

# Reducing energy-related CO<sub>2</sub> emissions using accelerated weathering of limestone

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## Abstract

The use and impacts of accelerated weathering of limestone (AWL; reaction:  $\text{CO}_2 + \text{H}_2\text{O} + \text{CaCO}_3 \rightarrow \text{Ca}^{2+} + 2(\text{HCO}_3^-)$ ) is explored as a CO<sub>2</sub> capture and sequestration method. It is shown that significant limestone resources are relatively close to a majority of CO<sub>2</sub>-emitting power plants along the coastal US, a favored siting location for AWL. Waste fines, representing more than 20% of current US crushed limestone production (> 10<sup>9</sup> tonnes/yr), could provide an inexpensive or free source of AWL carbonate. With limestone transportation then as the dominant cost variable, CO<sub>2</sub> mitigation costs of \$3–\$4/tonne appear to be possible in certain locations. Perhaps 10–20% of US point-source CO<sub>2</sub> emissions could be mitigated in this fashion. It is experimentally shown that CO<sub>2</sub> sequestration rates of 10<sup>-6</sup> to 10<sup>-5</sup> moles/sec per m<sup>2</sup> of limestone surface area are achievable, with reaction densities on the order of 10<sup>-2</sup> tonnes CO<sub>2</sub> m<sup>-3</sup>day<sup>-1</sup>, highly dependent on limestone particle size, solution turbulence and flow, and CO<sub>2</sub> concentration. Modeling shows that AWL would allow carbon storage in the ocean with significantly reduced impacts to seawater pH relative to direct CO<sub>2</sub> disposal into the atmosphere or sea. The addition of AWL-derived alkalinity to the ocean may itself be beneficial for marine biota.

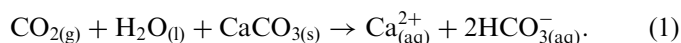
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## 1. Introduction

The climate and environmental impacts of our current, carbon-intensive energy usage demand that effective and practical energy alternatives and CO<sub>2</sub> mitigation strategies be found (e.g. [1,2]). As part of this effort, various means of capturing and storing CO<sub>2</sub> generated from fossil-fuel-based energy production are being investigated (e.g. [3,4]). One of the proposed methods involves a geochemistry-based capture and sequestration process [5,6] that hydrates point-source, waste CO<sub>2</sub> with water to produce a carbonic acid solution. This in turn is reacted and neutralized with limestone, thus converting the original CO<sub>2</sub> gas to calcium

bicarbonate in solution, the overall reaction being:



The dissolved calcium bicarbonate produced is then released and diluted in the ocean where it would add minimally to the large, benign pool of these ions already present in seawater.

Such a process is geochemically equivalent to continental and marine carbonate weathering which will otherwise naturally consume anthropogenic CO<sub>2</sub>, but over many millennia (e.g. [7–9]). We identify the enhanced form of this process as accelerated weathering of limestone (AWL). Previously, it has been shown that AWL can effectively convert a significant fraction of US CO<sub>2</sub> emissions to long-term storage as bicarbonate in the ocean, while avoiding or possibly reversing environmental impacts associated with either the ongoing passive or the proposed active injection of CO<sub>2</sub> into the ocean [6,10]. Being analogous to the

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wide-spread use of wet limestone to desulfurize flue gas, AWL reactors could be retrofitted to many existing coastal power plants at a typical cost estimated to be \$20–\$30/tonne CO<sub>2</sub> mitigated [5,11]. This paper further explores limestone availability, cost, transportation, and reaction kinetics as well as ocean and environmental impacts, and the overall economics and practicality of AWL CO<sub>2</sub> mitigation.

## 2. Limestone and seawater availability

Because the global abundance of water (i.e., seawater) and carbonate is orders of magnitude larger than the entire global reservoir of fossil fuels [12], all anthropogenic emissions of CO<sub>2</sub> could theoretically be mitigated by reaction 1. Indeed, over geologic time scales significant, natural increases in atmospheric CO<sub>2</sub> have been moderated and consumed via carbonate weathering, and the same process will eventually consume the majority of anthropogenic CO<sub>2</sub> as well [7,8]. But if we wait for nature to perform this task, the earth in the meantime would be subjected to much higher atmospheric CO<sub>2</sub> (and lower oceanic pH) than at present, and for many thousands of years. Thus, it is worth considering proactively speeding up the carbonate weathering process. If the employment of reaction 1 to reduce CO<sub>2</sub> emissions is then not in principle reactant-limited, what are the practical limitations to AWL as a CO<sub>2</sub> capture and sequestration tool?

Based on the stoichiometry of reaction 1, it would take 2.3 tonnes of calcium carbonate and 0.3 tonnes of water to react with 1 tonne of CO<sub>2</sub> to form 2.8 tonnes of HCO<sub>3</sub><sup>-</sup> in solution. While pure CaCO<sub>3</sub> (calcite and aragonite) is mined and commercially available, its relatively low abundance in this form and its high cost prohibit its use on the scale considered here. Rather it is envisioned that much more abundant and inexpensive limestone (containing 92–98% CaCO<sub>3</sub>) would be used. US production of this mineral is presently 10<sup>9</sup> tonnes/yr [13], about 76% of which is used in construction, about 19% for chemical and metallurgical applications, and the remaining for miscellaneous uses. While there are no figures available on the size of the US limestone reserve, it is reasonable to assume that it is sufficient to satisfy current US demand for many decades if not centuries. Channeling the entire yearly US limestone production to AWL could consume roughly 18% of the annual CO<sub>2</sub> generated by electricity production in the US. This implies that a substantial increase in the US limestone mining rate or foreign importation would be required to accommodate the US demands of both extensive AWL and conventional limestone uses.

There is an important caveat to the preceding conclusion in that currently more than 20% of US limestone production and processing results in waste limestone fines (<10 mm) that have little or no market value and are accumulating at limestone mining and processing sites [14,15]. This suggests that at least in certain locations a sizeable, free or low-cost source of limestone could be

available for AWL whose use could also help alleviate the significant limestone waste problem.

But even if a free source of limestone was available, it has been recognized that the cost of transporting such limestone to AWL reactors is a critical factor in the overall economics of the process [5,11]. Also, because of the significant quantities of water required to react the CO<sub>2</sub> and to carry and dilute the resulting bicarbonate (>10<sup>4</sup> tonnes H<sub>2</sub>O/tonne CO<sub>2</sub> [5]), AWL reactors in close proximity to seawater would be at a distinct cost advantage. Even with this geographic limitation, about 12% of CO<sub>2</sub> emissions from US electricity production occurs at plants within 10 km of the US coastline [11]. Fortuitously, the majority of this coastline is also within 400 km of known limestone reserves [16]. This is especially true of the southern and eastern seaboard, which also have the highest density of coastal US power plants and coastal electricity-related CO<sub>2</sub> production. For example there is more than 20 GW of fossil-fueled power generation (≈10<sup>8</sup> tonnes CO<sub>2</sub> emitted/yr) by coastal power plants in Florida [11], a state that essentially is entirely underlain by carbonate deposits [17]. In such ideal settings, if limestone (e.g., waste fines) was free and nearby (negligible transportation expense), the CO<sub>2</sub> mitigation cost offered by AWL could be as low as \$3–\$4/tonne CO<sub>2</sub> based on previous cost analyses [5,11]. This would especially pertain if the hundreds of millions of gallons of seawater already pumped and used for cooling by these plants each day were subsequently used as a “free” AWL water source.

The preceding baseline CO<sub>2</sub> capture and sequestration cost would significantly out-compete most other current or proposed abiotic technologies and is near DOE’s target of \$2.73/tonne CO<sub>2</sub> mitigated [4]. However, the number of ideal sites and hence the volume of CO<sub>2</sub> that could be treated at this very attractive cost would be small. What cost might be attainable in the more numerous but less favorable settings?

Again assuming free access to seawater and free limestone, the transportation cost of limestone using various modes is listed in Table 1. Assuming a base capital, operating, and maintenance (COM) cost of \$4/tonne CO<sub>2</sub> mitigated, and with carbonate supplied via 2.5 tonnes of low-grade limestone (92% CaCO<sub>3</sub>)/tonne CO<sub>2</sub>, a limestone transport distance of 200 km yields an AWL CO<sub>2</sub> mitigation cost of about \$6, \$9, \$21, or \$48/tonne CO<sub>2</sub> using freighter, barge, train, or truck transportation, respectively (Table 1). If limestone must first be purchased at a typical market price of \$5/tonne, this adds \$12.50 to each of the preceding calculations, with the resulting mitigation cost ranging from \$18 to \$61/tonne CO<sub>2</sub> using the preceding transportation modes. In addition, if fresh seawater rather than recycled cooling water must be used and pumped 2 vertical meters the cost increases to \$23 to \$66/tonne CO<sub>2</sub> (Table 1). By these calculations it is seen that in all but the least ideal cases AWL can be cost-competitive with other forms of CO<sub>2</sub> capture and sequestration, and is often below the cost of

Table 1  
Cost of accelerated limestone weathering under various water, limestone, and transport cost assumptions

	Limestone transportation mode			
	Freighter	Barge	Train	Truck
<i>Base capital, operating, and maintenance cost (\$/tonne CO<sub>2</sub>)</i>	\$4.00	\$4.00	\$4.00	\$4.00
Limestone transport cost rate (\$/tonne/km)	\$0.003	\$0.010	\$0.034	\$0.089
Limestone transport cost (rate × 2.5 tonnes × 200 km)	\$1.71	\$4.77	\$17.05	\$44.33
<i>Total cost including limestone transportation costs (\$/tonne CO<sub>2</sub>)</i>	\$5.71	\$8.77	\$21.05	\$48.33
Limestone cost (2.5 tonnes × \$5/tonne)	\$12.50	\$12.50	\$12.50	\$12.50
<i>Total cost including cost of limestone and its transportation (\$/tonne CO<sub>2</sub>)</i>	\$18.21	\$21.27	\$33.55	\$60.83
Pumped water cost (\$2.38 m <sup>-1</sup> per 10 <sup>4</sup> tonnes × 2 m)	\$4.76	\$4.76	\$4.76	\$4.76
<i>Total cost including limestone, its transportation, and water pumping (\$/tonne CO<sub>2</sub>)</i>	\$22.97	\$26.03	\$38.31	\$65.59

Base COM (capital, operating, and maintenance) cost (\$/tonne CO<sub>2</sub> captured and sequestered) under the assumption that waste (free) limestone and cooling water are immediately available with no transportation required (estimation derived from Sarv and Downs [11]). The increase to COM with the addition of limestone, transport, and water costs are listed for the respective transportation options, and for the cost rate, weight, and distances denoted. Limestone cost and transport cost rates from Everist and Burhans [38], assuming that 2.5 tonnes limestone is required/tonne CO<sub>2</sub> mitigated (see text). Water tonnage and pumping cost rate from Rau and Caldeira [5].

amine CO<sub>2</sub> capture alone (generally > \$30/tonne CO<sub>2</sub> [18]). AWL will clearly be more economical under circumstances where limestone and water are low-cost and close at hand.

### 3. Alternative reactor sitings

The preceding assumes an AWL reactor sited at the source of waste CO<sub>2</sub> (i.e. a power plant) and to which limestone and seawater are transported. While close reactor proximity to the ocean would seem required both to supply water and to dispose of the waste solution, this would not preclude the treatment of waste CO<sub>2</sub> produced inland and transported to coastal AWL reactors sited at or near limestone quarries. Transport of CO<sub>2</sub> can be inexpensive (\$0.06 tonne/km [19]) relative to the cost of transporting the AWL equivalent (2.5 tonnes) of limestone (Table 1). However, such CO<sub>2</sub> transport requires initial CO<sub>2</sub> separation, capture, and liquefaction, with associated technology and energy costs that are presently significant, as mentioned above. Still, if inexpensive CO<sub>2</sub> capture/separation is developed, piping CO<sub>2</sub> to coastal AWL reactors could prove cost-competitive with other forms of CO<sub>2</sub> sequestration such as underground storage, especially in regions where the underlying geology does not allow CO<sub>2</sub> retention.

Another alternative would place AWL reactors on or in seagoing barges or ships that would bring both the limestone and the AWL process to coastal CO<sub>2</sub> point sources accessible by seagoing vessel. In this way the capital expenditure of an AWL reactor and limestone transport are merged, avoiding potentially costly land-siting of the reactor, and with the ocean readily accessible as a water source and for effluent disposal. This configuration would require that flue gas be piped to and reacted within the docked vessel. Once the ship's supply of limestone had been exhausted by AWL, the ship would

be replaced by another loaded vessel/reactor. On its way back to port for limestone reloading, the vessel could dispose of the small amount of unreacted limestone spoils (anticipated to be mostly SiO<sub>2</sub>) at sea, subject to ocean dumping regulations. The preceding would obviously only be amendable to power plants (or coastal CO<sub>2</sub> sources supplied by pipeline) that are dock-accessible. It also assumes that a limestone-supplying port is within a reasonable shipping distance to the CO<sub>2</sub> source to be mitigated. Rather than the construction and use of new AWL-capable ships, the retrofitting and upgrading of retired or underutilized vessels should be considered as a means of both reducing costs and extending ship utility. Because of their existing hold configuration, freighters and especially tankers would be particularly attractive for such retrofits.

### 4. Reaction rates and densities

The rate at which reaction 1 occurs (on a per unit limestone surface area per unit time basis) determines the amount of carbonate surface area and time needed to transform a given quantity of CO<sub>2</sub> to HCO<sub>3</sub><sup>-</sup>. In turn, specifying a carbonate particle surface area per packed reactor volume ( $A/V$ ) of the carbonate particles determines the basic size of the reactor required for a given CO<sub>2</sub> conversion rate. While previous estimates of these parameters have been made [5], the reaction rates used were based for the most part on idealized dissolution experiments using pure calcite mineral in distilled water under conditions where the diffusional boundary layer around the mineral surfaces were greatly diminished (via stirring).

To provide a more realistic assessment of the reaction rate of impure limestone, an experimental, 370 ml (internal volume) bench-scale reactor was used to measure the dissolution rate of limestone in either distilled H<sub>2</sub>O or

seawater equilibrated with various %CO<sub>2</sub>/air streams, and with various water flushing rates, and internal stirring rates (see Fig. 1 legend). The results of these experiments yielded dissolution rates ranging from roughly 10<sup>-7</sup>–10<sup>-5</sup> mol/m<sup>2</sup> limestone surface area/s with positive sensitivity to flow rate, stir rate, and CO<sub>2</sub> concentration (Fig. 1). Dissolution rates in seawater were equal to or higher than those in distilled water under otherwise identical conditions (Fig. 1),

i.e., the impurities in seawater do not significantly diminish the AWL reaction rate.

Assuming the conditions and results of the 15% CO<sub>2</sub>, low-stir-rate and low-flow rate treatments would be characteristic of a large-scale reactor, a reaction rate of about 10<sup>-6</sup> mol/m<sup>2</sup> limestone surface area/s is implied (Fig. 1). A limestone particle diameter of 1 mm (within the range typical of waste limestone fines discussed above) yields an  $A/V$  of  $4.4 \times 10^3$  m<sup>2</sup>/m<sup>3</sup> or higher depending on the deviation of true particle shape from that of a sphere. Therefore, in this hypothetical case a maximum of about 60 m<sup>3</sup> of internal reactor volume packed with such limestone particles would be needed to react 1 tonne of CO<sub>2</sub>/day. For a cubic reactor volume (roughly 4 m × 4 m × 4 m), this equates to an areal reaction rate of about 4 tonnes CO<sub>2</sub>/m<sup>2</sup> of internal reactor footprint per day, or more than 5 orders of magnitude greater than optimum areal CO<sub>2</sub> uptake and sequestration rates in managed forests or algal ponds [19]. The experiments show that this density of CO<sub>2</sub> conversion to HCO<sub>3</sub><sup>-</sup> could be enhanced by increasing reactor solution stirring and flushing rate. This could be achieved in a full-scale reactor by vigorous bubbling of flue gas within the reactor, by actively recirculating the partially-reacted solution, or by other means, but all with added energy and cost penalties.

Based on the above rates, reaction densities on the order of 10<sup>-2</sup> tonnes CO<sub>2</sub>/m<sup>3</sup> of internal reactor volume/day might be attainable. This means a 20% reduction of the CO<sub>2</sub> emissions from a typical 500 MW coal-fired power plant (10<sup>4</sup> tonnes CO<sub>2</sub>/day × 0.2 = 2 × 10<sup>3</sup> tonnes CO<sub>2</sub>/day) would require an AWL reactor volume of 2 × 10<sup>5</sup> m<sup>3</sup>, roughly equivalent to a 60 m cube. However, we stress that optimum reactor size and configuration required for a given CO<sub>2</sub> mitigation application will be highly dependent on factors such as limestone particle size, shape and purity, water/gas/solids contacting efficiency (esp. boundary layer issues), the reactor's liquid/solids ratio, water flow and chemistry, and CO<sub>2</sub> concentration. For example, while particle size reduction will theoretically increase limestone surface area and hence reaction density within a reactor, water space between particles and hence flow resistance and contacting efficiency will be reduced. Further research and experimentation is needed to optimize AWL reactor designs for the best cost/benefit.

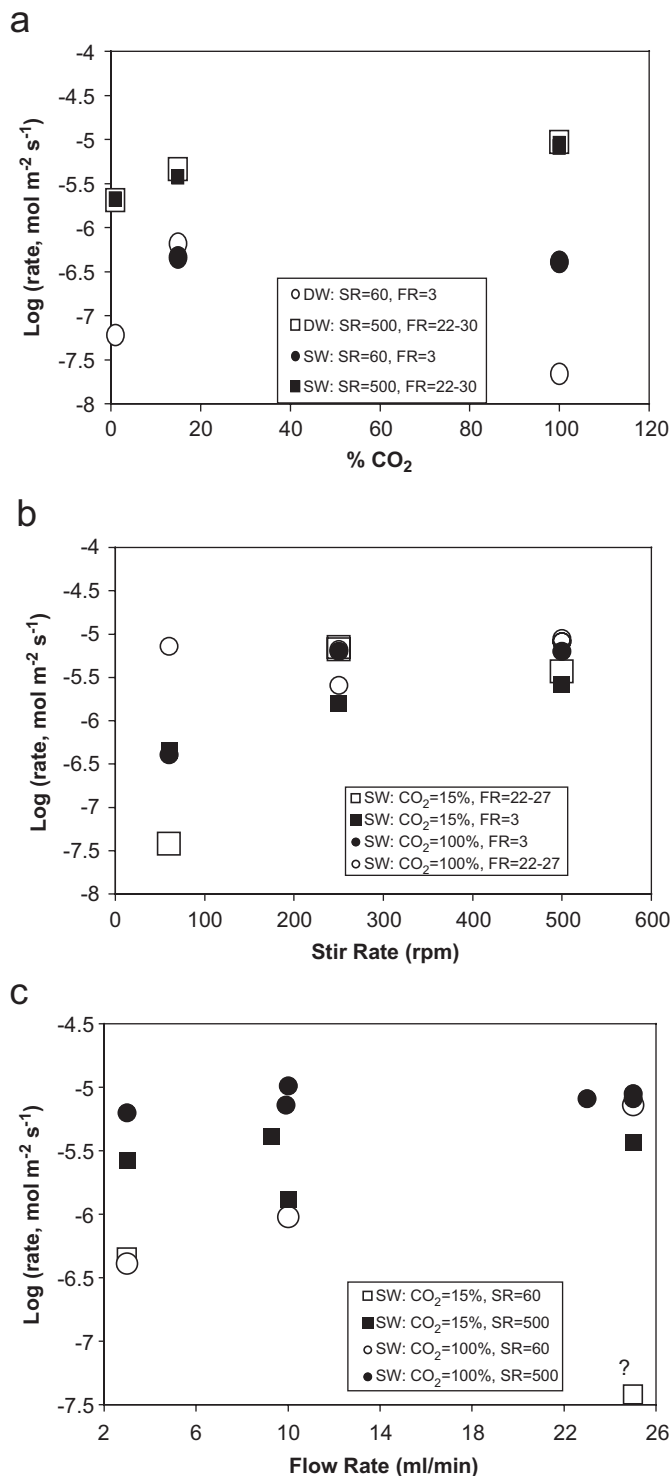


Fig. 1. Conversion rate of CO<sub>2</sub> to HCO<sub>3</sub><sup>-</sup> in an experimental carbonate dissolution reactor flushed with distilled water (DW) or seawater (SW) equilibrated with the % CO<sub>2</sub> shown, and at the various reactor solution flow rates (FR) and internal stir rates (SR) indicated. Stir rates are in revolutions per minute. Conversion rate =  $([Ca]_{out} - [Ca]_{in}) \times FR / \text{area}$ , where  $[Ca]$  refers to the concentration of Ca<sup>2+</sup> in the solutions entering or leaving a 370 ml reactor containing 5 g of limestone particles (size range 425–850 microns) under the respective solution %CO<sub>2</sub>, FR, and SR conditions at steady state and at room temperature and pressure, and where area refers to the total surface area of the limestone particles as determined by mean particle geometry [36]. The mean particle surface area-to-volume ratio was 0.489 cm<sup>-1</sup>, and the solid-to-solution weight ratio was 0.0136.  $[Ca]$  was determined by ICP-ES of discrete solution samples.

## 5. Effectiveness

Using a box model of ocean chemistry and transport Caldeira and Rau [6] showed that the release of the bicarbonate-charged effluent from carbonate dissolution would more effectively sequester  $\text{CO}_2$  over the long term relative to direct  $\text{CO}_2$  injection at equivalent ocean depths (Fig. 2). This has been subsequently confirmed for releases at several different ocean locations and depths in a 3-D ocean general circulation model (Fig. 3). Injection of pure  $\text{CO}_2$  at great depth in the ocean effectively stores most of the injected carbon for hundreds of years or more [6]. Therefore, additional slowing of  $\text{CO}_2$  leakage would be gained by releasing carbonate dissolution effluent at the same depth. We also note that carbonate dissolution can make a major contribution to  $\text{CO}_2$  storage with less costly shallow-water releases and greatly improves effectiveness of long-term ocean carbon sequestration regardless of the depth at which the effluent is released (Fig. 3).

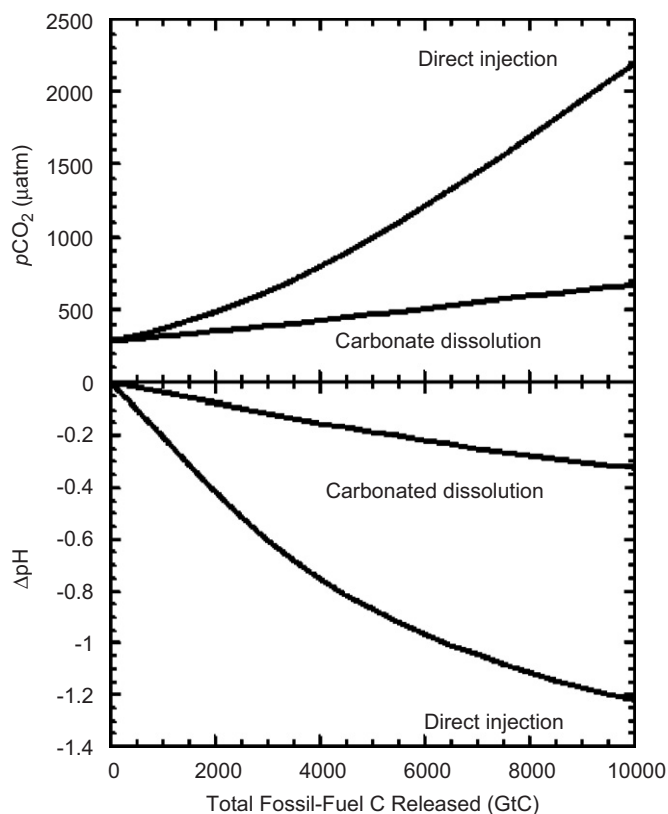


Fig. 2. Comparison of the effects on atmospheric  $\text{CO}_2$  content (top panel) and on deep-ocean pH (bottom panel) 1000 years after the injection of the specified quantities of either molecular  $\text{CO}_2$  or carbonate dissolution effluent into the deep-ocean (mean depth: 1950m). If the ocean's anthropogenic carbon capacity were determined by the amount of  $\text{CO}_2$  that would shift ocean pH by 0.3 units, then the carbonate dissolution technique would increase the ocean's capacity by roughly a factor of six. With the direct-injection method, for large amounts of anthropogenic  $\text{CO}_2$  released, over 45% of the injected  $\text{CO}_2$  is in the atmosphere after 1000yr. With the carbonate dissolution method, less than 15% of the initially released  $\text{CO}_2$  degasses to the atmosphere (from [6]).

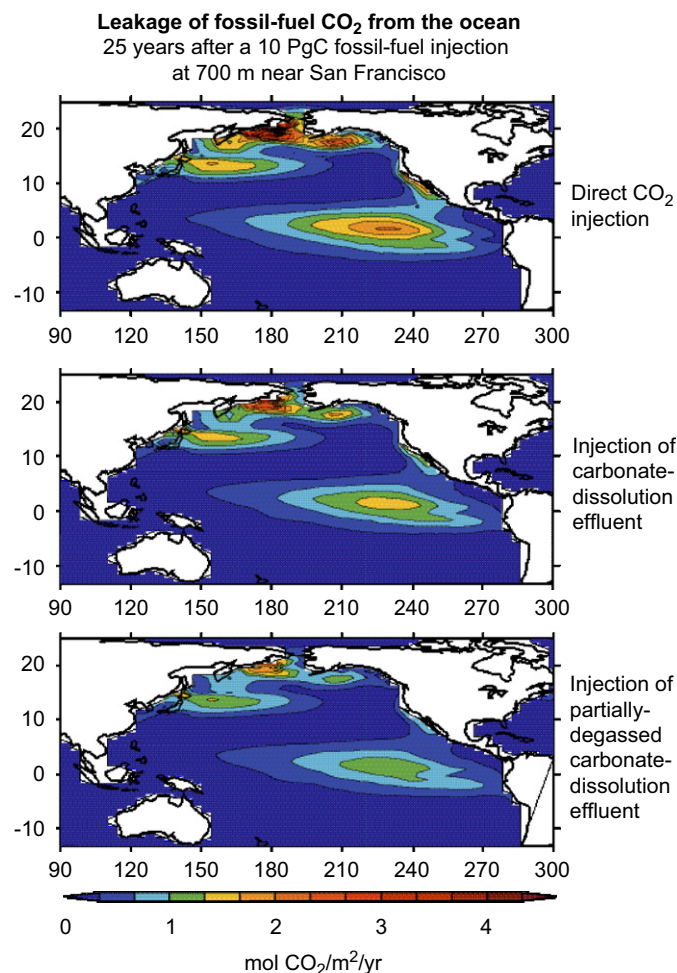


Fig. 3. Ocean general circulation model results showing the greater effectiveness (less  $\text{CO}_2$  leakage to atmosphere) inherent in the injection of carbonate dissolution effluent (with and without pre-injection  $\text{CO}_2$  adjustment) as compared to injection of molecular  $\text{CO}_2$  at equivalent depths. The model is a modified version of the Geophysical Fluid Dynamics Laboratory Modular Ocean Model [37].

## 6. Environmental impacts/benefits

An increase in ocean acidity (reduction in pH) is a serious environmental issue caused either by the ongoing diffusive uptake of anthropogenic  $\text{CO}_2$  from the atmosphere or the proposed purposeful injection of  $\text{CO}_2$  into the ocean (e.g., [10]). Storing waste  $\text{CO}_2$  in the form of bicarbonate balanced by calcium ions rather than as dissolved  $\text{CO}_2$  (i.e., carbonic acid; bicarbonate balanced by  $\text{H}^+$ ) substantially lessens the increase in acidity per tonne of carbon added to the ocean (Fig. 2), while reducing harmful effects to marine biota of direct ocean  $\text{CO}_2$  additions [20–22]. In fact the addition of bicarbonate-rich effluent to the ocean would be environmentally beneficial in that it would counteract the ongoing reduction of ocean pH, carbonate ions, and hence biological calcification rates and productivity [23,24]. Indeed, addition of calcium and/or bicarbonate ions to seawater has been shown to

significantly enhance the calcification and growth rate of marine corals (e.g., [25–27]). We also point out that AWL captures and sequesters CO<sub>2</sub> without the use of any exotic or toxic chemicals, unlike CO<sub>2</sub> capture methods using for example amines [4] or ammonia [28].

Nevertheless, negative marine environmental impacts could result downstream from the release of the reactor effluent solution. For example, oxygen concentration would be reduced in the effluent through partial equilibration with flue-gas streams, typically containing only 2–4% O<sub>2</sub>. There may also be impurities released into the effluent solution from the limestone or the flue gas that could be biotically impactful. This could be especially relevant in AWL processing of flue gas from coal-fired power plants, where SO<sub>x</sub>, NO<sub>x</sub>, trace element, and heavy metal contamination are characteristic. Processing relatively clean flue gas from natural-gas-fired plants or from integrated gasification combine cycle generators would be advantageous in this regard. To our knowledge, no previous studies have investigated the marine impacts of effluent streams like those that would emanate from AWL. However, we note that limestone/CO<sub>2</sub>/seawater reactors using chemistry identical to AWL are employed by saltwater aquarists to generate aquarium alkalinity in order to safely maintain or promote the health of captive marine organisms [29,30]. As well, the ocean naturally receives and accommodates about 2 × 10<sup>9</sup> tonnes of dissolved calcium bicarbonate/yr produced from continental carbonate weathering as delivered by rivers [12]. The threat of calcium carbonate precipitation (reversal of reaction 1) from AWL effluent after release into the ocean appears to be small because CaCO<sub>3</sub> ion concentrations in excess of 18X saturation are required to abiotically precipitate carbonate from seawater [31]. Further research is needed, however, to fully determine the benefits and impacts of AWL effluent on the ocean.

With regard to environmental effects of AWL on land, the current production of crushed stone creates environmental impacts, and these need to be considered for AWL. The impacts include dust and noise generated in mining and processing, but these are relatively benign and confined to the area at or very near the quarries. Most impacts can be controlled or kept within permissible limits through careful quarry planning and by employing best management practices. However, poorly designed or careless operated quarries, especially in areas of active karst (which occurs in some carbonate rock terrains), have the potential to create far-reaching, serious environmental impacts including lowering of the water table, changing surface- and ground-water flow, pollution of ground water, and sinkhole collapse [32].

The increased transportation of limestone required for AWL would also generate dust and noise en route and during off-loading, and depending on the magnitude of AWL deployment, could significantly

tax the existing transportation infrastructure. For example by our calculation using AWL to reduce CO<sub>2</sub> emissions from a coal-fired powered plant by 20% would more than double the material transport requirement to the plant [33]. Additionally, because some fraction of the limestone will not be reacted or be reactible, perhaps 5–10% of the original limestone mass transported to AWL reactors (principally SiO<sub>2</sub>) would ultimately need to be removed and transported to appropriate waste sites. In addition to ocean disposal of the solid waste (mentioned above), disposal might be performed by loading this waste onto the otherwise empty, overland transport mode would that return to the limestone source, wherein the waste could be used to fill in the original limestone mining excavations. This would make efficient use of the transportation stream and would help reclaim unsightly mining impacts while avoiding the need for new waste sites. Certainly, the energy and carbon penalties associated with both the mining and transportation of limestone would need to be included in calculating AWL's net CO<sub>2</sub> mitigation potential.

In summary, some environmental effects would result from limestone mining and transportation, but we point out that large-scale mineral extraction and transport is currently an integral part of energy production (e.g., coal, natural gas). We also note that limestone is already used on a large scale for environmental benefit, flue-gas desulfurization [34] and acid mine waste neutralization [35] being prime examples. While the benefits of AWL would appear to outweigh whatever environmental and societal impacts might accrue, further assessment of this technology's terrestrial, marine, and human effects is required.

## 7. Conclusions

In the appropriate settings, AWL is an attractive option for CO<sub>2</sub> mitigation because: (1) the required reactants are relatively inexpensive, abundant, and environmentally benign; (2) the technology is relatively simple, low-cost, and applicable to power plant retrofitting, even in developing countries; (3) the storage is effective and long-term; and (4) the waste products are stable and may have net positive environmental effects for marine life. All of these features derive from the fact that AWL merely enhances Nature's own CO<sub>2</sub> mitigation mechanism, carbonate weathering. However, as we have reviewed, these advantages must be weighed against more detailed engineering, economic, and environmental assessments of this method for reducing the carbon intensity of global power generation.

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