

suitability for GCS. For example, the Gunsan basin and the Jeju basin show high potential for GCS because the geologic structures are similar to that of natural hydrocarbon in analogous Chinese basins (Hong et al., 2005). The Ulleung basin contains natural gas deposits and is more than 1000 m deep, and thus structural trapping may be feasible (Hong et al., 2005).

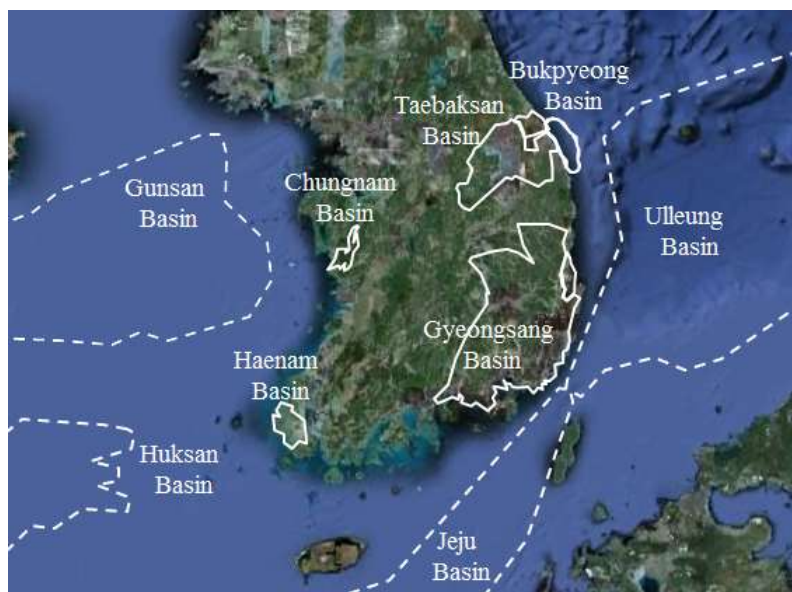


Figure 4. Potential storage sites and major CO₂ sources in South Korea

3.3 Evaluation of suitability of sedimentary basins in Korea for GCS

Bachu (2003) has proposed a method for systematic and quantitative evaluation of candidate sites in terms of their CO₂ storage suitability. Fifteen criterias are used with weight factors to assess the suitability. A series of criteria includes not only geological characteristics of basin, but other specific conditions such as basin resources, maturity and infrastructure. In this section, Korean basins were evaluated for their GCS potential using this method, based on parameterization and ranking, and also in comparing with foreign basins in which pilot- and commercial-scale projects are under way.

The results are shown in Fig. 5. As seen in Fig. 5, the scores of the sites investigated in this study range from 0.25 to 0.45. The Chungnam, Taebaeksan, Gyeongsang, and Bukpyeong on-shore sedimentary basins are shown to be relatively adequate candidates due to their large capacities and their proximity to major CO₂ sources. Among the offshore basins, the Ulleung basin is thought to be the most suitable site for geologic CO₂ storage due to the presence of nearby infrastructure constructed for natural gas recovery.

However, these potential Korean basins are less feasible for geologic CO₂ storage compared to several basins in Canada. Specifically, the scores of Korean basins are lower in the following criteria: size, hydrocarbon potential, maturity, and infrastructure. Most of the Korean sedimentary basins, except for the Ulleung basin, are estimated to be of small-to-medium sizes whereas the Alberta and Williston basins in Canada are considered giant-to-large size. Moreover, a lack of boring studies and

geophysical exploration exacerbate the problems of low maturity and insufficient infrastructure.

Meanwhile, given insufficient information available, a number of parameters were assumed for the assessment results shown in Fig 5. To reduce uncertainty, more data acquisition by exploration and more reliable numerical modeling and simulation should be performed in relation to site selection for the first Korean pilot project. Additionally, new alternative methods excluding approaches using deep saline formations are needed to safely and economically sequester carbon dioxide in Korea considering the geological characteristics of Korean basins and limitations.

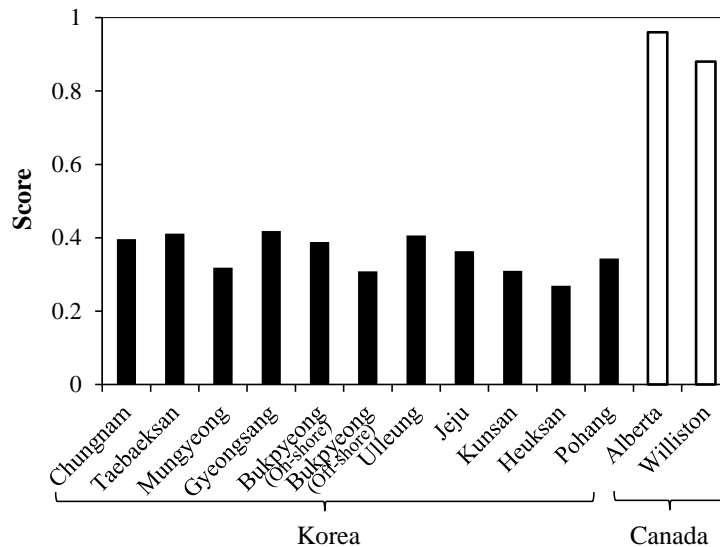


Figure 5. Scores for screening and ranking of Korean sedimentary basins.

4. GEOTECHNICAL ENGINEERING ASPECTS

Geologic CO₂ storage (GCS) involves (1) the selection of a suitable site with an adequate geologic structure, (2) the injection of CO₂, (3) the storage of CO₂ by physical or geochemical trapping mechanisms, and (4) the monitoring of the stored CO₂ to detect any unwanted leakage. Proper technologies must be developed and chosen for each process, taking into account geological characteristics. This section explores each process from injection to monitoring and addresses the geotechnical challenges related to GCS.

4.1 Injection Strategy

An effective and safe injection strategy for dealing with a large quantity of CO₂ is an important issue. In commercial-scale projects, the marginal cost for injecting CO₂ is estimated to be a maximum of 10 US dollars per CO₂ ton (e.g. 2.2 US dollars per CO₂ ton for the Weyburn project and 6.3 US dollars per CO₂ ton for the In Salah project; Hosa et al., 2010). Constructing infrastructure, such as installing wells, accounts for much of the initial costs. As more CO₂ is injected with a given time frame, it becomes more cost-efficient. Thus, a high rate of injection is favorable.

As the injection pressure should be higher than the pore-fluid pressure in the formation, a larger pressure difference would increase the CO₂ injection rate. While a high injection (flow) rate of CO₂ is cost-effective, a high injection rate can produce over-pressurization, which can result in opening of pre-existing faults or the creation of cracks. Thus, the maximum allowable injection pressure should be carefully estimated to prevent formations from fracturing.

Injectivity is defined as the injection rate divided by the pressure difference between the well and the reservoir (IPCC, 2005). Interactions among CO₂, rock minerals, and pore water (water-rock-CO₂ interaction) induce chemical reactions, such as mineral dissolution or precipitation, which can affect porosity and permeability. Therefore, the injectivity can progressively change with time from the area adjacent to an injection well as CO₂ causes chemical reactions. Accordingly, CO₂ injectivity is affected by various parameters, such as rock mineralogy, pore water chemistry, pressure, temperature, and flow rate of CO₂ (Bacci et al., 2011); thus, the CO₂ injectivity needs to be identified with consideration of water-rock-CO₂ interactions for selecting an adequate storage site.

In the In Salah project, a multiple well injection technique was used to inject CO₂ at a high rate because of the low permeability (5 mD) of the site. Meanwhile, the MRCSP R.E. Burger project was cancelled due to the low injectivity (0.0016 Darcy-meters) caused by very low permeability (0.08 mD) and low porosity (3.20%) (Hosa et al., 2011). Likewise, sedimentary basins in Korea with low porosity and permeability should be evaluated to address these concerns.

4.2 Storage Strategy

CO₂ injected into a reservoir can be stored via two mechanisms: physical trapping and chemical trapping. CO₂ can be physically trapped by overlying impermeable seals (caprocks). The physical seals include capillary, pressure, and permeability seals (Christopher and Iliffe, 2006). Seals keep CO₂ in the reservoirs from buoyancy-driven flow. The buoyancy pressure (P_b) can be expressed as follows:

$$P_b = \frac{\text{Buoyancy Force}}{\text{Area}} = \frac{(\rho_w - \rho_{CO_2}) \cdot V_{CO_2} \cdot g}{A_{CO_2}} \quad (1)$$

where ρ_{CO_2} is the CO₂ density, ρ_w is the water density, V_{CO_2} is the CO₂ plum volume, A_{CO_2} is the contact area between water and CO₂, and g is the gravity. Changes in the mass density difference, the volume of injected carbon dioxide, and the contact area of CO₂-water in sediments will affect the buoyancy pressure. At the pore throat in the seals, the capillary pressure (P_c) can be described as a function of the interfacial tension (σ), the contact angle (θ) between water and CO₂, and the pore throat diameter (d) (Washburn, 1921):

$$P_c = \frac{4\sigma \cos \theta}{d} \quad (2)$$

The capillary pressure increases with increasing interfacial tension between water and CO₂ at a pore throat and with decreasing diameter of the pore throat. When

buoyancy pressure of CO₂ is higher than capillary pressure at a pore throat, CO₂ would seep through the pore throat and flow into the next pore.

As chemical trapping mechanisms, CO₂ can be geochemically trapped in the form of carbonate minerals as a result of mineral-water-CO₂ reactions (mineral trapping), or it can be stored in gas hydrate clathrates. In deep subsurface areas (over 800 m), CO₂ can be stored in the form of a dissolved phase in pore water (solubility trapping). Mineral trapping is considered the most stable method (Gunter et al., 1993); however, this may have an impact on subsequent CO₂ injectivity as carbonate mineral precipitation decreases porosity and permeability (Izgec and Demiral, 2005; Sayegh et al., 1990).

4.3 Geophysical Monitoring of CO₂

CO₂ leakage from CO₂ storage sites can cause serious environmental problems. Geophysical survey techniques are available for large-scale field applications to detect CO₂ leaks and to identify CO₂ movement. The general principles of CO₂ monitoring include measuring the physical properties (density, stiffness, electrical resistivity, and thermal characteristics) and detecting chemical composition changes or subsidence and displacement of grounds (Espinoza et al., 2011).

The most widely used monitoring methods are the seismic survey methods using P-wave and the electrical resistivity survey methods (Nakatsuka et al., 2010). In particular, P-wave seismic surveys have been commonly used to detect CO₂ when it is injected into sediments in laboratory settings (Shi et al., 2007; Siggins et al., 2010; Xue and Lei, 2006) and in fields (Arts et al., 2004; Daley et al., 2008; Lazaratos and Marion, 1997; Mito and Xue, 2011), as CO₂-containing formations have less stiffness than brine-saturated formations. Using the bulk modulus and density of pure CO₂, the effective bulk modulus of a CO₂-containing sediment can be estimated as a function of CO₂ pore saturation using the Gassmann equation (Mavko et al., 1998). However, it has been reported that the Gassmann equation underestimates CO₂ saturation when using field VP measurements (Azuma et al., 2011). This is because of the patchy distribution of CO₂ in a given formation.

Meanwhile, sediment formations in Korean sedimentary basins are typically found to be layered, as opposed to the fact that most of the experimental studies to date have commonly used homogeneous sandstones. The physical behavior of CO₂-storing sediments is significantly affected by formation characteristics, such as the porosity, permeability, density, and effective stress. Therefore, an alternative experimental approach is required for geological storage and monitoring of CO₂ in Korea.

5. CONCLUSION

The presented study explores the current status and future direction of Korean CO₂ storage technology in relation to geological and geotechnical considerations. The geological conditions of on- and off-shore sedimentary basins in Korea were investigated and the suitability of the basins for GCS were evaluated. The Gyeongsang

and the Ulleung basin (respectively on- and off-shore sedimentary basins) were found to be the most suitable site for GCS, although their scores were lower than the scores of some basins where GCS is currently undergoing or pilot-tested in Canada. The process of geologic CO₂ storage was also explored and the geotechnical challenges related to GCS were discussed. The first step in the process of geologic CO₂ sequestration is to locate suitable geologic sites. Supercritical or liquid CO₂ is then injected into the subsurface, the CO₂ is stored by physical and geochemical trapping, and the stored CO₂ is finally monitored to detect leakages. The injection and storage mechanism strongly depends on various environmental and geological characteristics. Monitoring technology is already available for field applications to detect leaks and identify the movement of CO₂. However, further study is required for detecting CO₂ behavior in layered formations.

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