Commercial Prospects to Combat Ocean Acidification[1]

The Trillion Ton Problem

Humanity cannot survive without healthy oceans. According to the World Resources Institute, coral reefs generate nearly $30 billion annually and sustain 25% of marine life and nearly 1 billion people through coastal protection, food security and income. The oceans provide a large part of the oxygen we breath (likely more than 50% - meaning every second breath we take is coming from the oceans), 15% of the protein humans consume, and absorb about 40% of global CO_2 emissions. The oceans have probably sequestered about 30-50% of total manmade carbon dioxide so far.

Ocean acidification is possibly the most important environmental issue on the planet today due to the scale of the problem and implications for terrestrial life, yet most people have never heard of it. Acidification is being caused by increasing concentrations of atmospheric carbon dioxide (CO_2), coming predominantly from man-made activities. The oceans' ability to absorb atmospheric CO_2 is related to marine biological processes mainly through growth of coral reefs, zooplankton, and other calcifying organisms. Increasing acidity slows the growth of these organisms, which are also affected negatively by other pollutants (e.g., sewage discharges). The geologic record shows that global extinctions are associated with significant variations of atmospheric CO_2.[2]

Since the beginning of the industrial revolution, ocean acidity - as measured by pH - has declined from 8.2 to 8.1 and is expected to fall another 0.3 to 0.4 pH units by 2100. In the last 200 years, ocean water has become 30 percent more acidic, much faster than any known change in the last 50 million years. When oceanic pH declines to 7.9 or lower, coral reefs and calcifying organisms (as some zooplankton, algae and shells) cannot survive, and a cascading collapse of marine life can be expected to occur, possibly within a few years. The effects may include large extinctions of marine life, major disruptions or significant alterations of marine food web, with unimaginable repercussion on the whole planet, including humans. More than 50% of the world's coral reefs died over the past 50 years and 90% are expected to die by 2050, due to acidification, other pollution, and overfishing. Some scientists predict that by 2048 the oceans may be completely devoid of marine life.[3] Unless atmospheric CO2 concentrations are reduced back to around 320 - 350 ppm, this "6th extinction" scenario is inevitable.

Gigatech Solutions

Atmospheric CO_2 concentrations reached 412 ppm in 2018 and continue to increase, which presents an existential threat to humanity. In the long term, atmospheric CO_2 concentrations must be drawn down to 320 ppm or less. The long-term solution is to deploy negative emissions technologies that could remove up to 50 billion tons of CO_2 per year from the atmosphere for around 20 years. In the near term, the impacts of acidification can be mitigated locally utilizing bio-mimicry and geo-mimicry systems.[4] Acidification can be countered by calcification and cultivation of seagrasses which feed on CO_2. The key chemical reactions are:

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[1] Prepared by D. Millison, Sustainable Energy Technology Consultant / ADB SDCC Energy Sector Group. Developed from a presentation at the Regional Workshop on Blue Economy, Disaster Risk Financing and Ocean Infrastructure, Fiji, 1 May 2019.

[2] J.E.N. Veron. 2009. *Is the Great Barrier Reef on Death Row?* Presentation to the UK Royal Society. Veron clearly anticipated the extensive bleaching on the Great Barrier Reef in 2015-16. Presentation available at this link: https://www.oceanarkalliance.org.au/dr-verons-coral-crisis-presentation-to-royal-society-london/

[3] https://earthmaven.io/sustainablehuman/old-story/salt-water-fish-extinction-seen-by-2048-Udxlu7LsXkisG0OmuzAbcA/?utm_campaign=meetedgar&utm_medium=social&utm_source=meetedgar.com

[4] Wolf H. Hilbertz, 1992, Solar-generated building material from seawater as a sink for carbon, Ambio, 21, 126-129

Acidification: $CO_2 + H_20 \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$

Calcification: $Ca^{++} + 2\ HCO_3^- \Leftrightarrow CaCO_3$ (aragonite) + CO_2 (aqueous) + H_20

Calcium carbonate ($CaCO_3$) is the basic compound found in coral reefs and other key marine organisms, commonly precipitated in the mineral form of aragonite. Production of 1 ton of $CaCO_3$ sequesters 0.44 tons of CO_2; this sequestration is permanent as long as pH is above 7.9.**[5]** Artificial reefs can be grown at scale, but in the absence of a payment for ecosystem services mechanism, a commercial business needs to be created to monetize the economic benefits, i.e., ***natural capitalism based on circular economy principles***. Possible avenues to commercialization (covered in more detail below) include:

- Building products, floating docks, etc.
- Living breakwaters and other nature-based defenses
- Ecotourism
- Insurance policies
- Marine aquaculture

Reefs Can Be Grown Faster than the Climate is Changing

Electrolytic deposition of calcium carbonate ($CaCO_3$) from seawater was pioneered by Wolf Hilbertz in the late 1970s, whose original idea was to make sustainable building materials.[6] The trade names “Biorock,” “seacrete,” and “seament” are commonly used to refer to the resulting material. In this paper, the term “reeph” will be used hereafter: the PH represents the additional alkalinity created by the electrical current that facilitates $CaCO_3$ precipitation coral growth. The reeph process is derived from cathodic protection systems used for corrosion prevention on offshore oil and gas platforms. One of the pioneering scientists claims that electric reefs are more resistant to acidification and bleaching events compared to natural reefs and passive artificial reefs[7] (see Appendix 1).

Accelerated reef cultivation has 2 key steps: (i) grow $CaCO_3$ in seawater, and (ii) propagate coral on the $CaCO_3$ substrate (see Figures 1 and 2). Various researchers have reported that coral propagation can be accelerated up to 50 times natural growth rates using a micro-fragmenting process which has been the result of extensive research at the Mote Marine Laboratory in the Florida Keys and the Hawaii Institute of Marine Biology. At least one company is attempting to commercialize reef cultivation using the micro-fragmenting method.[8] Coupled with propagation, reephs can be grown faster than the climate is changing.

The reeph process is a form of 3-D printing and is ideal for custom but scalable production. Common rebar, the cathode, is formed in the desired shape analogous to concrete forms or molds. An anode is placed in the water and supplied with a 1.5 volt trickle charge.[9] With proper control over the system, $CaCO_3$ in the mineral form aragonite will be deposited on the rebar and

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[5] Because this reaction releases CO_2 back into the water, it appears coral reefs are net GHG sources. Several reactions occur simultaneously and in fact the oceans are net GHG sinks partly because coral reefs and other calcifying organisms capture, store, and utilize carbon (with obvious biodiversity benefits).

[6] Hilbertz, W. (1979). *Electrodeposition of Minerals in Sea Water: Experiments and Applications*, in: IEEE Journal on Oceanic Engineering, Vol. OE-4, No. 3, pp. 94–113.

[7] Goreau, T.J. (2014) *Electrical Stimulation Greatly Increases Settlement, Growth, Survival, and Stress Resistance of Marine Organisms*, Natural Resources, 5, 527-537, http://dx.doi.org/10.4236/nr.2014.510048

[8] https://www.dw.com/en/making-coral-grow-50-times-faster-than-nature/a-45794571
See: http://www.coralvita.co/coral-farming

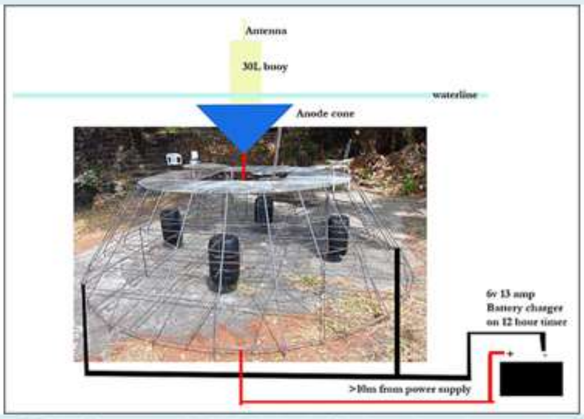
[9] Altering the voltage and current will result in precipitation of different minerals, e.g., $Mg(OH)_2$. There may be other more valuable minerals which could be grown in seawater, but very little research in this area has been published.

grow at about 1 - 2 centimeters per year or faster. The theoretical yield is about 1 ton $CaCO_3$ / megawatt-hour (MWh) of electricity; actual yields of 50-60% of the theoretical yield are reported (Goreau, 2014). Compressive strengths comparable to cast-in-place concrete (up to 80 Mega Pascals, or 3200-3500 pounds per square inch) have been reported.

Figure 1: 3-D Printing of $CaCO_3$

Step 1: 3-D Printing of $CaCO_3$ -- Proven science and engineering

- Cathodic protection systems widely used in petroleum industry
- Anode plus cathode of shaped rebar
- "Trickle" charge: no safety issues to divers or marine life
- Off-the-shelf materials + semi-skilled labor



W. H. Hilbertz & T. J. Goreau, 1996, Method of enhancing the growth of aquatic organisms, and structures created thereby, United States Patent Number 5,543,034, U. S. Patent Office (14pp.).

Figure 2: Propagating Coral

Observed $CaCO_3$ growth rates:
1 – 2 centimeters / year radial growth around rebar

Observed yield:
0.5 – 0.6 tons of $CaCO_3$ per Megawatt-hour electricity

Step 2: + coral propagation; 1 year growth at Nasugbu, Philippines

Source: Coral Triangle Conservancy, ree.ph

Two of the world's largest electric reef installations are in Indonesia, at Pemuteran on the northwest coast of Bali, and Gili Trawangan off the northwest coast of Lombok. [10] These appear to be successful ecotourism operations, but ecotourism is inherently difficult to scale up. A key potential benefit of large-scale artificial reef cultivation is that tourists can be drawn away from the high-value natural reefs that simply need to be left alone (if possible).

Commercializing Sustainable Building Materials Production

Table 1 summarizes information on conventional construction materials and quarried limestone markets, with indicative market prices ranging from about $40 per ton for cast-in-place concrete to $391 per ton (and much higher) for finished limestone slabs. Electricity is the key input which dominates the cost of production of reeph-based products, and for purposes of discussion, electricity is assumed to comprise half the total cost of production of $CaCO_3$. The market price of concrete and other materials is used to establish an upper limit on electricity costs which would be required for a financially viable process. E.g., to compete with cast-in-place concrete priced at $40/ton, a reeph-based alternative would need an electricity input price of less than $0.02/kWh. The market prices of concrete and Portland cement correspond to the current range of off-take prices for utility-scale ground-mounted solar PV plants. A reference price for bulk limestone blocks corresponds to the high end of retail electricity prices in Southeast Asia (e.g., comparable to retail rates in Thailand and Vietnam). An indicative price of finished limestone slabs corresponds to an electricity price comparable to diesel generation and floating PV. Labor costs will be much lower than that for cast-in-place materials, since the reeph process requires labor mainly for monitoring and occasional maintenance of the electricity supply system.

Table 1: Construction and Architectural Materials Market

Material	Unit Price	Break-even Electricity Cost	Comment
Concrete [a]	$40 / ton	$0.02 / kWh	Lowest of utility scale solar PV [d]
Portland Cement [a]	$75 / ton	$0.0375 / kWh	Low range of utility-scale solar PV [d]
Quarried limestone – bulk [b]	$160 / ton	$0.08 / kWh	Typical on-shore power in Southeast Asia (not including Philippines)
Finished Limestone slabs [c]	$649 / ton	$0.325 / kWh	Electricity cost is well above retail price of diesel generation or floating PV

Notes:
[a] Portland Cement and concrete markets are from solidiatech.com; Portland cement market is valued at $300 Billion for 4 billion tons/year; concrete market is valued at $1.3 Trillion for 33 Billion tons/year
[b] On-line price on 30 January 2017, accessed from:
http://www.stonecontact.com/products-320404/iran-beige-gohare-limestone
[c] This link to vendor selling slabs at $30 -50 / m^2, 1.5 cm, 2 cm, and 3 cm thickness, with density > 2.56 ton/m3 (high density):
https://www.alibaba.com/product-detail/Limestone-price-beige-limestone-limestone_60449241268.html
Unit price is $649 - $789 / ton. A retail home construction shop in Manila has polished limestone slabs at a price of $900 / ton. A retail tile shop in Newport News, Virginia sells limestone tiles for more than $3000 per ton.
[d] World Bank Group. 2016. *Price of Solar PV Electricity in Developing Countries*. World Bank, Washington D.C.

[10] For additional information on electric reef projects and other references see:
ree.ph and globalcoral.org

Table 2 uses the same unit prices as Table 1 to derive a simple break-even period assuming a prototype system powered by a 1 megawatt (MW) solar photovoltaic (PV) system with an installed price of $2 million (which assumes base cost of $1 million per MW for solar PV and an additional $1 million for balance of plant and operations and maintenance for 2 years). Onshore grid-supplied power could be used for many applications, but to achieve maximum sustainability a dedicated renewable energy source should be used. Also, as noted above, labor costs should be lower for grown-in-place than for traditional cast-in-place methods.

Table 2: Break-even Cost for 1 MW Solar PV-based System

Material	Unit Price	Annual Product Value	Simple Cost Recovery (years)
Concrete	$39 / ton	$27,300	73+
Portland Cement	$75 / ton	$52,500	38
Quarried limestone	$160 / ton	$112,000	17.9
Polished limestone slabs	$649 / ton	$454,300	4.4
Limestone tiles	$3000 /ton	$2,100,000	0.95
Key Assumptions: (i) 1 MWh of electricity input yields 0.5 tons $CaCO_3$ (1 kWh = 1 Kg $CaCO_3$) (ii) 1 MW solar PV with 4 hours per day output, 350 days per year = 1400 MWh / year = 700 tons $CaCO_3$ per year (iii) Total installed price is equivalent to $2 Million per Megawatt PV			

The calculated cost recovery periods in Table 2 indicate that reeph products could be financially viable in the price ranges of polished limestone slabs and tiles. The cost recovery period does not include 1-2 years for initial construction and start-up, so the best case would require 2-3 years to reach a break-even point, which indicates the need for "patient" capital. The foregoing discussion is obviously not an investment-grade analysis, as various simplifying assumptions have been made. However, it does appear that the reeph process could be commercially viable if finished products can be sold at higher product price ranges noted in Tables 1 and 2. Absent an advanced purchase commitment from a buyer, demonstrating a commercial system would require some concessional funding for prototype deployment, price discovery, and further feasibility study; with patient capital rather than a grant, the first prototype could be commercially viable. Price discovery is critical. The knowledge base for electric reefs is reasonably good, but there is no real operational experience using the electrodeposition process for building materials at the MW scale. At this point a traditional feasibility study will not provide any value; rather, a large-scale prototype is needed to transition from electric reefs, for which there is no commercial market to speak of, to a commercial building materials operation.[11]

As noted above, the electrodeposition process is scalable. Materials production can be done on a modular basis, with scale based on available power supplies and logistics of installation and harvesting of materials. Figure 3 shows that using less than 10% of the coastlines in developing countries of Asia would provide sufficient space for reeph production to sequester 50 billion tons of CO_2.[12] In theory, reeph systems are infinitely scalable; however, sequestering 50 Billion tons of CO_2 would require production of about 114 Billion tons of CaCO3 which would require electricity input of 228 Terawatt-hours of electricity.

[11] The author has not been able to find any information of any sites that have attempted to make a commercially viable system for building materials production. Based on the literature obtained, none of the electric reef projects have been initiated as commercial operations.

[12] Figure 3 is adapted from Millison, D. and S. Countryman. 2017. *Sustainable Pre-stressed Concrete from Seawater*. International Conference on Sustainable Infrastructure; American Society of Civil Engineers, New York City, October 2017.

Figure 3: System Scalability of 3-D Limestone Printing

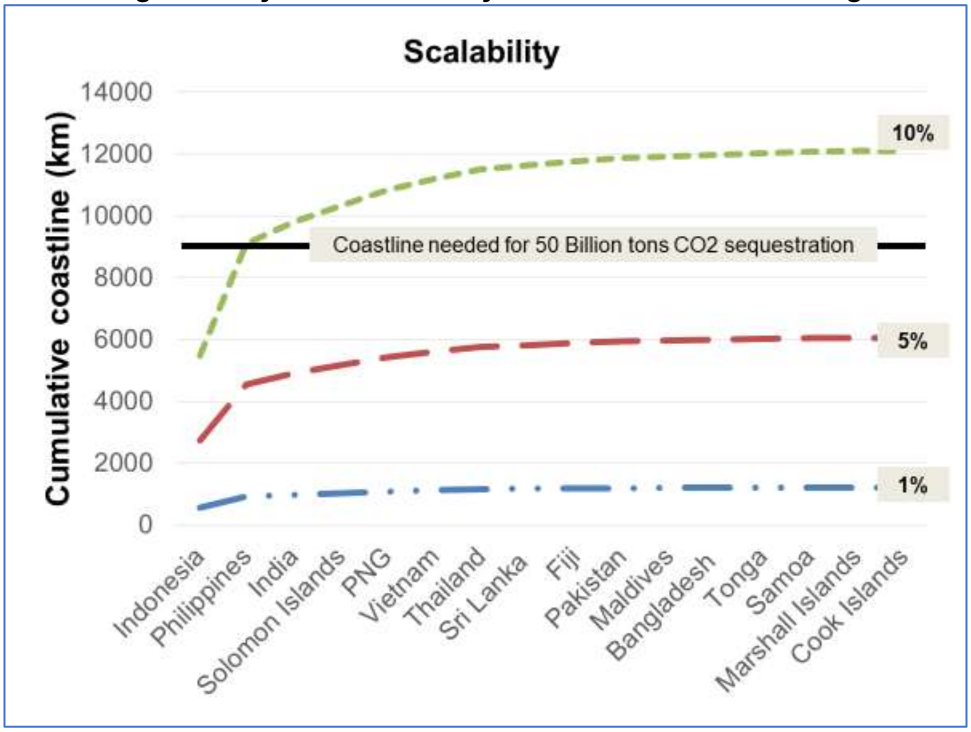


Figure 3 assumptions: Sequestration target: 50 billion tons CO2 = 114 Billion tons CaCO3 / 2.56 tons/m3 = 44.5 billion m3 CaCO3. Assuming 5 m water column, need ~ 9 billion m2 surface area; using a 1 km corridor @ 1 million m2 / km2 ➔ need 9000 km2 = 0.0053% of the Pacific Ocean surface

Nature Based Coastal Defenses: Living Breakwaters

Breakwaters, docks, and piers are some of the most common coastal infrastructure which are vulnerable to increasing storm severity. Traditional construction methods are based on dredging and cast-in-place concrete, with zero consideration for ecologically-friendly alternatives. It appears that breakwaters could be grown for less than the cost of traditional construction methods. The range of breakwater costs in Asia-Pacific is huge, ranging from $456 / meter to $188,817 / meter.[13] Assuming that electricity input is ½ of the total cost and electricity input cost is $0.05 – 0.20 /kWh, living breakwaters could be grown within the range of observed costs (see Figures 4 and 5). A key unknown is the solid volume required to protect against benchmark geophysical events, which is site-specific. A "no regrets" approach would be to grow a breakwater and determine through active observation when the solid volume is sufficient for the breakwater performance specification; after that, additional $CaCO_3$ growth could be for building materials production or floating structures.

There are at least 2 options to help promote the use of living breakwaters instead of traditional cast-in-place structures. One option is to provide viability gap financing to cover the cost difference (if any) between the traditional unsustainable method and the living breakwater. This financing could be achieved with concessional finance (grant or soft loan) to provide a capital cost buy-down or an interest rate buy-down. This could be useful for pilot / prototype deployment, but no such projects have appeared in the global adaptation climate change portfolio.

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[13] Cost range is from: https://www.researchgate.net/figure/Costs-of-construction-or-significant-maintenance-intervention-for-tropical-breakwaters_tbl1_262306245

Figure 4: Cost Estimates for Living Breakwaters

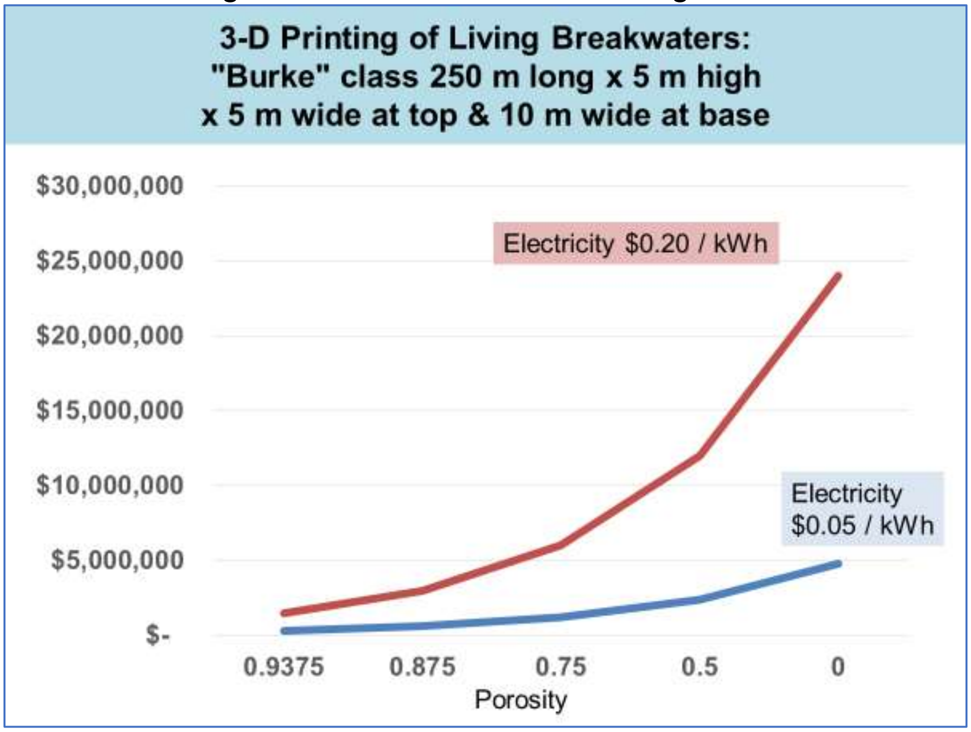
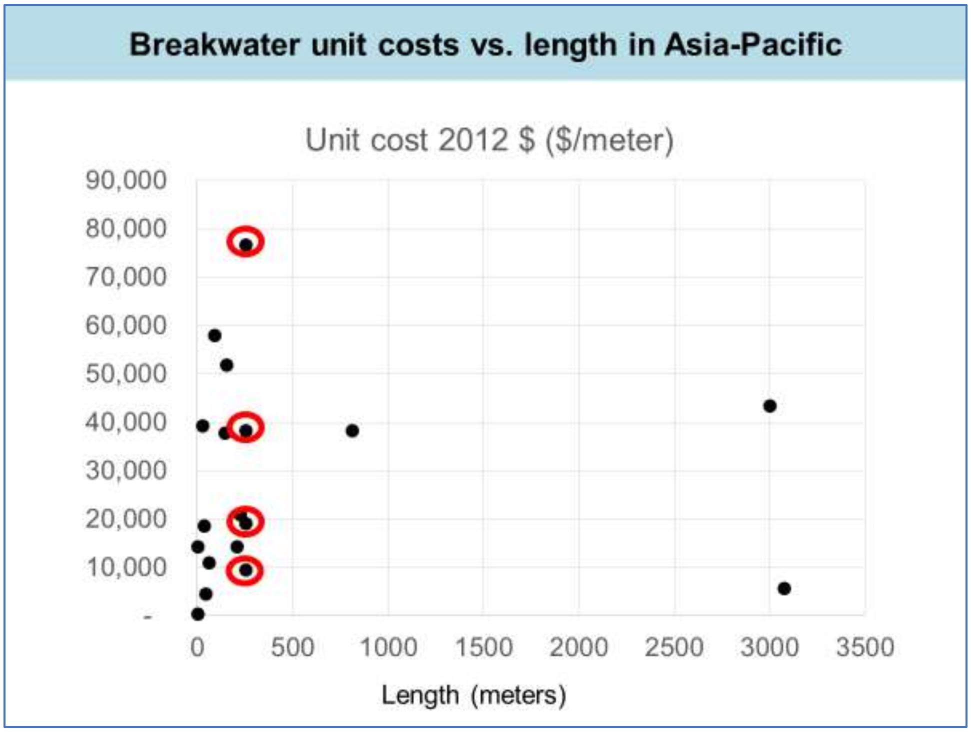
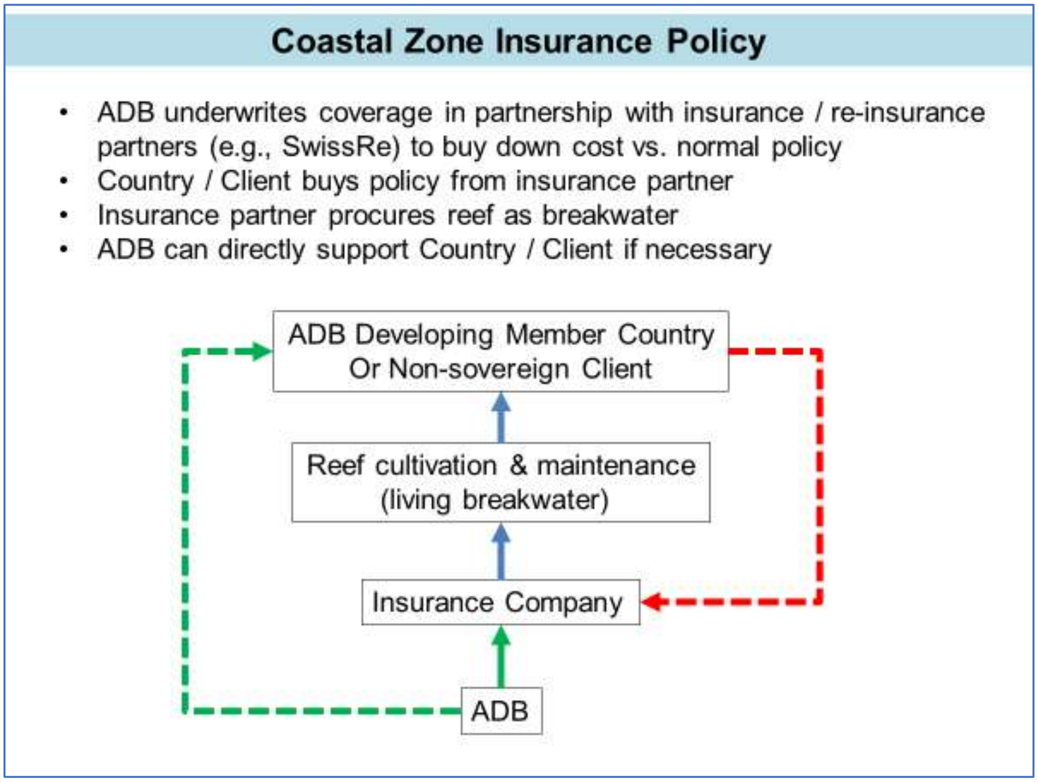


Figure 5: Breakwater cost ranges



A second option is to use the living breakwaters as coastal zone insurance policies, which would more clearly reflect the natural capitalism concept. This approach is a design advance on a reef insurance program being implemented by SwissRe and The Nature Conservancy in the Caribbean, where SwissRe provides a parametric insurance policy which pays out based on the intensity of storm events; The Nature Conservancy then implements reef rehabilitation. This is an interesting program, but it is only a "band aid" applied after the fact on specific storm events. However, this is a starting point for a proactive insurance policy to combat reef mortality. The design advance could be supported by a financier such as Asian Development Bank (ADB) as depicted in Figure 6.

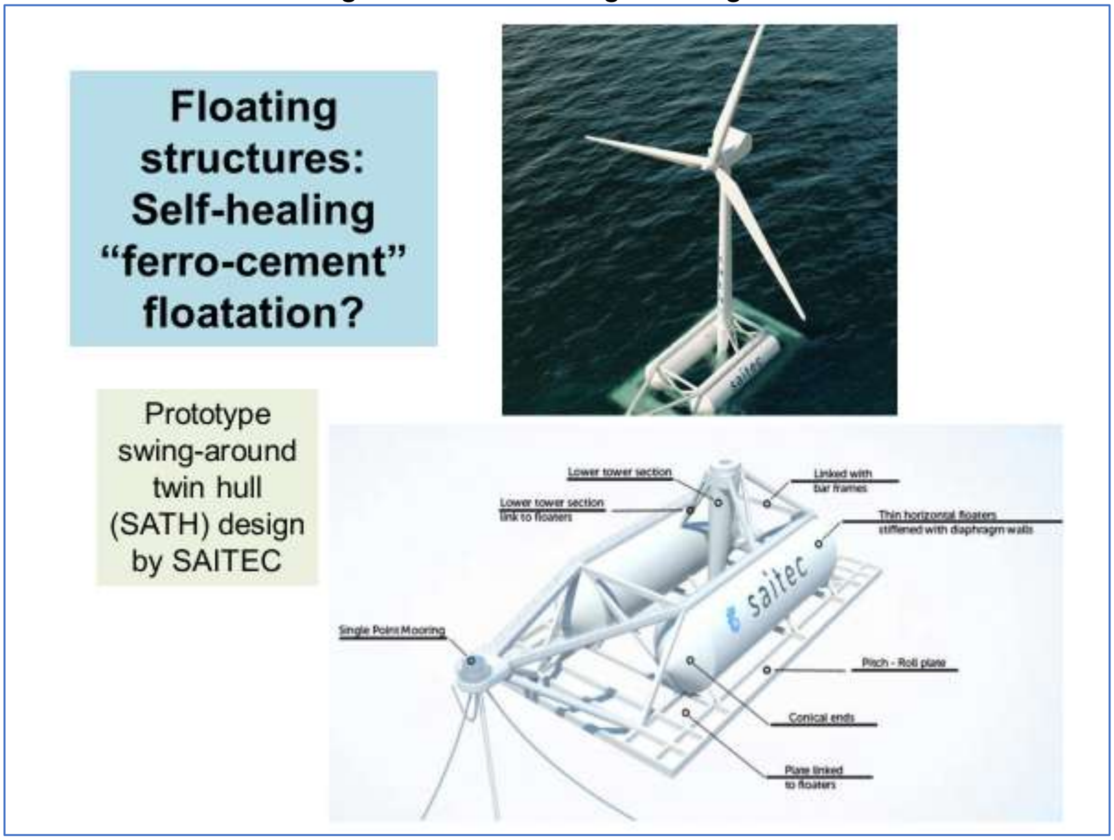
Figure 6: Living Breakwater as Coastal Zone Insurance



Floating Structures

Ferrocement ships, made of cast-in-place concrete, were popular some decades ago including some built for US Navy service during World War 2. These were relatively cheap compared to engineered steel ships, but lifetimes were limited to around 10 years due to corrosion of the cement and steel rebar elements. A self-healing version could be grown using the electric reeph system described above, but the time required to grow a pure $CaCO_3$ hull or pontoon is inherently limited to the 1-2 cm/year radial growth around rebar. A possible design option is to construct an inner shell of cast-in-place concrete surrounded by an outer shell of grown in place $CaCO_3$; as long as electricity is supplied, the outer shell will be self-healing and will prevent corrosion of the inner concrete shell. Spanish engineering company SAITEC is working on a prototype "swing around twin hull" (SATH) design for offshore wind development using 2 ferro-cement pontoons, accessory mounting systems, and a single-point mooring system (see Figure 7). Floating structures could also be grown for marine aquaculture facilities and other coastal infrastructure applications.

Figure 7: Self-healing Floating Structures



Marine Aquaculture: Improving Food Security and Reducing Ocean Acidification via CCUS

Marine aquaculture with co-located shellfish and seagrass cultivation to mitigate local pH appears very promising as a commercial proposition which directly reduces ocean acidification, albeit locally. A commercial operation which will combine seagrass plus shellfish is operating offshore California: the Catalina Sea Ranch[14] produces mussels for the southern California market, which were previously imported from Canada; the company expected to make 50% profit from its initial 40 hectare (100 acre) site and 90% margin after expanding to 400 hectares (1000 acres).[15] Mussels were selected as the initial crop due to low start-up and operating costs. Kelp will be added as the second crop, and other higher-value shellfish (abalone, clams, lobster, and scallops) are planned to be added later. Seagrasses and shellfish capture, store, and utilize carbon; if the seagrasses stay in the water and the shells are returned to the water, the carbon sequestration is effectively permanent. If shells are not returned to the water, the carbon will remain sequestered unless dissolved by reaction with acid.

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[14] See: https://catalinasearanch.com/ Commercial kelp farming has been in operation offshore New England for more than 10 years. See: http://oceanapproved.com/

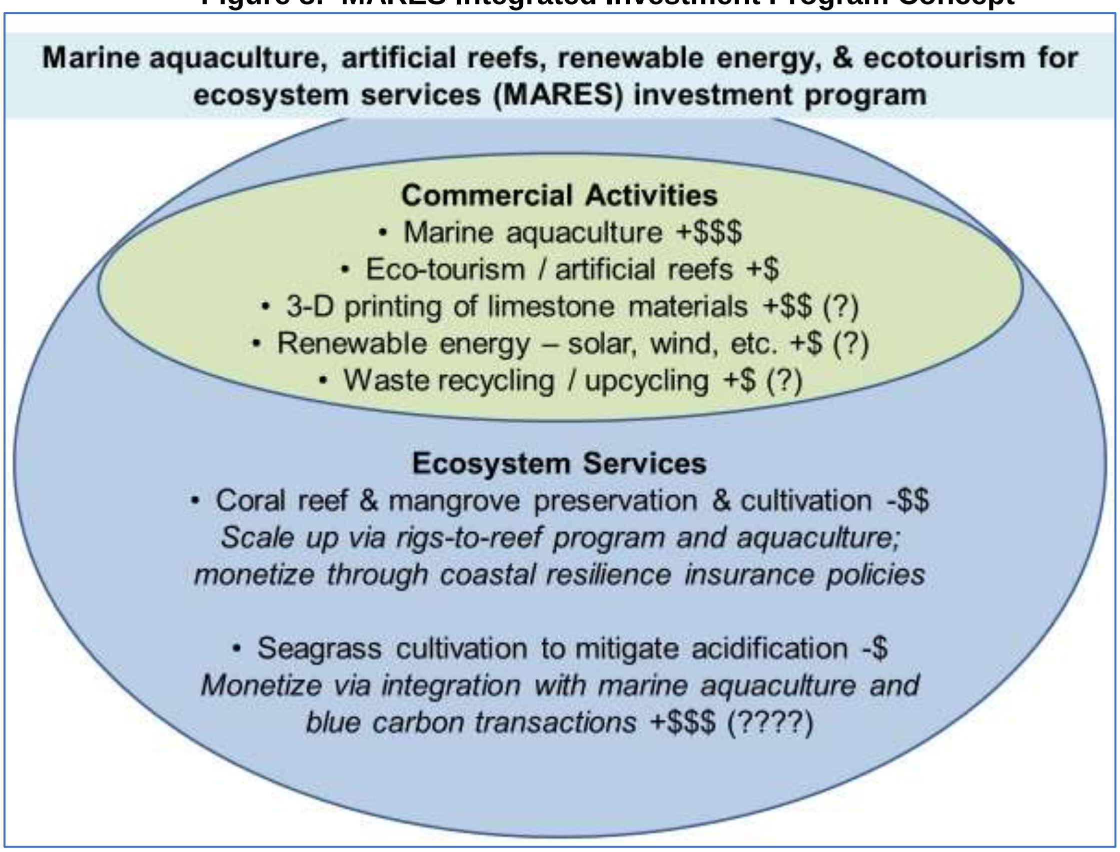
[15] See: https://static1.squarespace.com/static/591e33d3e6f2e191e5349dc6/t/596f7ebf37c58152ae4aff2b/1500479170878/Aquaculture+NA.pdf
and: https://www.undercurrentnews.com/2019/01/28/catalina-sea-ranchs-cruver-chomping-at-the-bit-to-expand-mussel-farm-on-federal-waters/

Surveys on the US west coast indicate that eelgrass effectively protects oysters from local acidification; on the US east coast, surveys by the National Oceanic and Atmospheric Administration indicate that at the Cheeca Rocks site in the Florida Keys, coral reefs are being protected from acidification by nearby seagrasses.[16] This knowledge from the US suggests that combining marine aquaculture with artificial reefs may be a relatively straightforward path to commercialization and scale up. Ecotourism can be developed around artificial reefs, but as noted above, growing electric reefs requires patience and patient capital which are both in short supply. There are possible short-cuts for large-scale artificial reef development in Southeast Asia, and an integrated development combining multiple activities – some inherently commercial and some inherently non-commercial – is suggested to achieve the scale of investment required to avoid the 6th extinction scenario.

Marine Aquaculture, Artificial Reefs, and Ecotourism for Ecosystem Services (MARES)

The traditional "ocean economy" includes seafood production; seaweed, kelp, and other biomass production; tourism; and offshore oil and gas extraction; all of which have been practiced unsustainably. These activities are ready to be "rebooted" using 21st century knowledge and principles of circular economy and natural capitalism. An integrated package of inherently commercial and traditionally non-commercial activities should be financially viable: marine aquaculture, artificial reefs, ecotourism, and seagrass and mangrove cultivation for ecosystem services (MARES). These activities have traditionally been done in isolation but can be integrated and co-located to become financially self-sustaining (see Figure 8) in various combinations and implementation sequencing.

Figure 8: MARES Integrated Investment Program Concept



[16] See: https://e360.yale.edu/features/kelp_seagrass_slow_ocean_acidification_netarts

Marine aquaculture appears to be the quickest route to revenue generation (e.g., as at Catalina Sea Ranch). The potential output from advanced marine aquaculture has been estimated at more than 100 times current global seafood consumption.[17] Marine seafood production in ADB's developing member countries (DMCs) is currently unsustainable due to overfishing and illegal fishing, but this industry can be transformed if governments provide leadership.[18] Applying best practices to marine aquaculture will improve sustainability and profitability of seafood production.[19] Artificial reefs and seagrass can mitigate ocean acidification locally, therefore colocation with aquaculture facilities will be mutually beneficial.

Artificial reefs are primarily for ecotourism and eco-system services: large-scale development of multiple sites will shift ecotourism away from natural reefs, which need protection by limiting rather than encouraging human visits. As discussed above, artificial reefs can be grown faster than the climate is changing by coupling the electric reef process with coral propagation.

Artificial reefs in the form of repurposed offshore oil and gas structures and decommissioned ships (referred to as rigs-to-reefs (R2R) for shorthand) -- are possible short-cuts to rapid large-scale development.[20] The world's R2R program is in the US waters of the Gulf of Mexico: from 1987 through 2016, 516 platforms were converted to reefs, representing about 11% of all decommissioned structures. Decommissioned ships may also be converted to reefs; the world's largest single ship conversion is also in US waters of the Gulf of Mexico.[21]

There are about 1800 offshore petroleum platforms in the Asia-Pacific region, about 1400 of which are in Southeast Asia (mostly in Indonesia, Malaysia, and Thailand). Many of these structures are nearing the end of their economic lifetimes and may be decommissioned in the foreseeable future. To date, there is only one known R2R site in Southeast Asia: the Seaventures Dive Rig offshore Sabah State of Malaysia (see Figures 9 and 10).[22] The rigs which host coral growth now are *de facto* small-scale marine protected areas, because marine vessel traffic not directly related to the rig operations is restricted.[23] Decommissioning such rigs via complete removal is environmentally detrimental and needlessly expensive.

[17] Gentry, R. et al. (2017), "Mapping the global potential for marine aquaculture", *Nature Ecology & Evolution*, Vol. 1/9, pp. 1317-1324, http://dx.doi.org/10.1038/s41559-017-0257-9.

[18] The suggested approach is to replace unsustainable high seas fishing (strip mining of the oceans) with inherently sustainable ocean farming. Indonesia has been particularly aggressive against illegal fishing during the last 2 years. See: https://globalfishingwatch.org/news-views/indonesia-must-continue-marine-transparency-leadership/

[19] E.g., see: https://www.unido.org/news/unido-fisheries-project-red-sea-state-implemented-funding-canada and https://www.drawdown.org/solutions/coming-attractions/ocean-farming
Development of 21st century marine aquaculture at scale can effectively bankrupt illegal fishing.

[20] See: https://tpwd.texas.gov/landwater/water/habitats/artificial_reef/rigs-to-reefs.phtml and also see: https://blog.nationalgeographic.org/2015/09/09/exploring-resilient-reefs-on-oil-platforms-in-the-gulf-of-mexico/
For additional reporting on offshore petroleum rigs as dive sites, see: https://www.afar.com/magazine/some-of-the-best-new-dive-spots-are-under-oil-rigs?inspiration=outdoor-adventure&sub_inspiration=water-sports&utm_source=Sailthru&utm_medium=email&utm_campaign=71318&utm_content=Final&utm_term=Daily%20Wander%20Newsletter

[21] See: https://www.atlasobscura.com/articles/great-carrier-reef-oriskany-artificial

[22] For more details and a comparison of biodiversity values on artificial vs. natural reefs, see: https://matadornetwork.com/read/matador-originals-presents-rigs-reef-transecting-borneo/

[23] See: Sally Ann Connell, "Is Rigs-to-Reefs Best Plan for Oil Rigs?", Los Angeles Times, 20 June 1999. In this article, Milton Love, a biologist with the UC Santa Barbara Marine Science Institute noted, the oil production platforms are not just potential artificial reefs: "They are in fact artificial reefs right now."

Figure 9: Rigs to Reef Conversion

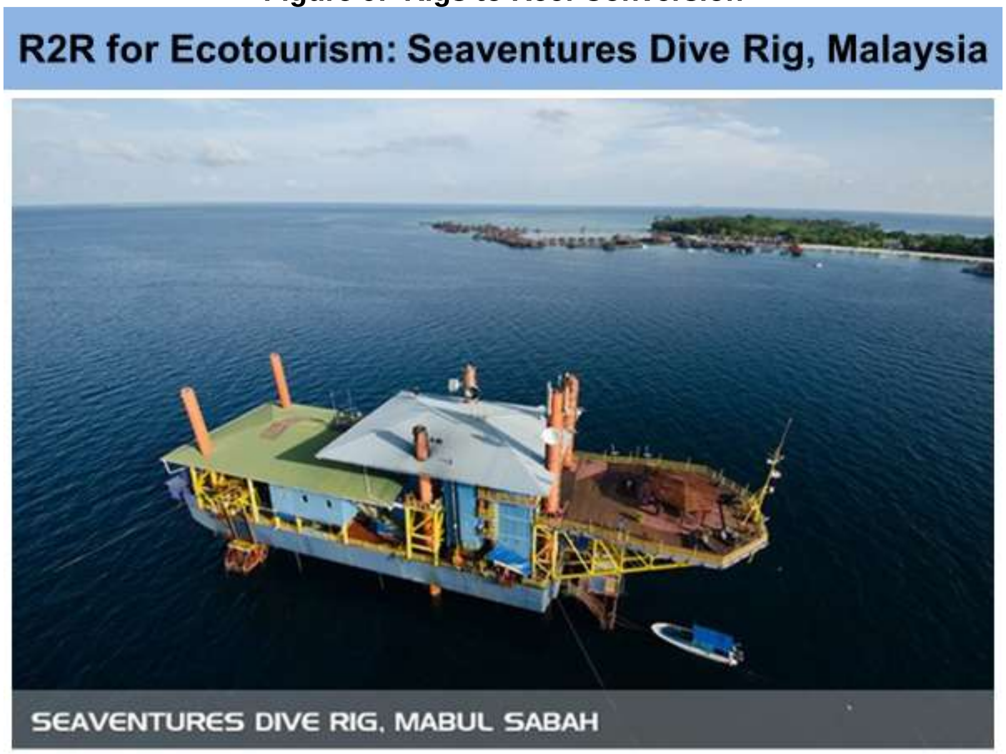
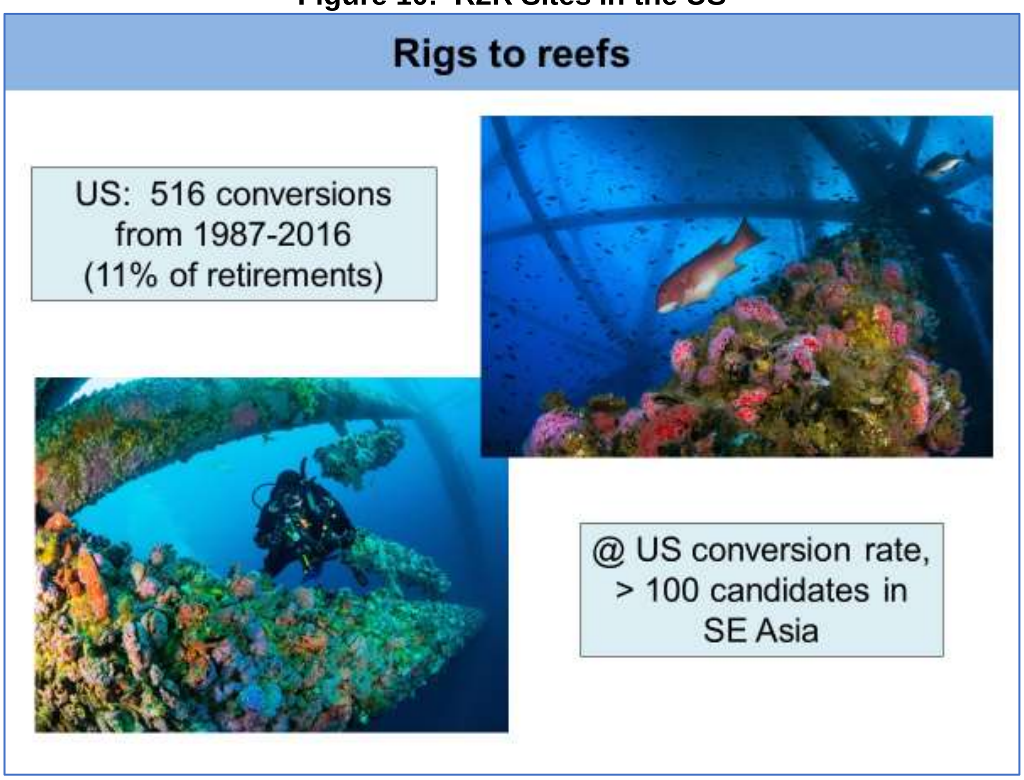


Figure 10: R2R Sites in the US



Based on the fleet conversion rates in the US Gulf of Mexico, Southeast Asia could have at least 100 rigs which are candidates for conversion to reefs, around which marine aquaculture can be developed in a mutually beneficial manner. When the topside structures are kept in place, decommissioned rigs could be retrofitted with relatively small-scale solar and wind generation (~ 1MW or less) to provide electricity for the 3-D $CaCO_3$ printing as well as crew and/or tourist facilities. Alternatively, rigs could conceivably serve as mooring points for floating solar and wind installations. These artificial reefs should be designated as "no take" marine protected areas, around which commercial aquaculture could be developed.

In the US, R2R is compatible with marine aquaculture[24]: commercial fishing for red snapper in the Gulf of Mexico is seen as highly dependent on oil platform habitat, which provides a hard substrate for aquatic life that is otherwise scarce in much of the Gulf. Dr. Bob Shipp, chairman of the University of South Alabama Department of Marine Sciences, and director of the Alabama Center for Estuarine Studies, has suggested 100 percent participation in R2R, and said of removing oil rigs from the Gulf: "*As a fisheries scientist, I think it's a very big mistake… (the rigs) are all essential habitat really, from the mouth of the (Mississippi) River to (South) Padre Island, snapper are totally reliant upon artificial structure. Before the 1940s, when those rigs started going in, there was practically no snapper in the northwest Gulf. Now, more than half of the catch is from that area*."[25]

Seagrass cultivation and other marine permaculture[26] can mitigate the local effects of acidification on shellfish and corals. Oceanic plants from seagrasses to plankton add up to only 0.05% of the plant biomass on land but are so pervasive and efficient at metabolizing carbon that they cycle through about the same amount of carbon every day as all land-based plants. Efforts to restore or farm such ocean plants could have a host of benefits including drawing down atmospheric carbon. Seagrass and mangroves can sequester carbon up to 35 times faster than terrestrial forests, presenting a possible "blue carbon" finance opportunity.[27] Seagrass and mangrove cultivation would be subsidized by revenue from aquaculture and ecotourism operations, pending the emergence of a blue carbon transaction or other payment for ecosystem services mechanism. Colocation of marine aquaculture, artificial reefs and marine permaculture is critical to facilitate overall commercial operations.

Preservation and cultivation of coastal mangroves and near-shore coral reefs will improve coastal resilience. Growing and preserving reefs, seagrass, and mangroves are insurance policies and it should be possible to engage the insurance and re-insurance industries in further development.[28] As noted above, seagrass and mangroves provide carbon sequestration benefits which are potentially much larger than onshore reforestation. Various other activities could be co-located and integrated with the MARES development for potential value addition, e.g.:

- Modular renewably-powered cold storage, ice-making, and water production.[29]

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[24] The concept of combining marine aquaculture with rigs-to-reefs is based on case studies of these topics in: OECD. 2019. *Rethinking Innovation for a Sustainable Ocean Economy*, OECD Publishing, Paris. *https://doi.org/10.1787/9789264311053-en*

[25] M.A. Fisher, "359 rigs slated for decommissioning, leading scientist says action is detrimental to red snapper plan", *The Louisiana Sportsman*, Feb 2013.

[26] https://www.drawdown.org/solutions/coming-attractions/marine-permaculture

[27] https://e360.yale.edu/features/kelp_seagrass_slow_ocean_acidification_netarts
https://news.grida.no/happy-seagrass-month

[28] SwissRe and The Nature Conservancy are partners in a reef rehabilitation program in the Caribbean. This model is now being considered in Vietnam with Global Environment Facility support.

[29] These can be offshore and onshore. E.g., see: https://solarcoldbox.com/solarcoldbox

- Digitization of seafood production and use of smart phone apps to provide direct-to-market sale of seafood, adapting what is already being done in some developing countries for terrestrial farming.
- Cleaner boats, i.e., electric, fuel cell, and hybrid propulsion systems, can be deployed on a pilot basis with future scale up for ecotourism operations.[30]
- Future horizontal integration could include utility-scale offshore wind and floating solar.[31]

Depending on specific countries and locations, there are at least 5 different variations on the MARES approach in the Indo-Pacific region:

(a) R2R-centric development, similar the US Gulf of Mexico program. Candidate countries are Indonesia, Malaysia, Thailand, and Vietnam where the bulk of the Asia-Pacific rig population is located. The proposed business model is to couple marine aquaculture with artificial reefs for ecotourism, with future horizontal integration of ocean energy and other activities. Seagrass and mangrove cultivation would also be required. Based on the US R2R conversion rate there could be well over 100 candidate R2R sites in SE Asia.

(b) Marine ecosystem preservation supported by marine aquaculture and artificial reefs for ecotourism. This might work in Palau, where about 80% of the exclusive economic zone (EEZ) has been set aside as protected area. The business model is similar to (a) but the artificial reef could utilize a decommissioned ship or purpose-built structures using the electric reef process discussed above. The long-term objective is to generate sufficient revenue to support protected areas management without the need for continuous grant infusions. Another candidate country is Cambodia, which has asked ADB for assistance on marine aquaculture as part of a broader regional agri-business development program.[32]

(c) Marine ecosystem restoration via marine aquaculture and artificial reefs. Nauru would be a perfect place for this, since the only other economic activity is the Australian government's refugee detention center. A sustainable ocean “mining” industry based on 3-D printing of limestone in seawater (see discussion above on limestone building products) could be developed to replace the defunct phosphate mining operations.

(d) Offshore wind, solar, or other renewable energy development based on a traditional power purchase agreement, with complementary development of MARES to enhance overall revenue creation. Thailand is a potential candidate, where ADB’s Southeast Asia Energy Division (SEEN) is reportedly in early discussions with the Ministry of Energy to support utility scale offshore wind.

(e) Ocean energy technology test bed. A series of meetings was organized by the ADB South Asia Energy Division (SAEN) with the Maldives' delegation to Asia Clean Energy Forum 2017

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[30] E.g., the typical bangka in the Philippines could be retrofitted with solar PV on the roof, and a 5 kW electric motor with detachable belt drive. Such hybridization would probably cost around $10,000 – 15,000 per unit for the first batch but costs would come down with scale of deployment.

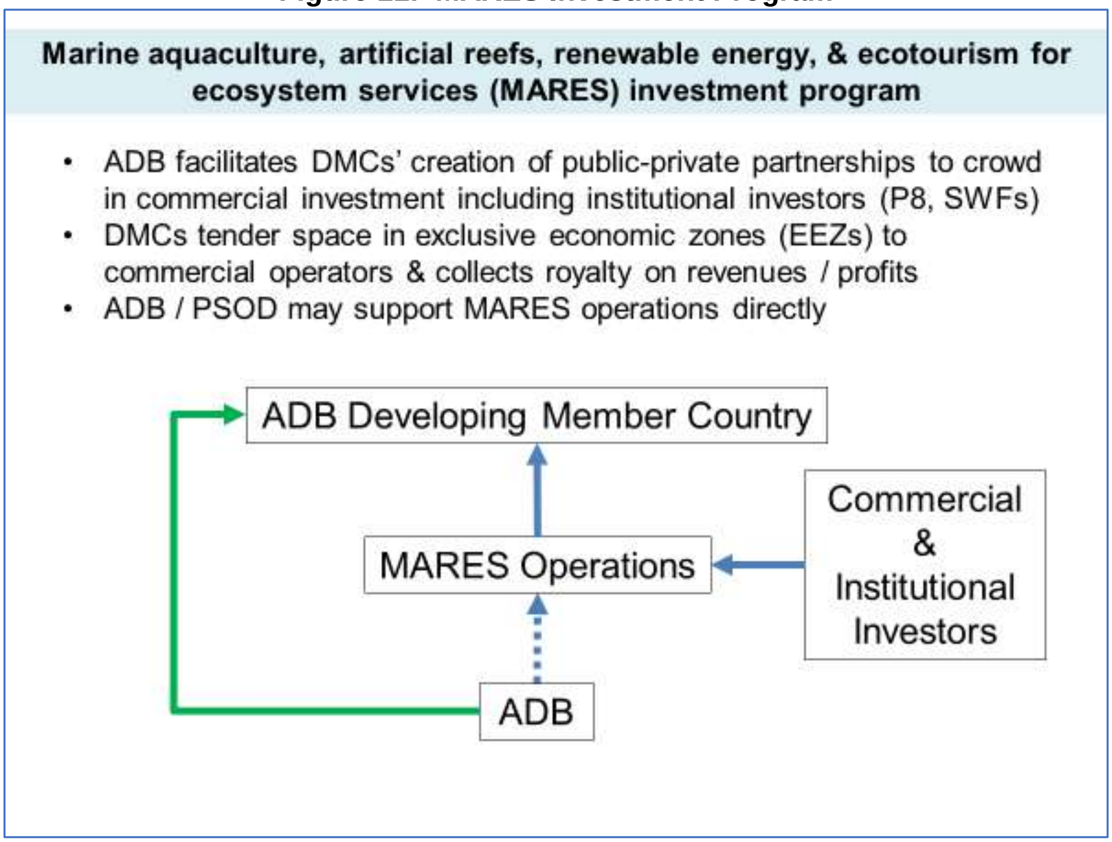
[31] Offshore solar and wind energy can provide the necessary energy for the MARES operations, which would otherwise be provided by petroleum-fired generators. Marine floating solar is already being deployed on a commercial basis at fish farms in Norway, and at private resorts in the Maldives; in both cases the solar development is displacing petroleum-fired generators and solar deployment is not based on a traditional grid-connected power purchase agreement.

[32] It is theoretically possible to use a decommissioned rig from a neighboring country (e.g., Thailand) as a “ready-made” artificial reef, around which the marine aquaculture activities could be developed.

about setting up a technology demonstration program. The main reason this has not progressed is that the current technical and financial assistance pipeline does not include any funds for energy sector operations.

The scale of investment needed to address ocean acidification is huge: billions of dollars of private investment are needed, which can be leveraged by modest amounts of public sector funds if investment opportunities are properly structured. In other words, MARES can be "weaponized" if governments are willing to try something different. This is the type of problem which ADB as a knowledge institution is supposed to diagnose, then develop solutions for financing at scale. The general approach is depicted in Figure 11.

Figure 11: MARES Investment Program



The MARES approach summarized in Figure 11 can be commercialized by adapting the business model for large-scale solar parks which has been successful in India, Cambodia, and other countries. The key elements are as follows:

(a) Government defines the program, specifying what activities are allowed and not allowed: marine aquaculture, ecotourism, ocean energy, complementary coastal zone development, etc. Government creates a special purpose MARES development company with technical assistance. The MARES company is capitalized with government funds, pre-paid contributions from petroleum operators, and possibly ADB financing support (sovereign or non-sovereign depending on government interest). If the government shares are held by a credit-worthy enterprise (e.g., Petronas in Malaysia) a bond issue may be possible.

(b) Government takes the lead on survey to determine which sites are suitable for marine aquaculture and artificial reef development including R2R conversion or other artificial reef options. For R2R, the rule of thumb is that rigs which are already artificial reefs are the preferred candidates.
(c) The MARES company systematically identifies the sites and implements the initial marine aquaculture and artificial reef development. Where R2R is implemented, there are two approaches: (i) top side removal and cutoff at 50-85 water depth (Gulf of Mexico model), or (ii) conversion of topside to accommodation and operations center (Seaventures Dive Rig model).
(d) The individual MARES sites are auctioned off via competitive tender to consortia of seafood producers, ecotourism operators, etc.
(e) Horizontal integration of additional activities could follow, e.g., development of wind farms and other ocean resources as specified in the MARES program.

Other approaches can be identified and developed based on DMC interests and local conditions. A regional TA is suggested for preliminary feasibility studies to identify candidate sites, business models, project structuring, and financing modalities and sources.

Summary and the Way Forward

The oceans provide 50% of the oxygen we breath and 15% of the protein humans consume, and store 40-50% of global carbon dioxide emissions.

- The oceans' ability to metabolize carbon and maintain ecosystem services is being compromised due to growing atmospheric carbon dioxide (CO_2) concentrations which are now greater than 412 ppm.
- Global emissions of about 40 billion tons CO_2-equivalent per year need to be drawn down to zero and then further reduced: CO_2 concentrations need to be in the range of 320 ppm to 350 ppm to ensure ocean health. The scale of drawdown required will not be successful unless bio-mimicry and geo-mimicry processes are commercialized and deployed at industrial scale, i.e., natural capitalism.
- Commercial investment can be crowded in at scale via integrated development in exclusive economic zones (EEZ) combining commercial + non-commercial activities. Marine aquaculture and ecotourism are proposed as the proven primary revenue-generating activities to facilitate development. Various forms of coral propagation and reef cultivation are the centerpiece of ecotourism, relieving pressure on high-value natural reefs. Artificial reef cultivation can be jump-started by conversion of existing offshore oil and gas structures to reefs; 100+ candidate sites are believed to exist in Southeast Asia. Cultivation and preservation of seagrasses complements the aquaculture and reefs by local mitigation of CO_2-induced acidification. Preservation and cultivation of coastal mangroves and coastal reefs complement the overall development by enhancing coastal resilience; these activities can be monetized in part via insurance policies.
- Investment from pension and sovereign wealth funds is needed to get the necessary scale of investment, which requires investments in [special-purpose] companies rather than project finance. The overall development approach must be structured to offer a low risk profile and predictable returns.

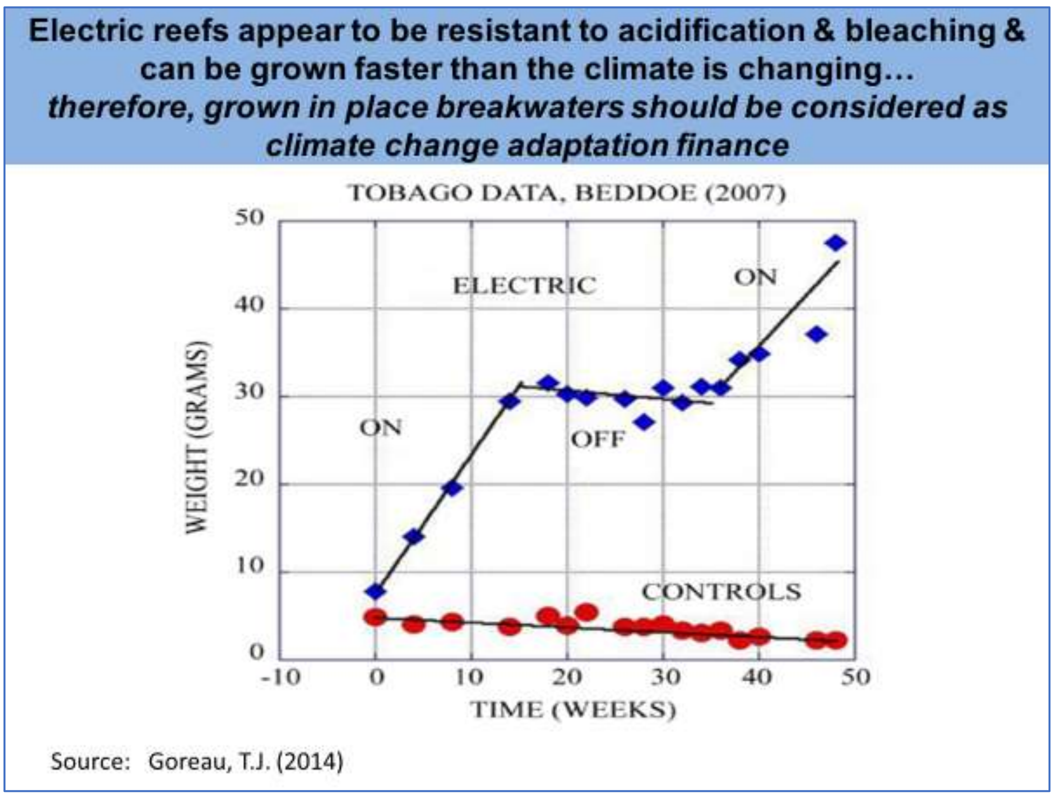
APPENDIX 1: Are Electric Reefs Climate Proof?

In early 2017, electric reef pioneer Thomas Goreau made the following claim, referring broadly to the coral bleaching around the world in 2016 and specifically to the bleaching at the Great Barrier Reef (which was anticipated by marine scientist J.E.N. Veron in 2009; see footnote 2):

> *"Despite the massive death of corals from high temperature in 2016, Biorock reefs in Indonesia maintained under 24-hour power suffered no noticeable mortality at all, making it the only method that protects corals from dying from global warming."* [33]

The Gili Ecotrust, which manages one of the largest electric reefs in the world at Gili Trawangan in Indonesia, makes similar claims on its website.[34]

Goreau's 2017 observation has not been subject to rigorous third-party review. However, it is consistent with data from other research in the Caribbean cited in one of Goreau's publications in 2014. The data in the figure below are consistent with general understanding of marine chemistry: as the aragonite saturation level decreases (mainly due to increased CO_2 in seawater), more energy is required to drive the calcification reaction to create $CaCO_3$, and this additional energy can be in the form of electricity.



[33] Accessed on 30 January 2017 from: http://www.globalcoral.org/2017-gcra-plans

[34] http://giliecotrust.com/biorock/ The site at Gili Trawangan was initially developed under the leadership of Wolf Hilbertz and Thomas Goreau.