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A Brief Technical Critique of Ehlig-Economides and Economides 2010: "Sequestering Carbon Dioxide in a Closed Underground Volume"

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Abstract: In their 2010 paper, “Sequestering Carbon Dioxide in a Closed Underground Volume,” authors Ehlig-Economides and Economides assert that “underground carbon dioxide sequestration via bulk CO_2 injection is not feasible at any cost.” The authors base this conclusion on a number of assumptions that the peer reviewed technical literature and decades of carbon dioxide (CO_2) injection experience have proven invalid. In particular, the paper is built upon two flawed premises: first, that effective CO_2 storage requires the presence of complete structural closure bounded on all sides by impermeable media, and second, that any other storage system is guaranteed to leak. These two assumptions inform every aspect of the authors’ analyses, and without them, the paper fails to prove its conclusions. The assertion put forward by Ehlig-Economides and Economides that anthropogenic CO_2 cannot be stored in deep geologic formations is refuted by even the most cursory examination of the more than 25 years of accumulated commercial carbon dioxide capture and storage experience.

Key Words: carbon dioxide capture and storage; CO_2 emissions mitigation; feasibility; structural traps; CO_2 storage mechanisms; cost; security of storage; carbon sequestration; climate change; global warming.

In their 2010 paper, "Sequestering Carbon Dioxide in a Closed Underground Volume,"[1] authors Ehlig-Economides and Economides assert that "underground carbon dioxide sequestration via bulk CO_2 injection is not feasible at any cost." The authors base this conclusion on a number of assumptions that have been proven invalid by the peer reviewed technical literature and decades of carbon dioxide (CO_2) injection experience. In particular, the paper is built upon two key assumptions:

1.) Effective CO_2 storage requires the presence of a hydrologically isolated, completely closed geologic structure; and
2.) Any other storage system is guaranteed to leak.

These two assumptions inform every aspect of the analysis presented by the paper, and without them, the authors' factually inaccurate conclusions are left unsupported by their analysis. Thus, it is critical to first address these two flawed premises.

Safe, secure geologic CO_2 storage does not require complete structural closure

In the Ehlig-Economides and Economides article, a closed system is defined as a finite subsurface volume, structurally bounded on all sides by impermeable geologic media and that is fully or nearly saturated with formation fluids – some combination of oil, natural gas, and brine. Given that the geologic formation where the CO_2 is to be stored and the associated formation fluids are largely incompressible, the assumption that the system is closed leads directly to the conclusion that the only volume available for CO_2 storage is created by increasing the pressure in the system to a level below the fracture pressure of the caprock, resulting in a very small marginal potential storage volume. Under these assumptions, Ehlig-Economides and Economides argue that the deployment of carbon dioxide capture and storage (CCS) technologies at a large CO_2 point source such as a base-load, coal-fired power plant would be extremely challenging because it would require an extraordinarily large storage field. The total number of suitable sites that would meet the highly arbitrary criteria set forth by the Ehlig-Economides and Economides paper while still satisfying the large capacity requirements to accommodate storage needs over a facility's 30-50 year lifetime would likely be extremely limited. Thus, based on these assumptions, the authors conclude that, "[CCS] is not a practical means to provide any substantive reduction in CO_2 emissions, although it has been repeatedly presented as such by others."

The arbitrary assumptions employed by Ehlig-Economides and Economides essentially describe a subsurface vessel, with defined, impermeable boundaries on all sides, into which fluid is injected and total injection volume is limited by the properties of the vessel itself. Though it is not based on scientific criteria for safe, secure CO_2 storage, this system definition drastically limits the total storage capacity and leads directly to the authors' pessimistic conclusions regarding the feasibility of large-scale use of CCS.

[1] Ehlig-Economides, C. and M. J. Economides. "Sequestering Carbon Dioxide in a Closed Underground Volume." *J. Petrol. Sci. Eng.* 70(1-2):123-130. Virtually the same paper was published earlier in 2009 as M.J. Economides and C.A. Ehlig-Economides. 2009. "Sequestering Carbon Dioxide in a Closed Underground Volume." Society of Petroleum Engineers Annual Technical Conference and Exhibition, 4-7 October 2009, New Orleans, Louisiana. DOI: 10.2118/124430-MS.

Given the impact of the authors' assumptions on their analysis and final conclusions, it is important to understand whether these assumptions represent a typical or realistic base case for CO_2 storage projects. Here, it is clear that they do not and instead represent a case so non-optimal that it is difficult to imagine a CO_2 source faced with this storage option to pursue it in the presence of other possibly less expensive mitigation options (e.g., transport to a more amenable site, fuel switching, purchasing CO_2 offsets). Moreover, the case is not reflective of the majority of storage opportunities that could be encountered in the large, regional storage formations likely to serve as "baseload" storage capacity in the U.S. and elsewhere (Dahowski *et al.* 2010, Dooley *et al.* 2009, Wise *et al.* 2007, Dooley *et al.* 2006, Dahowski *et al.* 2005). Instead of describing a typical storage project similar to those being implemented at commercial and demonstration scales around the world, the assumptions employed by Ehlig-Economides and Economides essentially describe a subsurface vessel, with defined, impermeable boundaries on all sides, into which fluid is injected and where total injection volume is limited by the properties of the vessel itself. This combination of characteristics is geologically rare, as well as unnecessary and possibly counterproductive in terms of safely storing large quantities of anthropogenic CO_2 in the deep subsurface.

The authors' assumptions regarding the pressure-limited injection volumes of closed structures severely constrains storage capacities, a finding which they invoke to support their pessimistic views of the viability of CCS. Methods for calculating CO_2 storage capacity have been under development for well over a decade (e.g., Holloway *et al.* 1996), and approaches like the one employed by Ehlig-Economides and Economides have been rejected in favor of methodologies that reflect more realistic assumptions, based in part upon knowledge gained from ongoing CO_2 storage projects. Instead of pressure-limited storage capacity estimation, current state-of-the-art capacity methodologies take a storage efficiency approach, representing the amount of CO_2 that can be stored in a given volume of pore space. Many current assessments of geologic CO_2 storage capacity employ tight constraints on storage space availability as a sensitivity analysis (e.g., NETL 2007, Dahowski *et al.* 2005, Dahowski *et al.* 2009, Edmonds *et al.* 2007) but these analyses are used to inform a discussion of the theoretical versus technically achievable storage capacity, not to account for the exclusive use of closed trapping systems, and by no means do the authors of these studies express this as a binding constraint, as asserted in the Ehlig-Economides and Economides paper.

The scenario proposed by the Ehlig-Economides and Economides paper would result in the buoyant mass of supercritical CO_2 rising quickly to the top of the assumed storage formation, where much of it would remain over long time scales as a single mass of free-phase CO_2. The vast body of peer reviewed literature makes it clear that this is not an optimal end state from a storage security perspective, and long-term retention via dissolution and capillary trapping are far preferable.

Capacity estimation methodology aside, the subsurface contains very few closed vessel-like structures of the volumes that would be of interest for CO_2 storage. Also, in the vast majority of cases, fluid in the deep subsurface – whether oil, natural gas, or brackish formation waters – is driven by pressure and density differences both laterally and vertically along preferential paths dictated by relative permeability (Bryant *et al.* 2006). This fluid flow within the storage formation can increase the security of long-term CO_2 storage. Research documented in the peer reviewed literature has demonstrated the value of CO_2 storage in large, regionally extensive

reservoirs (Bachu 2003, Burton *et al*. 2008). In particular, engineering CO_2 injection to promote the mobility of CO_2 through the brine-saturated rock of the storage zone has been shown to result in more secure CO_2 storage via secondary trapping mechanisms such as capillary and dissolution trapping (IPCC 2005, Benson 2008, Hovorka *et al*. 2006). These trapping processes result in storage that is significantly more secure than the buoyancy-driven hydrodynamic trapping process that dominates the early years of any CO_2 storage project. But without fluid flow to mix the CO_2 with formation waters, storage under the scenario proposed by Ehlig-Economides and Economides would rely on hydrodynamic trapping for a far longer period. Under their scenario, the buoyant mass of supercritical CO_2 would rise quickly to the top of the storage formation, where much of it would remain over long time scales as free-phase CO_2. Dissolution processes would still occur, but lacking fluid flow in the formation, this process would take significantly more time than it would otherwise. Increasing the amount of pore space and formation fluid that the injected CO_2 comes in contact with helps to speed the transition from pure hydrodynamic trapping to these longer-term, and higher security mechanisms. Both capillary and dissolution trapping mechanisms lessen the chance of CO_2 moving out of the storage formation due to immobilization of trapped CO_2 and a reversal of the buoyancy effect[2], respectively. This represents a far more secure end state from a storage perspective, and more desirable than hydrodynamic trapping of the free-phase CO_2 plume against the caprock for longer time frames. Considering that vertically and laterally extensive storage formations provide for greater contact between the stored CO_2 and the target storage reservoir, and that this leads to increased storage security over time, it is difficult to see why the Ehlig-Economides and Economides analysis is based exclusively on a closed system.

However, even if complete structural closure was required to store CO_2 in the subsurface, the assertion by Ehlig-Economides and Economides that total storage volumes would be so small as to negate the value of doing CCS is misinformed. While we have not specifically examined the arbitrarily over-constrained case put forward by Ehlig-Economides and Economides, we have published research demonstrating that, if only a relatively small fraction of the estimated CO_2 storage resource is actually achievable, the value of having CCS in society's portfolio of responses to climate change is still on the order of trillions of dollars (Edmonds *et al*., 2007). Thus, even if the actual realizable CO_2 storage potentials are orders of magnitude smaller than currently estimated, the relative cost of employing CCS as a means of addressing climate change could still be competitive with other large scale emissions mitigation measures. The assertion that "CO_2 storage is infeasible at any cost," is pure hyperbole.

Structural closure does not equate to the highest storage security

The assertion that CO_2 storage in open formations must inevitably lead to the release of CO_2 back to the atmosphere thus negating the effectiveness of geologic CO_2 storage as a means of addressing climate change is contradicted by an overwhelming volume of technical literature. Ehlig-Economides and Economides state that open formations would be unacceptable for geologic CO_2 storage because:

[2] While free-phase supercritical CO_2 is less dense than water, rising to the top of the formation under buoyancy, brine becomes more dense as CO_2 is dissolved, with density of the aqueous phase increasing as a function of CO_2 saturation. Thus, the most highly CO_2-saturated water sinks to the bottom of the reservoir, with brine with less (or no) dissolved CO_2 driven up by buoyancy (Garcia 2001).

> The open aquifer … must either outcrop to the land surface or in a stream, lake, or ocean bed where it would be in equilibrium either with atmospheric pressure or with the pressure at the stream, lake or ocean bottom. An outcropping aquifer would provide a potential path for injected CO_2 to escape back to the atmosphere, thereby defeating the purpose of CO_2 sequestration.

While injected supercritical CO_2 is buoyant within the storage formation at the time of injection and therefore reliant on structural and stratigraphic trapping as the primary retention mechanism, over time other processes – in particular solubility and capillary / residual gas trapping – become the dominant mechanisms keeping CO_2 in the storage formation (see Figure 1). These processes slow and eventually immobilize the CO_2 in the formation, reversing the density-driven flow to allow CO_2-saturated water to sink in the formation and decreasing the mechanisms behind buoyancy-driven leakage issues that must be considered early in the storage process (Benson 2008, Hovorka *et al*., 2006). This allows for the definition of a finite boundary on the extent of CO_2 migration during storage, contradicting the implication that injected CO_2 will simply migrate forever until it finds an outflow zone or other migration pathway out of the storage formation.

The Ehlig-Economides and Economides paper categorically dismisses the technical literature that has shown benefits associated with these secondary and tertiary trapping mechanisms for injected CO_2 because they involve "woefully slow process[es]." While buoyancy trapping tends to represent the bulk of CO_2 trapped in the near-term, the literature is clear that capillary, solubility and mineral trapping represent a higher degree of long-term security and stability of the stored CO_2. While sites must be characterized to ensure their suitability for buoyancy-driven trapping in the near-term, ultimately these secondary and tertiary processes will render the CO_2 immobile within the formation, preventing it from reaching distant migration pathways to the surface.

In response to the authors' implication that CO_2 loss at hydrologic outflow boundaries is inevitable, it is important to note that pre-injection site selection and characterization efforts are designed to identify these sorts of risks and ensure that the engineered system will not result in loss of CO_2 by migration from outflow boundaries or any other leakage pathway. Further, it is clear from the proposed EPA rulemaking on the governance of CO_2 injection into the subsurface (Federal Register 2008) that a project with a known leakage pathway for CO_2 that could not be adequately mitigated (e.g., by plugging an abandoned well penetrating the storage zone) would not be granted an injection permit. Thus, the sites that are selected and permitted for CO_2 storage are assured to be an adequate distance from outflow zones and are managed to prevent the migration of CO_2 out of the storage system.

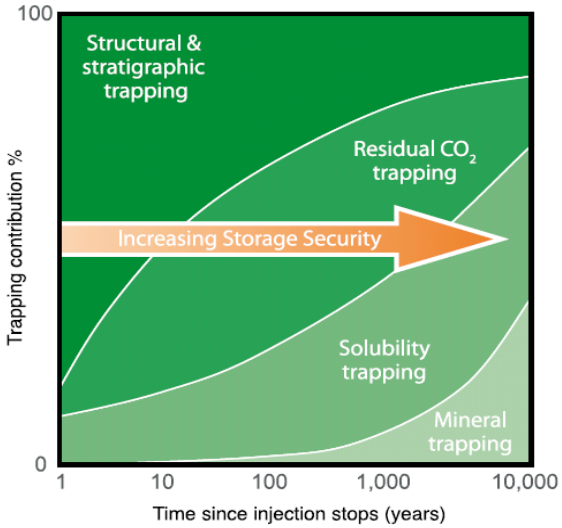

Figure 1. Both physical and chemical trapping mechanisms play important roles over the lifetime of a CO_2 storage project (from Benson 2008).

For scale, the timeframes required for solubility trapping via dissolution of the injected CO_2 are typically on the order of hundreds to thousands of years, not tens of thousands or millions of years (IPCC 2005 and Benson 2008). It is important to note that these are likely conservative estimates, and that the higher the flow gradient in the formation, the faster these processes take place. Modeling employed as a part of site characterization and project management is able to provide a more realistic estimate of this timeframe as a function of parameters specific to the reservoir being evaluated for storage. Coupled with a detailed understanding of the storage formation itself and the broader regional geology, projects can be selected and managed to ensure that injected CO_2 never reaches hydrologic outflow zones.

On the Economides' Conclusions

The conclusions asserted by the Ehlig-Economides and Economides paper are flawed and stand in stark contrast to the enormous body of literature and field experience on CO_2 injection and storage in the subsurface. The policy and regulatory communities must not rely on unsupported conclusions such as "underground carbon dioxide sequestration via bulk CO_2 injection is not feasible at any cost" and that "geologic sequestration of CO_2 [is] a profoundly non-feasible option for the management of CO_2 emissions" because they are not based on good science or thoughtful analysis.

The technical feasibility of storing CO_2 in deep geologic formations is entirely proven by the existence of the Statoil Sleipner project, which has been injecting approximately 1 $MtCO_2$/year into a deep geologic formation below the North Sea for nearly a decade and a half. The fate of the CO_2 injected at Sleipner has been monitored via an extensive and scientifically rigorous measurement, monitoring and verification (MMV) program. This MMV process continues to verify that CO_2 injected into the storage formation remains isolated in the subsurface where it cannot contribute to anthropogenic climate change. The more than 25 years of cumulative experience and the significant scientific and technological knowledge gained from Sleipner and the other three large commercial end-to-end commercial CCS projects – Snøhvit, In Salah and Weyburn – are further proof that "underground carbon dioxide sequestration via bulk CO_2 injection" is feasible and that the cost of doing so must not be infinite as asserted by Ehlig-Economides and Economides.[3]

The assertion that subsurface storage of large volumes of fluids is impossible is also inconsistent with the experience gained from CO_2 injection pilot projects around the world and countless other fluid injection projects over the last several decades such as the injection of hundreds billions of gallons of waste fluid into the subsurface under the auspices of the U.S. EPA Underground Injection Control Program (EPA, 2002). Not only are these projects technically and economically viable, they are effectively managed, and safely regulated.

The CCS policy and regulatory communities are in need of robust, well-founded science and engineering upon which to base their decisions regarding how to govern geologic CO_2 storage. Innovative ideas that challenge the conventional wisdom on issues critical to the success of commercial-scale CO_2 storage are and will continue to be welcomed by the technical

[3] Dooley *et al.* (2009) provide an overview of the CO_2 capture, storage and measurement, monitoring and verification technologies that have been successfully employed at Sleipner, Snøhvit, In Salah and Weyburn.

community. While the Ehlig-Economides and Economides paper does highlight the need for continued research and field work to better understand how CCS will deploy in the real world, unfounded conclusions such as “underground carbon dioxide sequestration via bulk CO_2 injection is not feasible at any cost” and “geologic sequestration of CO_2 [is] a profoundly non-feasible option for the management of CO_2 emissions” do not withstand scientific scrutiny. Unsupported opinions and hyperbole do not represent a constructive contribution to the ongoing technical, policy, or regulatory dialogues related to the potential benefits and challenges associated with CCS.

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