



Open or closed? A discussion of the mistaken assumptions in the Economides pressure analysis of carbon sequestration

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ARTICLE INFO

Article history:

Received 1 July 2010

Accepted 31 August 2010

Keywords:

Carbon dioxide

Capacity assessment

Saline aquifer formation

ABSTRACT

The proposition by Economides and Ehlig–Economides (E&E) in 2009 and 2010 that geological storage of CO₂ is 'not feasible at any cost' deserves to be examined closely, as this is counter to the view expressed in the overwhelming majority of geological and engineering publications (IPCC, 2005; IEAGHG, 2009). The E&E papers misrepresent this work and suggest that: (1) CO₂ cannot be stored in reservoirs that have a surface outcrop; (2) CO₂ storage capacity in reservoirs without outcrops has been over-estimated and (3) the potential for CO₂ storage in the deep subsurface is miniscule. We take issue with each of these, discussed in turn below. We also (4) review the evidence to date, which contradicts the Economides' analysis, and (5) describe common pressure management strategies that demonstrate a more realistic and rational assessment of the experience of CO₂ injection to date. We conclude that large-scale geological CO₂ storage is feasible.

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1. Conceptual models

Modern technological folklore includes several popular myths and flawed analyses which conceptually link complex systems to simple causes. The persistence of such myths is helped by the intermixing of valid concepts, which enable belief by many non-experts, with invalid concepts, which unfortunately negate the analysis. A good example of this is the mathematical 'proof' that bumblebees are unable to fly. This analysis was, within the limits of its own assumptions, correct. However, the assumptions were flawed as they were based on a faulty mathematical analogy between bumblebees and conventional aircraft, where lift is generated at the wing by forward speed. Further analysis showed that a helicopter comparison is more appropriate, as it includes the lift generated by turbulence (Peterson, 2004). The general point here is that scientific analogies can be drawn that are too simplistic and misleading, even if mathematically rigorous. It is commonly understood that, for subsurface reservoirs, the results of a model can be strongly influenced by the boundary conditions of the reservoir. It follows that an accurate framing of the initial problem is of vital importance, as numerical simulations can appear to support a false proposition when the approach is founded on a flawed conceptual model. Mathematical analysis can be persuasive, but needs to be critiqued by observations and experimentation. We suggest that E&E have framed their subsurface analysis incorrectly, with questionable numerical values, conceptual analogies and

boundary condition assumptions, which result in misleading calculations regarding the pressure response of storage formations to the sequestration of CO₂.

1.1. Outcropping reservoirs

E&E state that all potential reservoirs with exposures at the land surface can be discounted from a CO₂ storage analysis because of the possibility of CO₂ leakage. However, reservoirs with outcrop exposures at the surface can, and do, host hydrocarbon accumulations deeper down-dip. A simple example is the hydrocarbon stratigraphy of Alberta basin, which hosts abundant oil and gas fields down-dip to the west of exposed sandstones, despite a weak regional water drive to the east that has been flowing for millions of years (Garven, 1989). Additional well-known examples include the vast hydrocarbon volumes trapped in the porous and permeable reservoirs of Texas, such as the Smackover Formation, down-dip of their surface outcrop (Moore and Druckman, 1981), and also the giant Gröningen gas field of the Netherlands (Stauble and Milius, 1970; Whaley, 2009), which hosts abundant methane gas down-dip of the Rotliegend sandstone outcrop over much of western Europe. Water movement occurs over hundreds of kilometres in sedimentary basins (Sverjensky and Garven, 1992) but this does not prevent hydrocarbons from trapping (Rich, 1921).

1.2. Available pore space

E&E are correct in highlighting pressure as one of the limits on CO₂ injection, although pressure is only one of several important factors.

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However, they are not correct in claiming as a ‘discovery’ the implication that the volume available to injected CO₂ is only “1%” of the reservoir pore volume. Similar early approximations date back over a decade (e.g. van der Meer, 1995). All published estimates of such storage coefficients have been recently reviewed and a range of values identified (CSLF, 2008; USDOE, 2008; IEAGHG, 2009) by means of comprehensive numerical simulations. For instance, the USDOE (2008) have determined via Monte Carlo analysis that the realistic range for likely geological settings is between 1% and 4% for a 15-to-85% confidence interval, giving an average 2.4% efficiency for 50% confidence. The range used in regional assessments of storage capacity is typically 0.2% to 4%, while many recent evaluations use 1% or 2% of the pore volume (SCCS, 2009; IEAGHG, 2009). The “1%” analysis is neither news, nor an accurate reflection of the more considered estimates that both encompass and predate what is essentially a crude approximation by E&E. The total volume of capacity available for storage remains the subject of research in the USA and other countries around the world (GCCSI, 2009). There is little disagreement about the two principal types of resource that qualify, which are:

- Depleted hydrocarbon fields, with depressurised gas fields forming particularly attractive early targets.
- Deep saline formations, which are agreed to hold the most potential over the mid-to-long-term.

The current uncertainty is considered to be how to assess the commercially useful volume, which is site-specific and could be more or less than the “1%” first approximation described above (Qi et al., 2009). The key point is that the existing analyses of capacity, as a fraction of a percentage of the formation volume, for all regional assessments still provide predictions of extremely large storage volumes in Europe (GeoCapacity, 2009), in North America (USDOE, 2008), and in Australia (CO2CRC, 2008).

1.3. Numerical model

E&E present example calculations that make several highly questionable and poorly justified numerical assumptions. In our view, the assumptions entirely invalidate the calculations. Four key aspects of the E&E model (storage boundaries, reservoir properties, heuristic approximations, and geological setting) are discussed below:

- Firstly, the storage reservoir is assumed to be closed, with no-flow boundaries. This simplification is inappropriate for regional CO₂ storage modelling, as it is well understood that the shales that typically surround storage reservoirs have non-zero permeabilities (Yang and Aplin, 2010). The regional flow attributes of aqueous and hydrocarbon fluids through and across such porous and permeable media has been understood now for many decades (e.g. Lamb, 1932; Hubbert, 1957), and it is widely accepted that the no-flow approximation is only a good approximation for reservoir engineers working at a small scale when wishing to examine natural gas field production, or methane gas engineered storage and recovery (Dake, 1978; Cavanagh, 2010). Although the boundary shales that trap oil and gas are effectively perfect seals for multi-phase flow, for large CO₂ operations, the regional scale is significant. This includes consideration of single-phase pressure footprints and the flow of water through the low permeability shale boundaries, and shifts the emphasis to an open-boundary, single-phase, pore-water displacement model (Zhou et al., 2008), where the pressure change and rate of pressure variation are significant. Therefore, any subsurface formation, including those chosen for CO₂ storage is unlikely to have a zero-flow boundary. A no-flow boundary caricature of a natural rock body is unreasonable at a regional scale.
- Secondly, the reservoir is assumed to have an average permeability of 100 millidarcies and an average thickness of approximately 30 m.

Although these values exist in deeply buried reservoirs, they are unrepresentative of many hydrocarbon reservoirs or saline formations, which frequently have permeabilities of many hundreds of millidarcies and thicknesses of hundreds of metres. The CO₂ ‘Best Practice’ storage manual (Holloway et al., 2004) provides more appropriate and realistic guidance. The pessimistic parameter values chosen by E&E inevitably produce pessimistic calculations of capacity.

- Thirdly, confidence in the rigour of the analysis is undermined by a number of basic mistakes. For example, unrealistic values are chosen for the heuristic that represents the temperature gradient (18 °C/km instead of a more typical 35 °C/km), and the pressure gradient term is far too simple, ignoring both the atmospheric pressure contribution and salinity of the pore fluid. There is also an inadequately explained but important calculation at the heart of the E&E argument: a pressure equation in the 2009 paper that has a constant of proportionality with unspecified units. In the 2010 version the same calculation is used again, but appears to use different units. Consequently the value “141.2” in equation [8] of Economides and Ehlig–Economides (2009) becomes “0.069” in the same equation for Ehlig–Economides and Economides (2010). The underlying reasoning for this change remains obscure, but appears to be why the 2010 abstract reduces the predicted reservoir volume required for storage by a factor of ten compared to the earlier 2009 paper (i.e. “50 to 200” in 2009 becomes “5 to 20” in 2010). Although it may be quite correct to recalculate using standard units, it is very surprising that the results, interpretation and discussion remain unaltered despite this order-of-magnitude reduction in the headline figure for the required volume. Such a lack of connection between the text calculations and conclusions, which do not reflect the calculation results, does not inspire confidence.
- Fourthly, the calculation makes an explicit assumption that only a single 30 meter thick sandstone exists regionally beneath the ground surface that is to be used as a storage location. This is, again, extremely unrealistic. For example, any familiarity with the iconic images of the Grand Canyon will readily communicate that the subsurface can, and often does, contain many packages of porous sandstone and carbonate that are many hundreds of metres in thickness, and areally extremely widespread. Hydrocarbon basins such as the Illinois Basin (Swezey, 2009), Texas Gulf (Chowdhury and Turco, 2006), or the North Sea (Glennie, 1998) are also endowed with multiple layers of sandstone and each layer may be hundreds of metres in thickness. To imply that only one thin reservoir is available or viable for CO₂ storage, and that this is required to extend regionally for thousands of square kilometres is simply untrue: a misrepresentation in light of established geological fact.

1.4. Evidence to date

Since 1996, three CO₂ storage projects have been undertaken at Mt/yr (Sleipner, In Salah and Weyburn), injecting CO₂ into the deep subsurface accompanied by detailed scientific monitoring. The E&E papers comment that the most well-publicised of these, the Sleipner project, has stored less CO₂ radially than measured by seismic reflection, that significant leakage has occurred and that no pressure profile has been modelled. These are incorrect and unsupported assertions as shown by the detailed analyses of Arts et al. (2005) and Chadwick et al. (2009), and our own work (Cavanagh and Haszeldine, in review). No leakage from the storage reservoir has been detected or inferred. The pressure of injection has been measured at the wellhead since injection started in 1996, and no systematic pressure increase has occurred (Ringrose, 2010). This is entirely compatible with the consensus view that the Sleipner storage site is behaving as a large and effective reservoir for the storage of CO₂.

We have analysed the results of twenty CO₂ injection projects globally (SCCS, 2010). Of these, nine are at, or are intended to be at, an industrial scale, storing 1-to-130 Mt CO₂ during the project lifetime. Only the Midwest Regional Carbon Sequestration Partnership project at the Burger Plant, Shadyside, Ohio, has experienced severe pressure problems (USDOE, 2009; MRCSP, 2010), with a pressure build-up from 800-to-5400 psi (5-to-37 MPa) over 3 h 45 min. The Shadyside project was cancelled in 2008 after only a few tens of tonnes of the intended 3000 t CO₂ was injected. This is not surprising as the post-injection analysis showed the formation permeability to be extremely low at 0.001-to-0.08 mD. By contrast, the storage sites at Snøhvit (450 mD), K12-B (20 mD) and In Salah (5 mD), have adequate permeability combined with thickness (i.e. injectivity) and are on schedule to store several millions tonnes of CO₂ injected at each site.

1.5. Pressure management

The E&E papers ignore the ability to engineer around the problem of increased subsurface pressure. It is well established in reservoir engineering that the greatest increase of pressure during injection is expected close to the well bore. Established methods can engineer to reduce this pressure build-up, for example, by increasing the length of contact between the well bore and the reservoir formation, typically by using horizontal drilling. A second method, water production, is often used to manage water breakthrough or increased pressure as a consequence of water injection during hydrocarbon production. This method produces formation water from the reservoir and either re-injects that into shallower reservoirs with high porosity and permeability, or if the environmental regulations allow, discharges to the surface. This use of relief wells to manage pressure is proposed at Gorgon (Flett et al., 2009), and could be employed in the Utsira reservoir formation if required (Lindeberg et al., 2009). This would allow a storage capacity of greater than “1%” to be achieved.

2. Discussion

E&E question the potential for geological storage of CO₂ to provide an effective response to climate change, as they envisage the global industrial scale of this aspect of greenhouse gas mitigation to be cost-prohibitive. Their first-approximation calculations, based on annual US hydrocarbon and water production, correctly point to the unprecedented immensity of the endeavour as a carbon sequestration option. While a detailed cost analysis is beyond the scope of this paper – see McKinsey (2009) for a detailed review of cost curves – it is clear that the economics is manageable at a global level. Both petroleum industry knowledge and petroleum industry scales of implementation will be needed if CO₂ storage is to make the necessary global contribution to greenhouse gas emissions reduction (Lovell, 2009). It is also clear that the potential storage capacity of hydrocarbon fields is insufficient, and that drives us and others to the conclusion that saline formations are essential to achieve sufficient volumes of geological CO₂ storage. Similar conclusions have been reached in many global regions, where hydrocarbon fields typically form 5% of the storage and saline formations 95% (USDOE, 2008; SCCS, 2009). This is why current field tests are focused on such sites (USDOE, 2009; SCCS, 2010). The E&E assumption that an abandoned gas reservoir without water drive can be analysed in the same way as a large regional saline formation is incorrect. In fact, saline formations are not required to be closed systems, and pressure dissipation can occur down-dip, and then laterally, from structural traps with aquifer support, to displace existing formation waters, as well as vertically through the permeable shales at the upper and lower boundaries of regional saline formations.

From a review of current CO₂ injection and storage experiments, and a comparison of these with long-established models and concepts for hydrocarbon trapping and petroleum systems, it is apparent that

subsurface reservoirs are not hermetically sealed, but instead are flanked by semi-permeable rocks such as shale. The permeability of these shale boundaries at the reservoir top, base and sides is low but, crucially, not zero. Accurate and appropriate three-dimensional fluid flow models of reservoirs can simulate the feedback effect of the permeability of the enclosing shale rocks on the pressure build-up inside the reservoir during CO₂ injection (Cavanagh, 2010). Results from our simulations of CO₂ injection show that a critical range of values exist for shale, which retain oil and gas as a seal. These are within the range of shale permeabilities measured globally by Yang and Aplin (2010). However if the enclosing permeabilities are one hundred times less, then insufficient fluid transmission occurs and the pressure increases significantly in the reservoir formation. Rocks with such low permeabilities appear to be rare in the subsurface at the depths envisaged for CO₂ storage, and are associated with deeply buried zones of naturally elevated geo-pressures. Such reservoirs are not prime candidates for CO₂ storage, and do not feature as abundant storage in global assessments, primarily because of the expense associated with drilling complex and deep wells. Therefore we are confident that CO₂ storage will not reflect the extreme cases chosen by van der Meer and van Wees (2006), van der Meer and Egberts (2008) or the E&E papers (2009; 2010) to illustrate a hypothetical but unfounded risk of pressure build-up.

3. Conclusion

We have demonstrated that the Economides' analysis (2009, 2010) of an open system is flawed. Furthermore, the closed-system analysis is based on an incorrect conceptual model of the subsurface geology and fluid flow in the sedimentary basins where CO₂ will be stored. The overly simplistic mathematical analysis uses numerical values that are not well chosen or explained, and produces varying results from one paper to the next which are not reflected in the interpretation and conclusions. The assertion that CO₂ storage is “not feasible at any cost” is demonstrably untrue based on the results of worldwide injection experiments that are already successfully storing CO₂. While it is true that pressure is one of many relevant factors which need to be taken into consideration when planning a storage site, this single factor is widely anticipated and well understood. Pressure management strategies already exist to address likely pressure build-up scenarios. We propose that the conceptual model and mathematical analysis, is analogous in style to the theoretical approach which concluded that bumblebees cannot fly. Elegant mathematics and modelling must be consistent with real-world observations. The evidence to date, and geologically realistic flow models, clearly support the consensus that pressure build-up is certainly not a deal breaker for carbon capture and storage.

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