring using the broad technology of carbon capture and storage, or CCS. The required pace of development, and the enormous volumes of fluids involved, highlight the need to develop a large-scale CCS industry. This development requires large-scale infrastructure, demonstration of storage security, and regional political and economic support.

1. Introduction
The subsurface has played an important role in the development of current energy systems, which are based largely on extraction of massive amounts of fossil fuels. Solutions to the carbon and climate problems, including the drive to achieve net-zero carbon emissions by 2050, are likely to replace the extraction of oil and gas with massive injection of carbon-based fluids into underground formations. This includes geological storage of carbon dioxide associated with carbon capture and storage (CCS; also referred to as carbon capture, utilization, and storage, CCUS). It also includes possible storage of other energy-related fluids, including hydrogen, to address intermittency issues associated with large-scale wind and solar energy. The largest subsurface injections are expected to be associated with CCUS. Indeed, many studies have concluded that CCUS will be necessary to meet the objectives of the 2015 Paris Agreement ([1], [2]).

While CCUS is consistently been identified as a critical technology, development of a large-scale industry has been held back by the high cost of carbon capture, the lack of a consistent price on carbon emissions, scarcity of subsurface data in many parts of the world, and the lack of large-scale infrastructure needed to enable industrial development. There are also some technical issues associated with injection that remain to be fully addressed, including the possibility of induced seismicity or the unintended leakage of fluids. However, there have been a number of studies in major regions of the world, including North America, Europe, and Asia, which provide confidence that large-scale injection can be done safely (for example, [3]).

Given that carbon emissions are dominated by North America, Asia, and Europe, these regions need to develop leadership positions in carbon mitigation technologies, including CCUS. Each of these regions is at a different stage of CCUS development, with different challenges and opportunities. Below each region is considered separately, with a larger focus on North America.
2. Large-scale Development: Challenges and Opportunities across different Regions

Global emissions of carbon dioxide continue to rise globally, with the largest emitters being in North America, Asia, and Europe. These regions have special responsibilities to develop carbon mitigation technologies and implement them on a massive scale. With this in mind, each region is considered briefly in the following discussion.

2.1. North America

North America had a history of CCUS development that dates back over 3 decades. This includes important early studies in Canada, with a focus on the Province of Alberta, as well as the Regional Carbon Sequestration Partnership Program in the Department of Energy of the United States, which spanned the entire United States. These programs have provided detailed characterization of subsurface storage sites. Convincing technical studies like those in [4] provide confidence that sufficient storage capacity exists to develop a viable CCUS industry that can operate on a century time scale.

Given the availability of detailed geological data and associated estimates of storage capacity, the outstanding current challenge is to develop the large-scale infrastructure necessary to catalyze a CCUS industry. The major element of this infrastructure is a large-scale pipeline system to deliver captured carbon dioxide from the capture location (typically a power plant) to a suitable storage location. An initial study [5] proposed development of a pipeline system focusing first on ethanol plants whose exhaust stream is pure CO₂ – this eliminates the large gas-separation costs for capture. The so-called Section 45Q tax credit in the US tax code provides significant financial incentives to capture and store anthropogenic CO₂, with up to 50 US Dollars (USD) per tonne of stored CO₂ for direct storage in deep saline aquifers, and up to 35 USD per tonne CO₂ for use in enhanced oil recovery (EOR). The United States has ample capacity for both direct storage and EOR, with EOR providing the additional economic benefit that the EOR operators will pay the supplier for the delivered CO₂, with a typical price being around 25 USD per tonne CO₂.

Edwards and Celia [5] proposed a pipeline system to connect sources of anthropogenic CO₂ at ethanol plans in the upper Midwest of the US to EOR demand centers in West Texas. They showed that sufficient economic incentives exist to build this pipeline system. The proposed pipeline network is shown in Figure 1.
Figure 1. Proposed pipeline network to deliver captured CO\textsubscript{2} from ethanol plants to the Permian Basin in western Texas, US, for enhanced oil production. The figure is modified from [5]. While this is potentially important, emissions from ethanol production are very small compared to those from power plants. So, the current challenge is to develop the economic framework that includes coal- and gas-fired power plants – these studies are currently being pursued by multiple research groups.

2.2. Asia

The Asian region presents several important challenges and opportunities. Much of the continent needs broader geological data assess storage opportunities, although identified locations such as the Tarim and Junggar Basins in China and the Deccan Traps in India present promising opportunities. The Deccan Traps are particularly interesting because they are massive in scale and are composed of basalts which are highly reactive with injected CO\textsubscript{2}. While rock-fluid geochemical reactions are often insignificant in traditional sedimentary basins, the highly reactive nature of basalts make the modelling and prediction of system behaviour more challenging. Recent small-scale field tests [6,7] have been complemented by modelling studies [8,9] showing promising results for secure storage through mineral trapping of the injected carbon. Overall system behaviour at larger spatial and temporal scales remains to be demonstrated.

In terms of overall impact on emissions and the move away from fossil fuels, the Belt and Road Initiative (BRI) stands out as a major opportunity. While energy investment through the BRI has been dominated by coal power since the beginning of the BRI in 2013 (see Figure 2), a few recent trends show hopeful signs for a pivot toward renewable energy [10]. Implementation of the “Green” BRI concept represents one of the most consequential policy and economic drivers for a regional shift toward a net-zero emissions target.

Figure 2. (A) Cumulative power generation capacity, and (B) total number of power plant projects, associated with BRI in 15 representative BRI countries. The horizontal axis represents contract-signing dates for a project. The vertical red line indicates the start of BRI. Figure taken from [10].

2.3. Europe

Two of the longest-running industrial CO\textsubscript{2} storage operations are in the North Sea region of Europe: the Sleipnir injection and the Snohvit injection [11]. Significant learnings have been achieved from these operations. The European Union has also had a CO\textsubscript{2} cap-and-trade system in place for more than a decade. While prices have fluctuated substantially, especially in the early years, recent prices are in the range of 50 Euros per tonne CO\textsubscript{2}. New projects such as the Porthos Project in The Netherlands [12], focused on the Port of Rotterdam, and the Net Zero Teesside industrial cluster in the
United Kingdom [13], are leading new thinking on how CCUS can be integrated into carbon reduction strategies. Overall, while Europe has significant public opposition to onshore CCUS injection, the availability of significant offshore storage allows new ideas for offshore technologies to continue to advance.

3. Conclusion
The entire world must make an unprecedented commitment in order to reach the net-zero emissions target by 2050. The regions that need to provide overall leadership are North America, Asia, and Europe. Each has different opportunities and can provide different kinds of leadership. A cooperative, collective effort is the only way this daunting task can be achieved, requiring technical, economic, and political leadership.

4. References
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