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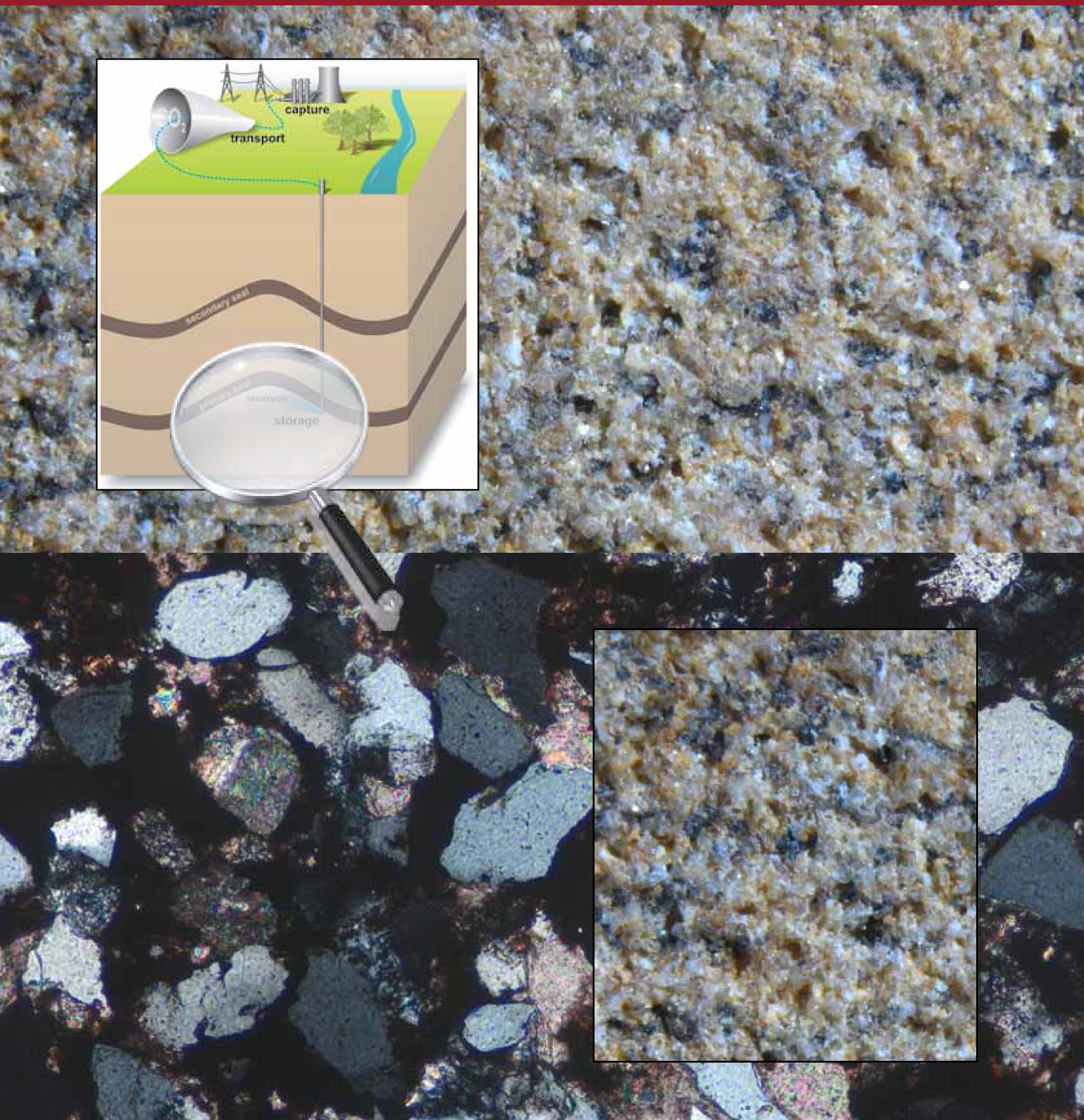
Carbon, capture and storage - potential in Europe and barriers to take up



The cost of CO_2 geological storage is more than a number

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CO_2 geological storage is the last stage in the CO_2 capture and storage process which aims to reduce CO_2 emissions into the atmosphere. The cost of storage has frequently been regarded as minor compared to the cost of the whole CCS process. There is, however, a multitude of cost parameters that will form a unique combination for each storage project, with costs projected from one to several tens of Euros per tonne of CO_2 stored. Several research efforts have recently been trying to identify the main cost drivers and relatively wide cost ranges. Reservoir type and location, geological uncertainty, injectivity and capacity are recognized as the main sources of cost variation between potential storage projects.

Le stockage géologique du CO_2 représente la dernière étape du processus de capture et d'emmagasinage du CO_2 dont le but est la réduction des émissions de CO_2 dans l'atmosphère. Le coût de stockage a souvent été considéré comme mineur en comparaison de celui de l'ensemble des opérations de capture et de stockage. Cependant, le coût global dépend d'une quantité de paramètres qui constituent une palette unique pour chaque projet de stockage, le prix pouvant varier entre un et dix euros par tonne de CO_2 emmagasiné. Plusieurs essais de recherche ont récemment essayé d'identifier les vecteurs principaux conditionnant le coût et cela dans un domaine de prix relativement étendu. Le type de réservoir et sa situation, l'alea concernant le contexte géologique, les conditions d'injection et les possibilités de stockage sont reconnus comme les causes principales de variation des prix entre différents projets d'emmagasinage potentiel.

El almacenamiento geológico de CO_2 es la última etapa del proceso de captura y almacenamiento de CO_2, cuyo objetivo es reducir las emisiones de CO_2 a la atmósfera. El coste del almacenamiento se ha considerado frecuentemente como un coste menor en comparación con el coste total del proceso. Sin embargo hay multitud de parámetros del coste que constituyen una combinación única para cada proyecto de almacenamiento, con costes estimados que varían entre uno y carios cientos de euros por tonelada de CO_2 almacenada. Recientemente se han realizadodiversas investigaciones para intentar identificar los principales responsables dedichos costes y sus relativamente ampliosrangos de variación. El tipo de almacén y su ubicación, la incertidumbre geológica, las condiciones de inyecicón y su capacidad se consideran las principales razones de las variaciones del coste entre diferentes proyectos de almacenamiento.

Storage costs in the CO_2 capture and storage chain.

Global climate is influenced by the anthropogenic emission of large quantities of greenhouse gasses, including carbon dioxide (CO_2), into the atmosphere. CO_2 capture and geological storage (CCS) is, amongst others, a possible option to achieve deep emission reductions and can be applied to large industrial CO_2 sources. It is a succession of processes in which CO_2 is captured, purified if necessary, compressed and transported to a suitable injection location where it is stored safely and permanently in a geological reservoir (IPCC, 2005; ***Fig. 1***). Possible reservoirs include depleted oil and gas fields, deep saline aquifers and coal sequences (Holloway, 2005). CCS is currently in a transition between pilot and demonstration phase, with a commercial deployment projected around 2020.

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In the CCS chain, capture is generally regarded as the most expensive part, while transport and storage are relatively cheaper. Storage costs include exploration, monitoring, well drilling and several other parameters that will be highlighted later. The European Technology Platform for Zero Emission Fossil Fuel Power Plants has recently published a series of reports on the costs of CCS (ZEP, 2011). Herein, average storage costs are estimated to be 2 to 15% of the total cost of electricity production (LCOE, levelized cost of electricity), depending on the production technology. The average storage cost is indeed expected to be only a minor part of the total cost of CCS. It forms, however, an important part because it includes a large up-front investment, from the planning phase on. The cost of the storage part is generally expressed in euro per tonne of CO_2 captured and stored. ZEP (2011) gives a range of 1 to 20 €/t CO_2 for storage; the earlier assessment by McKinsey (2008) provides a range of 4 to 12 €/t CO_2. Geo-techno-economic simulations for Belgium have provided a range of 2 to 18€/t CO_2 (Welkenhuysen *et al.*, *in prep.*). These cost ranges give a first indication of the case-specific costs and uncertainty ranges of CO_2 storage. For specific cases, costs can be even higher than the upper values stated here. Vidas *et al.* (2009) calculated storage costs of up to 80 $/t CO_2 for saline aquifers. Although a cost reduction of the entire CCS process is needed and expected, no significant reduction is expected for the storage part, mainly because of the experience from the oil and gas industry.

When making cost calculations for CCS, an average cost figure for storage is often used. However, the cost ranges from the reports cited above, already indicate that each potential reservoir is unique and storage costs depend heavily on the geological environment. An overview is given hereafter of the relevant cost factors. Those introducing the largest variations in cost are discussed in more detail. The uniqueness of each storage possibility provides a distinctive cost pattern for each project. This paper is a summary of the most important cost drivers, since it is impossible here to cover all of the factors.

Analysis of the cost factors

The geological storage of CO_2 can be subdivided into three phases: pre-injection, injection and post-closure. In the pre-injection phase a potential reservoir must first be identified and characterized through geological exploration. After identification, an in-depth exploration and monitoring plan is conducted. This exploration typically consists of several exploration wells and a 3D seismic survey. Data is gathered to ensure reservoir quality and containment, and to create a pre-injection reference state, so as to be able to track the injected CO_2 over time with subsequent monitoring. The exploration wells can be reused as monitoring wells if the situation permits.

For the operational phase, one or more injection wells are drilled and equipped for injection of CO_2. The storage operation itself consists of compression and pumping and in some cases heating of the CO_2 to bring the CO_2 to reservoir conditions. During injection, several monitoring techniques have to be used to keep track of the injected CO_2 plume and make it possible to remediate the CO_2 in case any leakage from the reservoir occurs. The chosen set of monitoring techniques is site-specific and is partially imposed by law (EC, 2011). The most common techniques are pressure, temperature and CO_2 monitoring in the injection wells, aquifer monitoring in the monitoring wells, 3D seismic studies at certain time intervals and surface CO_2 detection using a number of techniques. Other possible monitoring techniques include well logging, 2D seismics, CO_2 flux measurements, surface deformation, micro-seismicity and surface water monitoring.

When injection is finished, the injection wells are plugged, and monitoring is continued. The guidance documents to the EU CCS directive (Directive, 2009/31/EC) demand at least 20 years of monitoring before liability of the storage site is transferred to the authorities. McKinsey (2008) suggests a post-closure period of 50 years before liability transfer. Before starting injection operations, sufficient financial provisions are required by the EU Directive to account for leakage risks. In the post-closure phase, before the liability transfer, the EU directive also demands a financial contribution to continue 30 years of monitoring to ensure permanent and safe storage. The total of these liability funds will be a function of the amount of CO_2 stored.

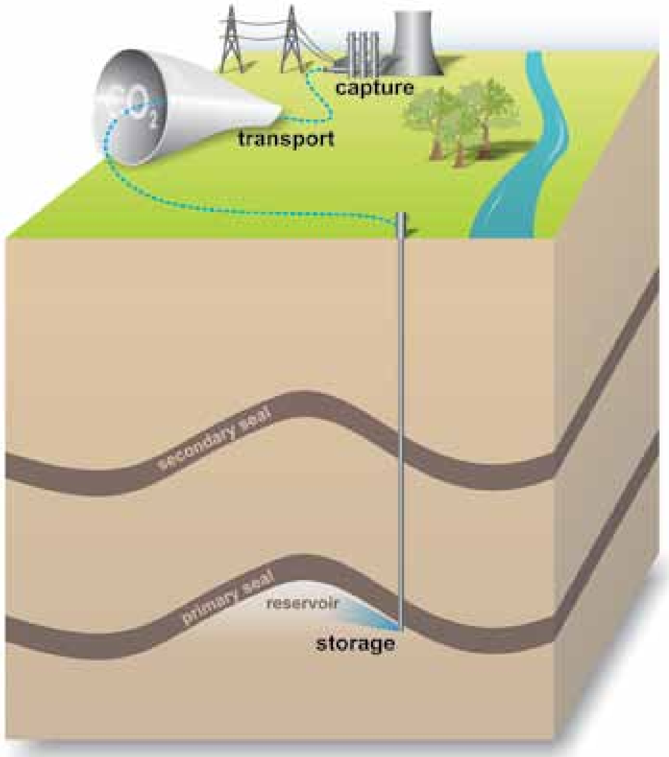

Figure 1: Simplified illustration of a CCS project. CO_2 is captured at an industrial installation, transported via ship or pipeline, and injected into suitable reservoir rock. Multiple sealing formations help to prevent CO_2 from migrating out of the reservoir.

The most expensive individual cost factors in the storage operation are the 3D seismic monitoring, at around 25,000 €/km², injection and monitoring well drilling and completions at several millions of Euros per well (depending on depth, lithology and location), and post-closure well plugging at about 15% of the well construction costs (ZEP, 2011).

Reservoir type driving storage costs

The reservoir type and location introduce a very large cost variation. Geology is unique to each location, and each storage project will need a customized solution. An initial distinction of reservoirs can be made between storage onshore or offshore. Most offshore operations, such as injection, drilling and monitoring, are more expensive, due to the demanding environment. This results in a cost range difference of about a factor of 2 between on- and offshore (***Fig. 2***).

Major cost differences also occur between depleted hydrocarbon fields and saline aquifers. Deep saline aquifers contain salty water that is of no commercial interest. These potential reservoirs are therefore less explored. Depleted hydrocarbon fields are generally well explored, and have a proven capacity and containment. This greatly reduces exploration and monitoring costs. Furthermore, these reservoirs might have reusable infrastructure, wells or platforms. On the other hand, saline aquifers generally have a larger capacity which reduces costs by the effect of scale, while depleted hydrocarbon fields generally have a limited capacity. The cost of storage in coal is highly variable due to the very site-specific requirements for ensuring sufficient injectivity, and potential methane production through ECBM operations. Coal layer thickness, permeability, sequence build-up and fracturing are just some of the factors influencing storage operations. Vidas *et al.* (2009) estimate coal storage costs to be at the higher end (about 7 \$/t CO_2 for the United States), though revenues from methane production can keep costs low. There is, however, an important difference in permeability between the average American and European coal: injectivity in European coal is expected to be much lower, which will increase costs per tonne of CO_2.

The volume affected by the injection of CO_2, the storage complex, is in most cases far greater than the volume where CO_2 is

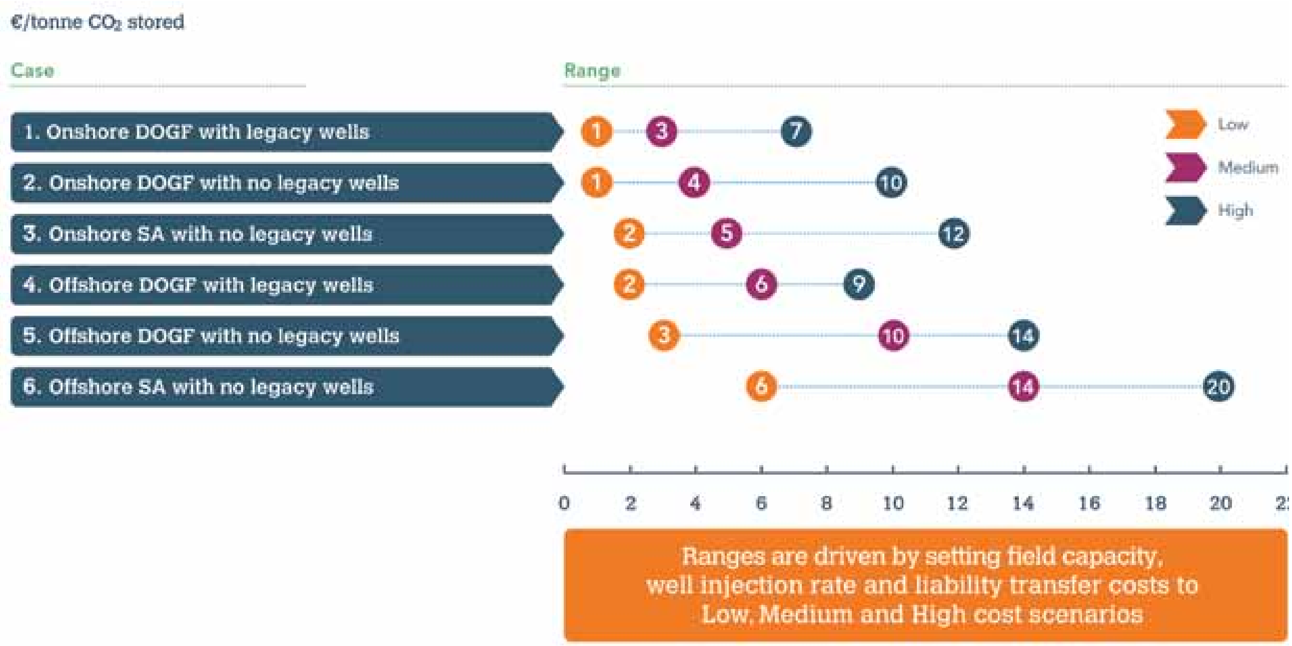

Figure 2: Storage cost ranges for different reservoir types. Offshore storage is up to twice as expensive compared to onshore. The use of existing wells and equipment (legacy wells) for depleted hydrocarbon fields can reduce costs by a few € per tonne. Storage in aquifers on the other hand is more costly because less is known about these reservoirs. This is most apparent for offshore storage (ZEP, 2011).

actually stored. Added pressure, for example from CO_2 injection, will propagate through the storage complex farther than the CO_2 itself. The EU Directive therefore demands not only characterization and monitoring of the storage site, but of the whole storage complex. This difference between injected volume of CO_2 and the area of the storage complex is unique to each reservoir and can be very large. Large aquifers and the pressure increase therein can extend for hundreds of km, while storage in a closed sandstone body will hardly influence the surrounding formations.

The role of geological uncertainty

Uncertainties are inherently connected to geology, simply because it is practically impossible to characterize the whole subsurface. Exploration can greatly reduce this uncertainty, but it will always exist. This uncertainty will also result in the fact that not all reservoirs on which exploration has started will be fit for storage. Even for projects where injection has started there might at some stage in their lifetime appear an unforeseen reduction in injectivity. This will increase the investment risk and the cost per tonne of CO_2 that is eventually stored in other reservoirs. In poorly explored areas, geological uncertainties are large. As mentioned before, this causes an important difference in storage cost between depleted hydrocarbon fields and the less known aquifers (***Fig. 2***). Generally, the characterization of large unknown structures will pose a higher cost than better-known, local storage options, because of the need for more exploration.

The storage cost calculations by ZEP (2011) result in a cost range of up to a factor of 10 per reservoir type, originating mainly from geological uncertainty (***Fig. 2***). Decreasing this uncertainty is essential to increase the rate of exploration success and reduce costs. Keating *et al.* (2011) found that geological uncertainty significantly influences CCS infrastructure in general. Results for Belgium also indicate that geological uncertainty has a significant impact on storage costs, reservoir choice and the overall economic deployment of CCS (Piessens *et al.*, in press; Welkenhuysen, *in prep.*).

Injectivity and pressure management

It is important for a CCS project to have a match between the CO_2 production and the injection rate, or injectivity, into the subsurface. This injectivity has a substantial influence on the total storage cost and specific cost per tonne of CO_2 stored. Closely related to the injection rate is pressure management, which is essential when injecting CO_2 into an underground reservoir. If the reservoir pressure exceeds the host rock's strength, the reservoir and possibly its sealing cap rock will fracture and CO_2 might leak out of the reservoir. Moreover, pressure is not equally divided throughout the reservoir during injection. As with hydrocarbon or water production wells, a pressure cone is created when injecting CO_2 into a reservoir, and pressure decreases with increasing distance from the injection well.

The first and most evident factor influencing injectivity and pressure is reservoir rock permeability. A highly permeable reservoir rock will in general provide high injectivity and a fast pressure propagation throughout the storage complex. The boundary conditions of the reservoir also influence the pressure build-up of injection. A closed structure will, for example, have a lower injectivity than a comparable open reservoir where pressure can disperse through a large storage complex.

There are a number of possible techniques to manage injectivity and pressure build-up in the reservoir. An obvious method is using multiple injection wells. Pressure increase is spread more evenly and injectivity can be multiplied by the number of wells. Formation water production from the reservoir is an option to lower reservoir pressure and allow a greater injec-

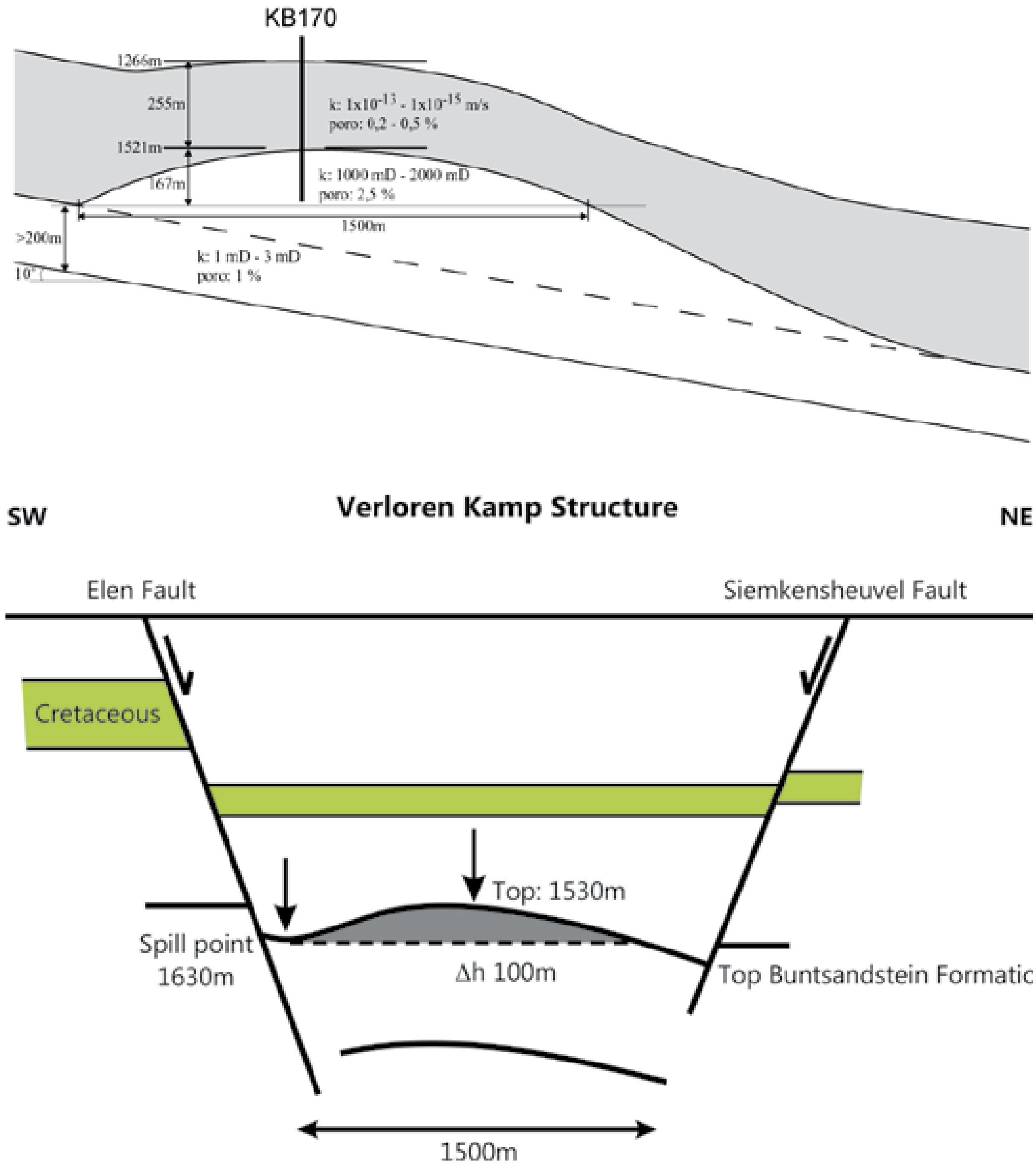

Figure 3: The effect of scale on monitoring costs, illustrated by two potential Belgian reservoirs, the 3 Mt Poederlee dome structure (a) and the 20 Mt Verloren Kamp structure (b) (figures are not to scale). Monitoring costs are projected to be 13 M€ and 25 M€ respectively, or 4.3 €/t CO_2 and 1.25 €/t CO_2 (Piessens et al.*, in press; Van Tongeren, 2004).*

tivity using a push-pull configuration. It is also possible to fracture part if the reservoir hydraulically, increasing permeability. This technique should however be used with caution as there is a risk of fracturing the reservoir seal as well. All techniques pose significant extra costs and it is therefore essential to perform a detailed reservoir characterization to select the most suitable reservoir and avoid unpleasant surprises during injection.

Monitoring cost and the effect of scale

Monitoring is mostly regarded as a marginal cost factor compared to the cost of the whole CCS sequence, often well below 1 €/t CO_2 (e.g. Benson *et al.*, 2005).For large projects injecting millions of tonnes per year over several tens of years, this is likely to be true. It is however very scale dependent, since monitoring costs do not increase linearly with injected amounts of CO_2.

A calculated example of two potential Belgian storage structures, the Carboniferous Poederlee dome structure and the Verloren Kamp structure in the Triassic Buntsandstein Formation, provides insight (Piessens *et al.*, in press; ***Fig. 3***). Both structures are comparable in surface area. Their different geological configuration causes the Verloren Kamp structure to be able to store about 20 Mt, while only 3 Mt of storage capacity is expected to be available in the Poederlee structure. Monitoring operations for a storage project in the Poederlee dome would amount to almost 13 M€ in total, or 4.3€/t CO_2. A comparable storage project in the larger Verloren Kamp structure would provide a monitoring cost of 25 M€, or only 1.25 €/t CO_2. This effect becomes even larger when working with very low injectivities, e.g. for coal CO_2 storage, which results in monitoring costs of up to several tens of € per tonne of CO_2 stored. This also illustrates the need for proper geological exploration and modelling to ensure sufficient injectivity over the whole injection phase.

Conclusions

When analysing the cost factors it becomes clear that the cost of storage cannot be summarized in one number. Overall storage costs can range from 1 to several tens of euros per tonne of CO_2 captured and stored. The reservoir type, geological uncertainty, injectivity and capacity are the main cost drivers for storage. The most important cost factors are injection and monitoring well construction and 3D seismic monitoring. The effect of scale and the extent of the storage complex are important with regard to monitoring costs; for small projects monitoring might become a main expense, while a large storage complex will pose higher costs than a small storage project.

Each storage project will have a unique combination of cost factors and will need an individual geo-economic analysis to accurately assess total storage costs.

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