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Geophysical methods for CO_2 plume imaging: comparison of performances

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Abstract

Geophysical methods are adequate for imaging the CO_2 plume in order to follow its migration within the reservoir and possible leakages through the caprock formation. In particular, changes in density, seismic velocity or electrical resistivity are associated with changes in the gas saturation and make methods such as gravity, 4D seismic and electrical resistivity tomography (ERT) or CSEM powerful tools to follow up the fate of injected CO_2. Respect to the minimum amount of CO_2 stored that can be quantified for verification purpose, there is an order of magnitude between 4D seismic (few 100s of Kt) and the other two methods (few Mt). Respect to the detection of leakage at the reservoir level, only 4D seismic could be considered as useful. Using downhole measurements, such as crosshole electric or downhole gravity will increase the resolution of these methods and therefore its ability to detect leakage. In case of CO_2 leakage upwards and accumulation within a secondary reservoir located at a few hundreds of meters depth, the resolution of the three methods is increased by several order of magnitude and small amounts of CO_2 could be detected, depending whether it is in gaseous phase or dissolved. It is expected that controlled experiments of leaking CO_2 at shallow depth will help to define more precisely the conditions of use of the three methods.

Keywords: Monitoring; CO_2; Geophysics; 4D seismic; Electrical; CSEM; Gravimetry

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1. Introduction

Safe and proper storage of CO_2 requires its permanent storage in the reservoir and that the risks of leakage are minimized. Monitoring is an essential part of storage operations and risk management since it allows: 1) Controlling the normal behaviour of the injected CO_2 within the reservoir; 2) Verifying the CO_2 mass actually stored for carbon credits accounting; 3) Detecting any abnormal behaviour, i.e. either leaking CO_2 through the caprock formation or

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wells or any direct or indirect impact on the environment; 4) Quantification of any emission into the air or the water column, should the CO_2 reach the surface or the sea bottom [1]. Monitoring must cover the different phases of the lifecycle of storage (site characterization, injection, closure and post closure) and its different compartments: i.e. the reservoir and its overburden, among which the caprock and the possible secondary storage formations, the near surface and the surface. From the HSE point of view, the detection of any abnormal behaviour of the storage must trigger corrective and remediation measures in order to minimize health and environmental impacts, during the injection time and possibly during the closure phases.

The evaluation of the different available monitoring methods and its efficiency respect to these four objectives have been already discussed elsewhere [1], [2] and [3]. Recent regulations such as the EU Storage Directive (2009/39/EC) [4] give a general outline of the role of monitoring in the different phases of a project and establish a generic list of which main components should be included in the monitoring plan. Guidelines to design an adequate monitoring strategy in the framework of the risk management plan are already available in the final report of the CO_2QUALSTORE project [5] or as a future outcome of the CO_2ReMoVe project. The experience accumulated from the on-going industrial and pilot projects show that complying with the objectives 1 and 2 is not straightforward, even if it is the operator's duty to show to the regulating authorities and the public concerned that injection is controlled properly and that the storage fulfils its emissions reduction objective. The Sleipner example has shown that 4D seismic could image the CO_2 plume with a precision of ca. some thousands of tons, meanwhile in other examples mapping the extension of the plume is an ongoing process. Fulfilling objectives 3 and 4 is considered as more feasible from the technical and cost/benefit point of view. Because the main risks of leakage could come from small objects, i.e. wells or faults, and then affect secondary storage zones or drinkable water aquifers prior to reaching the surface. The latter being located closer to the surface, direct measurements through observation wells would be less costly and indirect monitoring methods become more efficient. As a consequence, a monitoring strategy could focus mainly on pressure control and methods of wide coverage for imaging the CO_2 migration within the reservoir and, in case of abnormal behaviour, the implementation of high density measurements over specific areas where leakage is suspected to occur. In particular at the surface (or at the sea bottom in the offshore case), in order to estimate the quantity of CO_2 released to the atmosphere. Sensitivity of the measurements methods, i.e. the minimum quantity of CO_2 that can be detected is an important issue, as far as it will define if a method can be used either to map the plume and/or to detect leakages. It has been proposed for a monitoring method to be used for emission accounting, that its detection limit should range from 1000 tons to 10 000 tons of CO_2 per year [1].

Geophysical tools are recognized to be adequate to image plume migration, since they are able to monitor over a wide area changes in the physical characteristics of the reservoir when brine is (partly) replaced by CO_2. As already mentioned, 4D seismic is already used in many sites with outstanding results, while other methods like gravimetry or electrical/EM resistivity tomography still needs case histories to prove their effectiveness. In the present paper, we analyze the different characteristics of these methods, paying a special attention to Electrical/EM methods and discussing for each case the quantities of CO_2 that can be monitored in the reservoir and its sensitivity respect to the detection limits previously mentioned.

2. Seismic methods

Changes in seismic velocity are linked to changes in gas saturation and make a method such as 4D seismic a powerful tool to follow up the fate of injected CO_2. The P wave velocity (Vp) is noticeably decreased by a small amount of gas in the pre-existing brine, which effect is to increase wave travel times and consequently to "pushdown" the reflectors. For gas saturation higher than 10 %, the effect is much lower. Changes in acoustic impedance (i.e. the product of density by wave velocity) have also an impact on the amplitude of reflections. Chadwick et al. [6] and [7] have amply discussed the various assumptions used to map precisely the plume migration and to quantify the stored CO_2 in the very favourable case of Sleipner. It appears that the 4 D seismic was able to map the plume since 1999, 3 years after the storage had started and ca. 2.35 Mt of CO_2 were injected. They showed as well that the minimum volume that can be detected at the top of the reservoir depth, ca. 800m, is of the order of 4000 m^3, i.e. 2000 to 2500 tons, depending on temperature and pressure in the reservoir, and consequently on CO_2 density [6]. Simulations in the less favourable case of the injection in a depleted oil field at about 1500 m depth in the Paris Basin Dogger carbonates with low porosity and high bulk modulus show that seismically measurable effects of CO_2 replacing the oil/water mixture are close to detection threshold in terms of time shift and amplitudes [8]. Theoretical AVO analysis carried out in that case shows that fluid substitution could have an effect at large incidence angles, but data processing would not be easy because of the presence of overlaying converted events. Other example of application of the 3D surface seismic at the Pembina Cardium pilot site [9] shows that the geological specificity of the site impedes the detection of 40 000 t of injected CO_2 at 1650 m depth. The reason is that the layer constituting the reservoir is too thin (20 m) to allow the effects on time shift and amplitudes to be resolved. However, a previous VSP survey at the same site using a downhole fixed array of 8-geophone was able to detect the effect of 15 000 t of CO_2, injected during the first eight months of the experiment [10].

In conclusion, we may say that while 4D seismic is presently without any doubt the most powerful method in terms of plume mapping, quantification of the injected volume in the reservoir and early detection of leakage, a special attention should be paid to the geological specificities of each reservoir which could severely limit its performances and imply complementary data acquisition. This has to be considered in its cost/benefits assessment and the design of the monitoring plan.

3. Electrical/EM methods

Several teams have proposed to use electrical/EM methods (such as DC electrical and low-frequency, diffusive electromagnetism) as less expensive alternatives to active seismic methods for monitoring the resistivity changes caused by CO_2 injection [11] [12] [13] [14]. Given the similarity of the problem with oil exploration and to achieve a good horizontal resolution, the transmitter/receiver array appropriate for CO_2 monitoring should be similar to that used in CSEM [15], i.e. a grounded current injection combined with a grid of sensors at the surface. It must be underlined that these methods do not achieve a comparable spatial resolution as seismic-based methods, but prove to be a valuable complement to 4D seismic surveys in the hydrocarbon exploration field (for instance, marine CSEM and land TEM)[15]. The main limitation of such techniques stems from the target characteristics. Considering the interest of the supercritical state for storage efficiency and safety, and given that CO_2 is supercritical at a depth greater than 700-800 m (depending on temperature and pressure gradients), most existing or envisaged CO_2 injections occur below 1000 m [16]. On the other hand, adequate reservoirs with sufficient porosity and permeability are relatively thin (<100 m) compared to this depth. In these conditions, if the current is injected from standard electrodes at the surface (*e.g.* in the "gradient" or dipole arrays), it can be anticipated that the fraction of current flowing through the reservoir, hence energizing the CO_2 plume, will be too small to detect any resistivity variation in the reservoir. This was numerically investigated by Bourgeois and colleagues in the Paris basin context [14] [17]. These authors showed that the relative time-lapse anomaly induced by a 2 km × 2 km, 70-m-thick and 1700-m-deep CO_2 plume is only about 1-2% of the initial field, when using standard electrodes at the surface for the current injection (NB: such a plume corresponds to 25 Mt of CO_2 injected in physical conditions typical of the Dogger geological formation, as described in [18]). Such a value is too low compared to the noise threshold commonly adopted in electrical exploration methods, ca. 1% of the primary field [19]. Alternative current injection techniques have been proposed to bring the current source closer to the CO_2 target.

3.1. The Ketzin pilot site experiment

A first approach is based on the Electrical Resistivity Tomography (ERT) [12] which has been evaluated by GFZ on a real implementation case at the Ketzin test site (Germany) [13]. Downhole ERT surveys were performed to monitor a small CO_2 plume (a few tens of thousand tons) by means of three closely spaced wells, each of them equipped with 15 permanent ring-shaped steel electrodes, placed around a coated steel casings at the depth range of 590–740 m with a spacing of about 10 m (the so-called VERA system). It is worth noting that one of these wells is the CO_2 injector. The main limitation of such a technique is that the lateral investigation is limited to the inter-well area. To overcome this difficulty, the system is combined with surface-to-borehole measurements enabling to enlarge the observation area. The whole system includes 16 transmitting (Tx) bipoles (150 m long) distributed on two concentric circles at the surface centred on the three wells at a distance of 800 and 1500 m and uses the VERA electrodes in the three wells for the potential measurements. Several lessons can be drawn from the Ketzin experiment [13]. The system is very sensitive to resistivity changes in the reservoir so that a CO_2 saturation of only 30%, representing a resistivity increase ρ/ρ_0 of only 2, is sufficient to be "detected" by the Ketzin electrical monitoring system. However, the main drawback is the spatial resolution. ERT is not capable of imaging details of the CO_2 saturation on length scales well below the electrode separation (10 m in Ketzin case), but it gives a smoothed image of the CO_2 distribution. The lateral coverage seems to be about 30 m around each well. In addition, from a practical point of view, the development of such systems requires specific well completions with electrodes buried behind the casings, and with these being non-conductive on a sufficient section above and below the electrodes, implying additional costs [14].

3.2. LEMAM-based techniques

To overcome such a practical limitation, alternatives have recently been proposed relying on the use of the existing deep metallic casings (such as observation or abandoned wells) as long electrodes to distribute the current deeper into the ground [14] [17]. The first field trials on the Ketzin site within the CO_2ReMoVe EU project have shown the practicability of such an approach [20] [21]. The new distributed current source is designated as LEMAM (for "Long Electrode Mise-A-la-Masse"). Using this array, a range of detectability thresholds from a risk management perspective can be provided by numerical simulations [14] [17]. A generic layered model based on the Paris Basin context was used, in which the storage aquifer formation is a 75-m-thick carbonate formation of Bathonian age (the Dogger oolite), located at a depth of about 1700 m below ground surface with a resistivity of 1 Ω.m, corresponding to an idealistic salinity up to 50-70 g/l of NaCl in the aquifer (the real salinity of this aquifer is much lower). Calculations were performed by means of the EM3D software of University of Utah [22]. The numerical investigations have shown:

(1) the ability of the method to detect a target at the reservoir depth, considering a CO_2 plume of 1 km × 1 km × 70 m at a depth of ≈1700 m in the Paris basin context. Assuming a uniform gas saturation of respectively ≈ 30%, 55%, ≈ 69% and 80%, this target represents a plume of respectively ≈1.79, ≈3.4, 4.20 and 4.9 Mt, in the physical conditions typical of the Dogger geological formation as described for instance in [18]. Figure 1 depicts the relative in-phase electric response (difference between the in-phase electrical field after and before the injection normalized by the in-phase electrical field before injection) versus the total amount of stored CO_2. Using a repeatability threshold of 1%, this sensitivity analysis shows that a 1.3 Mt CO_2 plume may be monitored. This corresponds to a contrast of resistivity between the target and its surrounding (i.e. the storage aquifer) of 1.6 based on Archie's law (assuming a saturation exponent of 2.0), which is in agreement with the field results at Ketzin site [13].

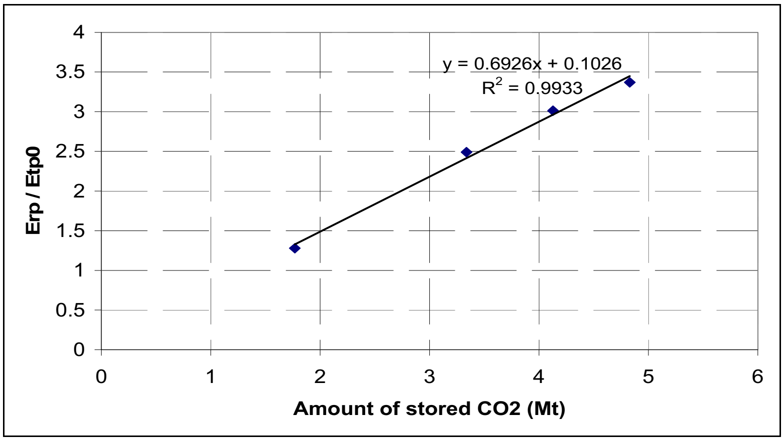

Figure 1: Evolution of the difference (denoted Erp) between the in-phase electrical field after and before injection (in % of the initial field, denoted Etp0) versus the total mount of stored CO_2 at depth (Mt), for a 1km × 1 km × 70 m CO_2 plume located at 1700 m depth in the Dogger formation of the Paris basin (physical conditions described in [18]).

(2) the good sensitivity to detect variations in size, strike and position of the CO_2 plume [17]. Figure 2 depicts for instance the in-phase electrical field for different orientations of the plume;

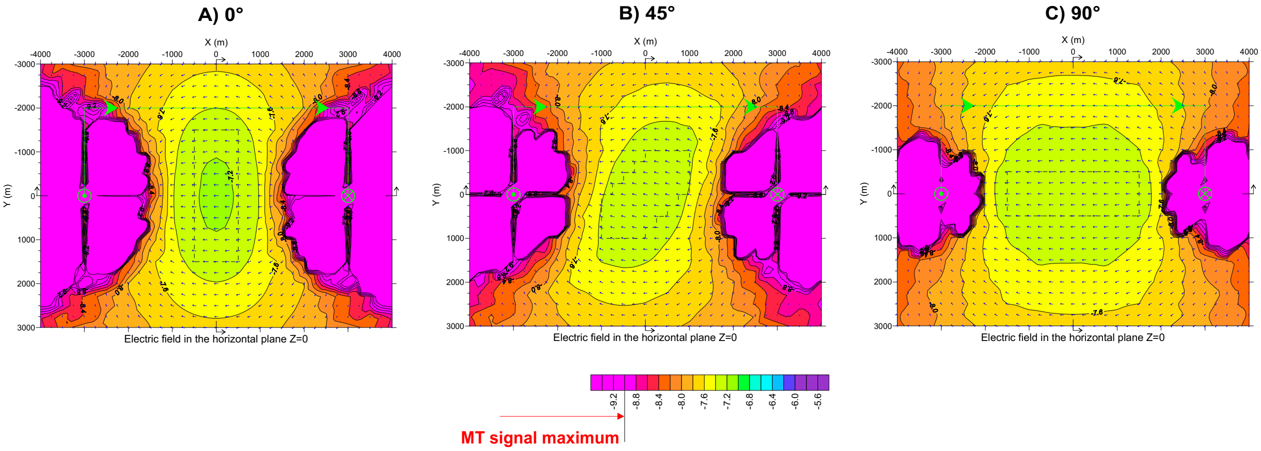

Figure 2: In-phase secondary electric field at 0.5 Hz for a 1 km × 3 km× 70 m CO_2 plume of 10 Ω.m resistivity (S_{CO2}≈68 %), embedded in a 1 Ω.m reservoir at 1700 m depth, for a LEMAM injection via a pair of 1900 m long vertical casings for 3 different strikes angle of the plume: respectively 0°, 45° and 90° [17]. It is observed that the response is much larger than the MT signal with a signal to noise ratio larger than 20.

(3) the ability to detect a shallower resistivity anomaly that can represent a secondary accumulation of CO_2 resulting from an accidental leakage from the reservoir. Figure 3 displays the in-phase electric response for a small (500 m × 500 m × 10 m) CO_2 accumulation at a depth of ≈700 m; corresponding to only about 25 kt of CO_2 assuming a 15 % porosity and a 30 % CO_2 saturation. For this model, the resistivity contrast ρ/ρ_0 between the CO_2 accumulation and the host reservoir is only 2.0, corresponding to a uniform gas saturation of ≈30 % (assuming a saturation exponent of 2.0 in the Archie's law)..

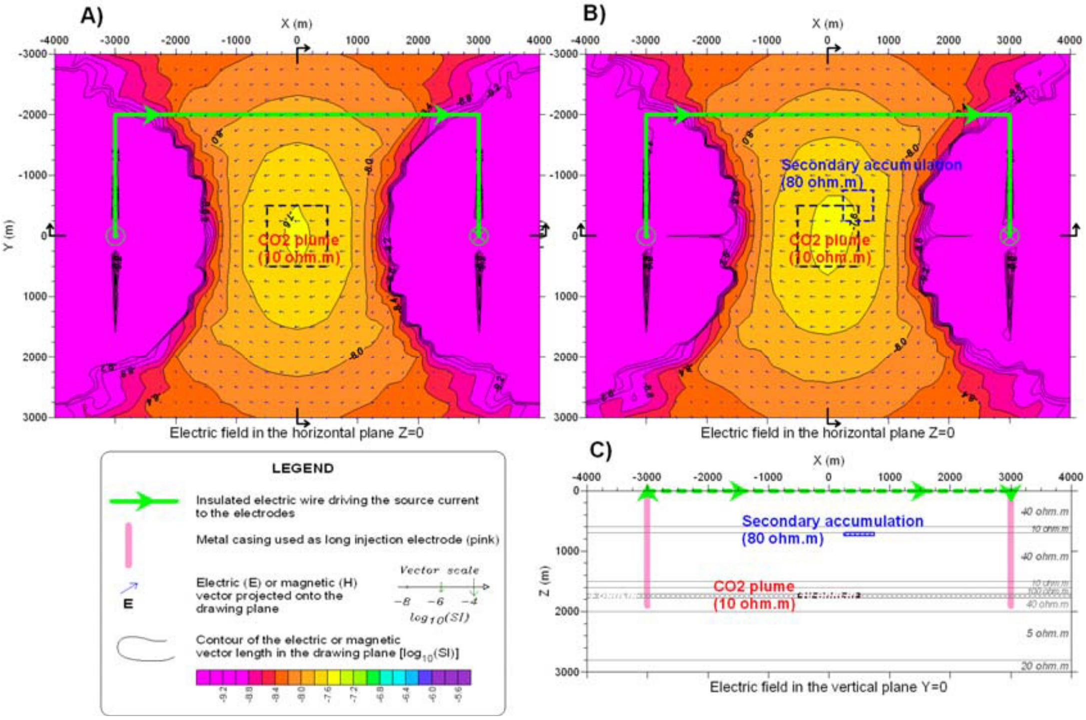

Figure 3: In-phase secondary electric field at 0.5 Hz from a 1 km × 1 km × 70 m CO_2 plume of 10 Ω.m resistivity (S_{CO2}≈68 %), embedded in a 1 Ω.m reservoir at 1700 m depth, for a LEMAM injection via a pair of 1900 m long vertical casings for the following configurations: A) with no secondary accumulation, B) with a 0.5 km×0.5 km×10 m CO_2 accumulation of 80 Ω.m resistivity (S_{CO2}≈30 %), embedded in a 40 Ω.m reservoir host aquifer formation at ≈700 m depth; C) geometry of the conceptual model (vertical cross section XZ).

3.3. Summary

Though not achieving the high resolution of seismic-based techniques, resistivity-based techniques can provide useful information for risk management and be a good complement to seismic surveys in order to: (1) detect a resistive target of a ≈1 Mt CO_2 plume at reservoir depth larger than 1000 m using electrical current injection through existing metal casings (LEMAM array, [14] [17]) or a CO_2 plume of tens of thousands of tons at reservoir depth of ≈700 m through "ERT" techniques (at Ketzin site, [13]) or "Mise-à-la-Masse" techniques [21] [22]; (2) to detect resistivity anomaly with contrast of ≈2.0. Preliminary numerical investigation have shown the ability of detecting either changes in the fate of the CO_2 plume within the reservoir at depths larger than 1000 m using the LEMAM array or the changes resulting from a potential secondary accumulation due to leakage from the reservoir, but this still requires further investigations.

4. Gravimetry

Finally, the gravimetry method could be also very useful, as it brings direct information on the global changes of density in the reservoir [23], whatever the state of the injected CO_2. Nevertheless, as other potential methods, gravity decreases as the square of the distance to the sources which has two major drawbacks: first, it makes it difficult to detect tiny changes in the reservoir. Second, considering the fact that the density contrast between brine and brine plus super-critical CO_2 is generally less than 5 %, the mass movements to detect are close to the limits of what can be reached with the traditional gravity methods. Direct detection of changes in density has been measured experimentally at Sleipner by repetitive gravity profiles carried out at the sea-bottom with a ROVDOG (Remotely Operated Vehicle deployable Deep Ocean Gravimeter), in 2002 and 2005 respectively, which corresponds approximately to the injected quantity of 3 Mt [24]. New results from sea-bottom and onshore measurements are expected in order to confirm the actual sensitivity of the method.

Simulations carried out for the specific case of the Paris Basin show that the minimum quantity of CO_2 located at a depth of 1 km and capable to create a 10 µgal anomaly at the surface is at least 1 to 2 Mt, depending on CO_2 density (Figure 4). It is assumed that a variation of 10 µgal should be considered as significant, respect to a commonly accepted value of noise of a few µgals for on shore microgravity measurements [24].

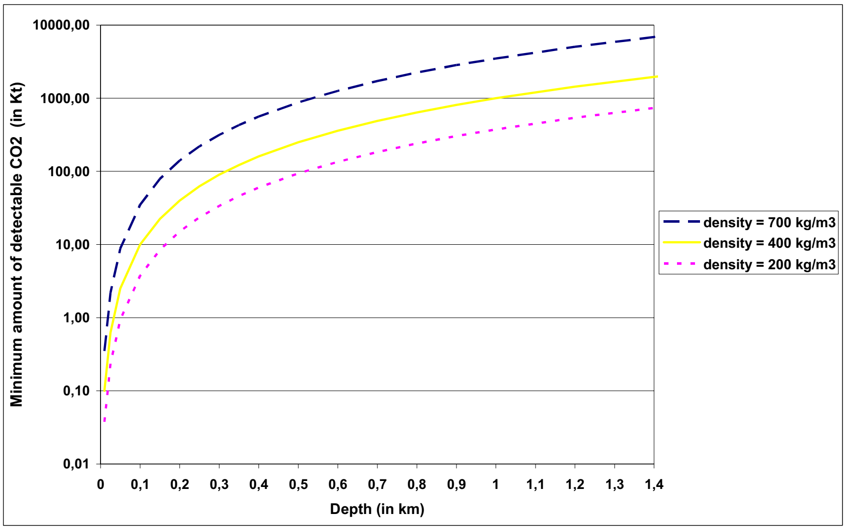

Figure 4: Estimation of the minimum detectable CO_2 quantity (in Kt) vs. depth, capable to create an anomaly of 10 µgal at the surface, given that all the corrections have correctly been made.

Should the CO_2 leak and be trapped in a shallower secondary reservoir, we see in figure 4 that the minimum amount of detectable CO_2 is of the order of few tens of kilotons at depths lower that 200 m. In that case, gravimetry could be contemplated to be used as a complementary method to other geophysical method to quantify a leakage

Nevertheless, gravity measurements are highly sensitive to mass changes in the vicinity of the gravity station, e.g. the water table, that may hide the signal due to the reservoir itself. Gravity gradiometry is therefore investigated as a way to separate the contributions of the reservoir and of the hydrological seasonal effects.

5. Conclusions

Three geophysical methods which have the capability to detect and map the CO_2 plume at the reservoir depth have been compared from literature examples and modelling of simple cases. Main characteristics and limitations of each method are synthesised in Table 1. Respect to the amount of CO_2 stored that can be quantified for verification purpose, there is an order of magnitude between 4D seismic and the other two methods. Respect to the detection of leakage at the reservoir level, only 4D seismic could be considered as useful, regarding the range recommended in [1]. Nevertheless, it is clear that using downhole measurements, e.g. electric crosshole or downhole gravity will increase the resolution of these methods and therefore its ability to detect leakage. The combined use of the three methods is recommended, as they may bring complementary information about density and saturation, which may be very helpful for multi-phase flow transport modelling. In case of CO_2 leakage upwards and accumulation within a secondary reservoir located at a few hundreds of meters depth, the resolution of the three methods could be increased by several order of magnitude and small amounts of CO_2 could be detected, depending whether it is in gaseous phase or dissolved. It is expected that controlled experiments of leaking CO_2 at shallow depth will help to define more precisely the conditions of use of the three methods.

Method	Minimum quantity for verification (at reservoir depth > 800 m)	Minimum quantity for leakage detection (at reservoir depth)	Secondary reservoir detection (at depth ca. 200-300 m)	Minimum quantity in theory detectable in secondary reservoir	Geological limitations (specific to CO_2 storage)
4D seismic	Hundreds of Kts	Few Kts	Yes	Few hundreds of tons	Reservoir : Low porosity, layers thickness (decreases the tuning effect)
Electrical CSEM	1 Mt Few tens of Kts (at Ketzin at 600-700 m deep)	Not yet proved	Yes	Few tens of Kts	Low resistivity, thin layers (either resistive or conductive)
Gravimetry	1 Mt	Not yet proved	Yes	Few tens of Kts	Seasonal surface variations

Table 1: Comparison of the performances of 4D seismic, electrical/EM and gravimetry methods.

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