

SEAWATER DESALINATION AS A BENEFICIAL FACTOR OF CO₂ SEQUESTRATION

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ABSTRACT

It is becoming increasingly recognized that the flood of anthropogenic CO₂ into the atmosphere should be reduced in order to mitigate the Earth's atmospheric greenhouse and slow climate change. If immediate action is required, then a number of greenhouse gas reduction strategies may need to be implemented even before complete study of their impacts can be fully understood. Energy production through combustion produces large amounts of CO₂ in a relatively small number of locations at which CO₂ capture and compression to a liquid, transportable form can be achieved. Physical disposal offers the best option for sequestering this waste CO₂. Because of the costs of transportation, geological sequestration will be most applicable for one set of power plants, deep ocean sequestration may be most applicable for some others. In both cases, the sequestration processes can provide some economic benefits. Ocean CO₂ disposal can produce desalinated, treated water as a byproduct.

Keywords: CO₂ Hydrate, Desalination, Climate Change

INTRODUCTION

Human induced global warming is now regarded as unequivocal; although the degree to which climate will change is unknown. Slowing and reversing the threat of global warming is a defining challenge that may be near the limit of humanity to adapt [1]. Recently, it has been recognized that urgent action is required to decrease CO₂ emissions [1, 2, 3] because the cost of reducing CO₂ emissions now is likely to be much smaller than the cost of reducing emissions in the future when more cumulative damage has been done. Any action that can be taken to reduce the flood of anthropogenic CO₂ into the atmosphere may be worth undertaking as soon as possible. Emissions-reduction projects on an industrial scale promise to provide a useful assessment of technologies and methods more rapidly than would be possible with a conventional research and development plan.

Carbon dioxide (CO₂) is a naturally occurring product and a primary constituent of the global carbon cycle of the Earth's biosphere. Because CO₂ is a greenhouse gas, when naturally produced CO₂ is augmented by anthropogenic abundance, the planet's ability to remediate the oversupply may be overwhelmed. Products of combustion exhausted directly into the atmosphere are the main cause for concern. The amount of CO₂ emitted is increasing as industrialization and energy generation increase [4]. About 25 million tons of fossil fuel CO₂ is being discharged into the atmosphere every day [5,6]. The oceans, which currently have absorbed about 400 billion tons of anthropogenic CO₂ is already about 0.1 pH units more acidic than before emission of industrial CO₂ [7].

Both geological and deep ocean sequestration of CO₂ are feasible options and

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both of these basic methods have a number of different means of implementation. The only economic uses of the CO₂ that have thus far been discussed in detail are geological sequestration and the use of the CO₂ as an industrial consumable. Although current assessments of both options appear to favor geological over deep ocean sequestration, this may be more the result of purely economic factors driven by power and energy companies that may be able to include geological sequestration directly in their value chain. We introduce a new economic option of using the CO₂ to carry out seawater desalination that will produce low-salinity water as part of the deep ocean sequestration process.

The Future for Carbon Capture and Sequestration (CCS)

Carbon Capture and Sequestration (CCS) is a term that refers to a global objective for first reducing the CO₂ emissions to the atmosphere and then decreasing them. Ideally, anthropogenic CO₂ can be reduced to some minimum that will have little impact on the global warming component of climate change. In addition to the present burning of hydrocarbon fuels, over 5000 Gt of combustible carbon fuels remain on Earth [8] and it is likely that a large portion of these will be used for energy. The largest component of the U.S. energy base is its estimated 250-year supply of coal. As it is unlikely that CO₂ emissions will be significantly reduced in the near future, strategies are under development to deal with the present excess of CO₂ produced by anthropogenic emissions. It is critical that any implemented strategy encompasses plans for at least the remaining combustible fuel supply.

The Kyoto Protocol, which was ratified by most UN member nations, with the continuing notable exception of the United States, is part of a United Nations program that deals with man-made greenhouse gas emissions to the atmosphere and their impact on global climate change [9]. Even in the United States, however, there is an emerging realization that excess atmospheric CO₂ constitutes a significant problem and that action to further reduce its emission to the atmosphere is urgently required.

Two main options for CO₂ storage within a CCS program have been identified: geological and oceanic. Geological CO₂ sequestration requires a sufficiently deep and stable geological

reservoir, existing or expensively drilled holes and pressure control fittings, and high-pressure pumping apparatus, among others, all of which are expensive and consume considerable energy. Oceanic sequestration consists of delivering the CO₂ to full ocean depths or to near-seafloor sediments in such a manner that there is little opportunity for the CO₂ to return to the surface ocean or the atmosphere. If an immediate effort to sequester CO₂ can be made on a human timescale, the impact of global warming may be mitigated.

We agree with Herzog et al., [10] that geological and oceanic sequestration technologies are only a temporary response to this urgent problem. But a temporary solution may be sufficient in this case, because the timescales during which CO₂ can be removed from the ocean-atmosphere system may be adequate to prevent catastrophic climate change [11]. CO₂ is almost certain to eventually leak back into the atmosphere from both geological and ocean sequestration although the rates of leakage are difficult to quantify. It appears that both geological and ocean sequestration can at least lessen the net flow of CO₂ into the atmosphere. The choice that seems to be developing is that we either stop the flood of anthropogenic CO₂ into the atmosphere or sequester it in a temporary manner to stop the immediate acceleration of the atmospheric greenhouse before irreversible harm can be done. Ansolabehere, et al. [12] note that it is likely that CCS is the critical enabling technology that would reduce CO₂ emissions significantly while also allowing combustible fuel to meet the world's pressing energy needs.

Ocean Sequestration

The oceans are a huge potential reservoir for dissolved CO₂. Over 10,000 Gt of carbon could be accommodated with most of it residing in deep ocean water, where it would be unlikely to enter the atmosphere on a scale of hundreds [13] to thousands of years [8]. Sarv [14] concluded that large-scale CO₂ transportation and deep ocean disposal below 3000 m is technologically feasible, although injection of CO₂ at shallower depths and its plunging to the seafloor as a density plume [15,16] could be less expensive. Haugan and Drange [17] point out the advantage of creating naturally downward flowing plumes of pre-dissolved dense, CO₂-

enriched water over liquid CO₂ injection from mid-water depths. Because CO₂ hydrate is denser than seawater, it is intended to form in such a way that the aggregate will deliver the CO₂ to the seafloor where the hydrate will dissolve until the local seafloor water is saturated. Lee, et al. [18] and Riestenberg et al. [19, 20] describe apparatus for direct turbulent injection of liquid CO₂ at mid-water depths that forms a dense, semi-solid mixture of CO₂ hydrate and saline water and gaseous CO₂ so that it would sink as a gravity flow while dissolving as a downward plunging plume as a means of disposing of CO₂ in ocean abyssal depths.

The primary concern for sequestering CO₂ on the seafloor is its effect on biota through reducing pH [21, 22]. In shallow seas, absorption of CO₂ by atmospheric exchange has the potential to cause carbonate shelled or skeletal animals, such as corals, to be stressed because ocean acidification caused by elevated levels of dissolved CO₂ changes the saturation state with respect to CaCO₃ [23]. Although immobile biota in the bathymetrically low areas in which the CO₂-enriched seawater will concentrate will be most affected, mobile deep-sea animals also may not necessarily avoid low-pH discharge sites [24]. The method of CO₂ release to the deep seafloor will be important in determining the extent of the detrimental biological impact; the more concentrated the discharge of liquid CO₂, the greater the likelihood of significant impact. Herzog & Adams [25] show that liquid CO₂ direct injection into the ocean for the sole purpose of dissolution and disposal may yield complex dispersion halos for both deep and shallow injection, owing to existing density and temperature gradients and differential water movement.

The London Convention on Marine Pollution of 1972 allows the disposal of wastes or other matter directly arising from, or related to the exploration, exploitation, and associated offshore processing of seabed mineral resources and for other special exemptions as they may determine. The disposal of CO₂ generated by the production of oil and or natural gas at sea is permitted under the Convention, so long as the corresponding processing operations are carried out at sea [13]. CO₂ produced by manufacturing or processing operations on land, however, is regarded as waste that cannot be dumped at sea,

even though it may be very similar material. The same legal position exists under the Marine Pollution protocol of 1996, which will replace the 1972 convention when it is ratified although the number of exempted materials that can be dumped at sea is expanded; CO₂ is not presently included among these excepted materials. The use of the deep sea for CO₂ sequestration as part of CCS, however, was not a part of the considerations for either the 1972 or the 1996 Marine Pollution documents. The legal status of CCS carbon storage in the deep ocean has not yet been adjudicated [26].

Offsetting the costs of CO₂ sequestration

Considerable attention has been given to offsetting the cost of geological sequestration by enhancing petroleum recovery as part of CCS. CO₂ injection into oil fields is a well-known secondary petroleum recovery technique that has been used for many years to enhance petroleum recovery in fields where the petroleum is too viscous in the reservoir or where reservoir pressures have to be artificially increased. Enhanced Oil Recovery (EOR) is attractive because the chance of leaks to the atmosphere is minimized by injection into geological traps that once held petroleum. The beneficial aspect of CO₂ injection EOR is that additional oil is recovered; less beneficial is that CO₂ may be recovered along with the oil, particularly where it has dissolved in the oil. Where CO₂ is returned to the surface, it must either be re-injected or it will migrate to the atmosphere. Re-injection requires additional cost; where escaped CO₂ is not re-injected, it should not strictly be referred to as sequestered. Where CO₂ flood is used only to pressurize a reservoir without the CO₂ being significantly dissolved in the extracted petroleum, injected CO₂ that does not come to the surface with the petroleum may be considered sequestered.

CO₂ injection has also been suggested for enhanced coal bed methane (ECBM) recovery [27], but given the open underground system and large amounts of water recovered, it seems likely that leakage could be significant. Injection into saline aquifers is an attractive option for geologic sequestration as many of these occur at generally shallower depths than petroleum traps within which EOR could be practiced, which would reduce pumping costs. However, the chemical

interaction of the CO₂ and the reservoir rock, particularly where it may be carbonate, may introduce dissolution, or cementation of the reservoir, which would affect injection.

Although the technology involved in deep ocean sequestration is well known, no offsetting economic applications for deep ocean sequestration have yet been foreseen [28]. We present a new paradigm for adding value to CO₂ disposal. CO₂ intended for oceanic disposal can be used to carry out seawater desalination through the formation of CO₂ hydrate.

Desalination through the use of CO₂ hydrate

Gas hydrate is a solid crystalline material that forms spontaneously under suitable conditions of pressure and temperature when source water is supersaturated with hydrate-forming material. In the gas hydrate structure, water molecules form a network of cages that are largely occupied by individual gas molecules; weak electrostatic force (van der Waals bonding) stabilizes the entire structure. Rejection of all other material is an attribute of hydrates, which tend to form quite pure crystalline aggregates. The hydrocarbon gases, N₂, O₂, chlorine, H₂S, SO_x, etc., are common gases that form hydrate; each has their individual fields of pressure-temperature stability and different preferences for forming gas hydrate. CO₂ hydrate is different than water-ice in that pressure and temperature can be utilized to both cause the hydrate to form and dissociate (melt), whereas only temperature will cause water-ice to change state.

As an outcome of the desalination process, CO₂ is sequestered at full-ocean depths dissolved in dense, enhanced-salinity residual water produced during hydrate growth. The marine CO₂ hydrate desalination process is intended to operate at about 300 m water depth, where full ocean depths are immediately adjacent to or below the industrial desalination plant. This allows the enhanced salinity waters to flow to depth as they are negatively buoyant. The bathymetric configuration that would allow this sequestration is on narrow continental shelves, such as off the SW and SE coasts of the United States, Mediterranean countries, the southeastern Australian coast, South Africa, and on oceanic islands virtually everywhere.

Delivering pre-dissolved CO₂ to the

seafloor as part of the sequestration process will result in a potentially less harmful condition than direct injection of CO₂ at depth in that the CO₂-saturated water may be less acidic than in the immediate vicinity of CO₂ injection. Injection of gaseous and liquid CO₂ onto or just beneath the deep seafloor for CCS has been proposed for some time [29, 30]. Formation of CO₂ 'lakes' in abyssal depressions has been proposed by direct injection of gaseous CO₂ at various depths and by injection of liquid CO₂ (referred to henceforth as LCO₂) through a long vertical pipe from the surface [31]. As LCO₂ is a compressible fluid, it is only denser than seawater below a certain water depth in the cold, deep oceans [32]; delivery pipes must be in excess of 2,500 to 3,000 m length. LCO₂ delivered to full ocean depths will naturally form hydrate.

Using CO₂ to achieve seawater desalination has also been outlined in detail both in its own right without a disposal function [33] and as part of a combined process for desalination and CO₂ ocean sequestration [34]. The MDS process for seawater desalination using CO₂ hydrate operates using surface-effect crystallization wherein the hydrate is grown on chilled surfaces within an enclosure where dissolved CO₂ saturations can be maintained in the growth region for hydrate at the levels required for continued hydrate formation. The process consists of hydrate nucleation, growth from solution, separation from the treated seawater, which becomes more saline, and finally, dissociation and natural separation of the constituent CO₂ and low-salinity water. Although methods of bulk crystallization (suspended in seawater) could be used, the negative density of CO₂ hydrate presents certain process issues [32, 35]. Raw seawater is used, with no pre-treatment such as is required by other desalination methods. No membrane separation processes are used and no chemicals other than the CO₂ are added to the source seawater. The ambient temperatures and the natural pressure found at approximately 300 m depth in the ocean lower energy requirements for the MDS process, as they are already suitable for hydrate formation.

Preparing the seawater for hydrate growth is accomplished by injecting CO₂ into the water at pressures (or suitable water depths) that are suitable for growing hydrate. At the same time, temperature is reduced to just above the

CO₂ hydrate phase boundary by vaporizing LCO₂ (Fig. 1). Hydrate crystallization takes place on special heat exchangers whose temperature is within the field of hydrate stability. The heat exchangers control hydrate growth acting to separate the hydrate from the seawater in which it has formed. Dissociation of the hydrate takes place in a region that is separated from the seawater region. The process is described in detail elsewhere [34, 35, 36].

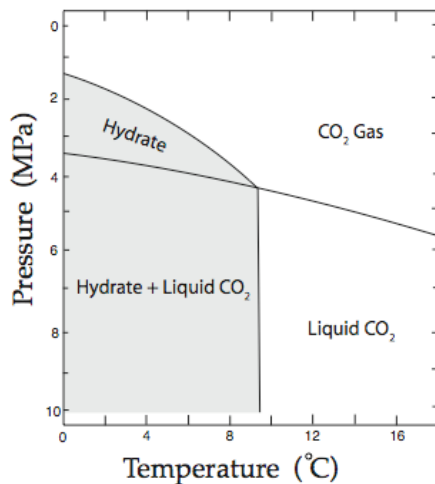


Figure 1. Pressure-temperature field of hydrate stability and the gas and liquid phase regions of CO₂.

The immersed hydrate desalination process operates either in a portable marine installation (Fig. 2a), which would be most efficient for servicing a number of relatively low-demand locations such as groups of oceanic islands having relatively small populations, or fixed (Fig. 2b), which has the advantage of weather and physical security [34]. A number of intermediate engineering solutions that involve fixed, semi-fixed, and mobile operations are also possible, depending on local requirements and constraints. In any case, some additional cost for water storage, treatment, and distribution will be required, although these may be on a small scale and low cost framework.

In both of these installations only LCO₂ is pumped down and only fresh water is pumped back up to the surface, albeit with dissolved CO₂. The lower pressure of the dissociation region at depth determines the pressure in the fresh water return system. This will cause the fresh water in the fresh water return pipe to naturally rise

almost to surface level. Thus, fresh water will not have to be pumped from depths. Return pumping costs will be comparable with those of a shallow well on land. The CO₂ desalination process may also be carried out on land, but this would necessarily involve additional water pumping costs and require additional infrastructure to allow the residual seawater to be piped to a suitable water depth to insure the sequestration of its dissolved load of CO₂.

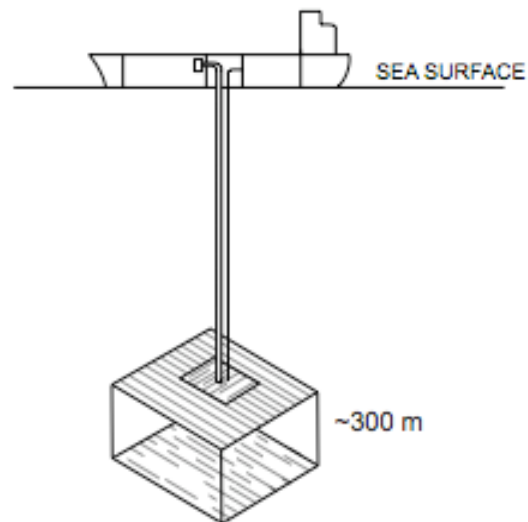


Figure 2a. Floating or portable desalination installation (not to scale)

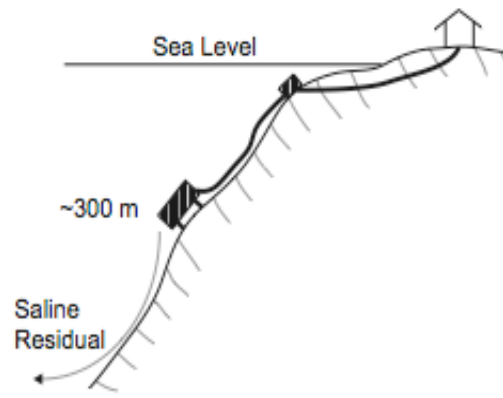


Figure 2b. Fixed desalination installation (not to scale).

The high-density residual seawater from the desalination apparatus takes the dissolved CO₂ away from the mid-water depths at which the desalination takes place. Except for some minor leaking of CO₂ at operational depths

which may have a temporary affect on pH around the apparatus, biological systems should not be adversely affected. As the CO₂ -laden residual water sinks to full ocean depths, however, biological impact can be expected. A dense CO₂ plume similar to that modeled by Chen [37] will produce a local pH drop of about 1.6. In principal, hydrate desalination can be regarded as only a different means for dissolving large volumes of CO₂ in the sea than has already been envisaged [22]

As the CO₂-enriched water sinks, its pressure rises. The level of saturation of the dissolved gas falls with increasing pressure, which insures that the dissolved gas cannot return to the upper ocean and the atmosphere. There will also be mixing dilution. In contrast, if simple dissolution of the CO₂ was attempted at shallow depths, it could reach the atmosphere in a relatively short time. Haugan and Drange [17] point out that seawater containing dissolved CO₂ that is injected at about 400 m would be more dense than seawater in the upper ocean and predict that it would sink as a mass; as such it would be an analog of the 'dense plume' concept of Herzog et al [31].

The only consumable in the patented surface-effect hydrate industrial crystallization process [32, 33] is LCO₂, the cost of which is the largest factor in the cost of the produced water. Although LCO₂ is one of the least expensive of industrial gases [38], the cost of the produced fresh water is not precisely fixed to the volume of CO₂ used because the CO₂ may be re-used multiple times. A variable amount of water can be produced with a given mass of CO₂, depending on the local requirements.

The CO₂ hydrate process for desalination and sequestration may be operated either primarily for desalination, in which case the CO₂ is reused as much as possible, or for disposal, in which case the process is operated in a high - disposal mode. As greater volumes of CO₂ are re-circulated from recovered gas and used to grow another cycle of hydrate, water production increases. The more times the CO₂ can be recycled and reused, the more water can be produced from any particular mass of CO₂. The greatest water production is achieved when all CO₂ (other than that which remains absorbed in the residual water and which is expelled from time to time) recompressed from all possible

sources of CO₂, although this is impractical because of the energy that is consumed for recompression.

The availability of CO₂ is an important consideration because a dependable supply of CO₂ is necessary for dependable water production. A typical 1000 MW power plant (coal) produces about 1360 metric tons of CO₂ per hour [39], which translates to in excess of 8 million gallons of fresh water per day from sequestering 99+% of the CO₂ using hydrate desalination.

Purity of the waste product CO₂ captured from stack gas is a determinant of produced water quality. This is because some of the hydrate-forming gas will be dissolved in the product water. Gas-fired power stations have been regarded as the natural sources of CO₂ because of its naturally cleaner exhaust (when compared with most oil and coal). However, technological achievements such as use of oxy-fuel combustion, may render even coal-fired power stations capable of producing almost pure LCO₂ that would be suitable for hydrate desalination without further processing [40]. According to Sussingham [41], there are plans to build clean coal-fired 300 MW power plants that will be capable of capturing about 8000 tons of CO₂ per day, intended for disposal.

A number of other processes deliver high enough purity to allow the CO₂ to be used directly. Solvents can be applied to stack gas exhaust, resulting in almost pure CO₂ [31]. Mitsubishi Heavy Industries, Ltd. achieved CO₂ purity of 99.9% and above [42] in operating commercial CO₂ strippers. Dry sorbents, such as lithium silicate also appear to be effective for CO₂ capture [43]. If hydrate-forming sulfur compounds dominate then these may have to be removed. In any case, contamination of the LCO₂ by non-hydrate forming materials or hydrate formers having a low preference for hydrate formation, is not a major hindrance because these materials should be largely rejected during hydrate growth.

Co-locating power plants and CO₂ desalination installations may be the most economic arrangement, as the transport step of the CCS process is minimized. Alternatively, the CO₂ may be transported to a disposal site. A CO₂ desalination-sequestration facility could accept CO₂ from any source or a multitude of sources

for disposal.

The CO₂ desalination/disposal process is not yet a commercial product. Nonetheless, laboratory experiments using natural seawater are currently underway having shown a number of proofs of concept and reliability in removing relatively pure water from seawater [44]. Dissolved ions, non-ionic impurities such as boron, and suspended solids also appear to be substantially rejected by the hydrate-forming process, when hydrate growth rate and a number of other industrial factors can be properly controlled. MDS is bringing a demonstration unit into operation and has plans for a marine pilot plant as part of a commercialization initiative for seawater desalination using CO₂ hydrate. Superabundant CO₂ that is sequestered as part of a solution to one problem, global climate change, may also be a key to the solution to a possibly more immediate problem, and one not open to any dispute; that of the increasing requirement for supplies of safe, potable water.

CO₂ Disposal Cost Compensation Benefit

One of the greatest barriers to commercialization of either geological or ocean sequestration of CO₂ is the lack of structural financing provided under the Kyoto protocol. Under Kyoto, the financing of research and engineering of CCS procedures fall to private industry, government and non-governmental organizations, but no internationally agreed upon standards and practices have yet been determined. As a result, the main thrust of sequestration research is for applied industrial projects. Large-scale research and development partnerships for geological sequestration are in various stages of development and operation in Australia (Otway basin project, Gorgon Project), and Norway (Statoil's Sleipner project), the U.S. and elsewhere in Europe, with other countries joining the effort.

The CCS process consumes energy and, therefore, introduces new costs associated with energy generation and industrial processes using combustion. The cost of capturing and disposing of the CO₂ are greater than if the exhaust is dispersed. Capture of CO₂ from point sources, such as the exhaust gases of fossil-fuel power plants, has been commercially demonstrated [45]. Transport of highly compressed, dense (supercritical), and LCO₂ by pipeline and in both

land and sea tankers or barges is already common practice. Several pilot CCS projects are currently underway both in the United States, (e.g., by the Midwest Geological Consortium) and overseas. Once that is complete, the regulatory environment required for the control over such an industrial process is likely to be developed.

For most nations, the cost of compressing CO₂ and sequestering it will likely be subsidized under an emissions credit plan [46]. But the world is not yet a level CO₂ playing field. Regulatory requirements needed to verify CO₂ emission reduction for credits have not yet been developed in the US, although they have been clearly defined in the European Union. Environmental issues related to storage, both oceanic and geological [47] are in the very early stages of being addressed and with the increasing levels of public concern and political response a practical framework may soon exist.

Carrying out CCS in conjunction with industrial processes that use the CO₂ as industrial feedstock that effectively sequesters the CO₂ in a product, and thus prevent it from effusing into the atmosphere would be advantageous. However, this form of sequestration is almost certainly of limited value because of the relatively small amount of CO₂ that would be sequestered. In addition, storage of CO₂ for use in existing industrial processes is not currently considered to be valid sequestration.

In a CCS economic framework, CO₂ will be relatively abundant and will also be a global waste product that must be regulated. Companies that specialize in transport and disposal of CO₂ will be formed and they will derive their income through disposal of CO₂. Where the CO₂ can be used to produce a useful product, its value can be set against the cost of the overall CCS system. As it is likely that all of the costs for CCS will be borne either by government and then by industry and energy producers with the direct cost passed on to consumers, the result of combining disposal with hydrate desalination underwrites the cost of disposal with water production.

DISCUSSION

A new type of 'cogeneration', which is a term often applied to co-located power generation and desalination installations that share water-handling infrastructure, may be defined. Improvements in carbon capture from

large exhaust streams and the purity of CO₂ that can be produced even from coal-fired power stations now begs a solution. Where power plants are near to ocean water deep enough to conform with the requirements for deep ocean sequestration, the waste CO₂ that is removed from the stack gas can be used directly for desalination on the path to deep ocean disposal. Although all power plants that capture and compress CO₂ have the potential to provide the consumable feedstock of liquid CO₂ directly to the desalination/disposal facility, transport costs would be partly borne by the value of produced water. Other power plants that are relatively far from a location where deep-ocean sequestration could be applied with acceptable transport costs would probably have to rely on geological sequestration, with its potentially higher costs and lack of economic trade-offs where no EOR is possible.

There are several recognized gaps in ocean sequestration knowledge and practice that must be filled in before a commercial demonstration can proceed. These include: biological and ecological studies of the response of biological systems in the deep sea to added CO₂; the creating of research facilities where ocean storage concepts can be applied and their effectiveness and impacts assessed; engineering issues including technological developments for working in the deep sea, and development of equipment that can be used for CO₂ injection and monitoring that can be operated and maintained cost-effectively and; the development of techniques and sensors to detect CO₂ variations, and their biological and geochemical consequences [22]. With market inducements, and commercially viable and demonstrable technologies, the barriers to addressing these issues and creating these regulations will become much less prohibitive.

Desalination and Water Treatment Without Direct Disposal

Desalination using CO₂ hydrate can be carried out without deep ocean disposal. The capture and compression components of the CCS system will provide an abundance of CO₂ that can be used for desalination and water treatment. In a similar manner to that using immersed apparatus, the LCO₂ will provide most of the energy required for the process, the

pressurization, and the hydrate-forming material itself. It is not known whether the cost of artificially pressurized apparatus would be significantly different from immersed apparatus.

CONCLUSIONS

If the urgency to abate the flood of anthropogenic CO₂ into the atmosphere and mediate the greenhouse requires immediate action, then pilot projects for both geologic and ocean sequestration should be undertaken at once. The political imperative is strong enough to preclude the years of study that such projects would otherwise require. Full environmental monitoring must accompany all pilot sequestration projects so that industrial scale data sets can be established quickly to guide decision-making.

Whereas some biological impact assessment has been made for ocean sequestration, no such impact assessment has yet been made for geological sequestration. The same form of evaluation should be made on all pilot sequestration sites using the same criteria wherever possible to provide a dataset suitable for evaluating two different environments.

The disposal cost of CSS is probably considerably less expensive for deep ocean sequestration than for geologic sequestration owing to the inherent cost of pumping. Ideally, disposal should take place as close to where the CO₂ is generated in bulk so that transport costs can be minimized. Both geologic and oceanic sequestration has its place. Comparing these methods should not be a matter of excluding one or the other for all cases. Rather, care should be taken to select a sequestration methodology that makes best economic and environmental sense for each location at which concentrated CO₂ is produced.

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