White Paper

ACCELERATED RESTORATION AND PROTECTION OF THE GREAT BARRIER REEF BY APPLYING INDUSTRIAL SCALE COMBINED *MICRO-FRAGMENTATION AND FUSION* & *ELECTROLYTIC REEF RESTORATION*

Authors

Harald van Hoeken, BSc
Precision Energy Group Ltd

Brigitte Vlaswinkel, PhD
Oceans of Energy BV

Dan Millison, MSc
Asian Development Bank

Contributing Authors

Francesco Ricciardi, PhD
Asian Development Bank

Capt. John W. Koster USCG (ret.), M.S.
University of California

Geoffrey Swain, PhD
Florida Institute of Technology

Chris Haver, Bsc
H4 Capital Partners

Mike McDowell
Antarctic Logistics Expeditions

Ahmad Allahgholi, Msc
Coralive.org

ABSTRACT

On a global scale, about 50% of coral reefs have died and a total of 90% of the world's corals are predicted to die by 2050, as a direct consequence of human-caused global warming. Anthropogenic drivers of climate change result in ocean acidification, coral bleaching events and other environmental stress factors such as Crown of Thornes starfish outbreaks, coral diseases and cyclones, all of which kill corals at alarming rates. Therefore, it is no surprise that The *Great Barrier Reef Outlook Report 2019*[1] has highlighted the urgent need for accelerated action to improve the outlook of the Great Barrier Reef. To halt and reverse coral reef decline, reef scientists advocate for the reduction of atmospheric CO_2 concentrations from the current 414 ppm to under 350 ppm. Thus, if net zero CO_2 emissions are attained on a global scale and CO_2 from both the atmosphere and the ocean is actively sequestered, this goal will be achievable.

By combining the techniques of *Micro-Fragmentation and Fusion* and *Electrolytic Reef Restoration* and deploying it on an industrial scale on the Great Barrier Reef and other reef locations worldwide, there is potential to grow reefs faster than human-caused environmental stresses are killing them.

Whilst *Micro-Fragmentation and Fusion* (a technique that consists of breaking corals into smaller pieces of 1 to 5 polyps) have been developed and scientifically proven to be effective[2], more scientific research is required for *Electrolytic Reef Restoration* (a process of precipitating calcium carbonate from seawater using an electric field). New scientific research is required to validate decades of empirical data and to gain a better understanding of the relationship between accelerated coral growth rates, resilience to extreme events, optimal voltage and electrical currents over extended periods. Funding of USD 10 million for several 5-year research projects will obtain required data and results, where-after industrial scale deployment of combined technologies may become viable. This initial investment is a fraction of the AUD 700 million (USD 481 million) that the Australian government has committed to The Reef Trust[3] to improve coastal habitat and water quality in the Great Barrier Reef.

Industrial scale deployment of combined *Micro-Fragmentation and Fusion* and *Electrolytic Reef Restoration* can make a meaningful impact on restoring and protecting the Great Barrier Reef. A one-time capital investment of USD 0.99/m^2 is needed for a 25-year project, and though this figure is cost-effective, due to the extensive area of the Great Barrier Reef, this results in large capital requirements. A USD 4.1 billion initial capital investment in *Electrolytic Reef Restoration* systems would be required to restore and protect an area of 4,136 km^2, equating to twenty percent (20%) of the total surface area of near-sea-surface coral reefs within the Great Barrier Reef[4]. This is approximately the size of the US state of Rhode Island. The investment is not only in ecosystem services but also in other public goods, including

[1] Great Barrier Reef Marine Park Authority, *Great Barrier Reef Outlook Report 2019,* 2019 http://elibrary.gbrmpa.gov.au/jspui/handle/11017/3474

[2] Page, Muller and Vaughan, *Microfragmenting for the successful restoration of slow growing massive corals*, Ecological Engineering, 2018 Nov, Volume 123, Pages 86-94 https://www.sciencedirect.com/science/article/pii/S0925857418303094

[3] Department of the Environment and Energy, Australian Government [internet] https://www.environment.gov.au/marine/gbr/protecting-the-reef

[4] Harris, P. et al, *Submerged banks in the Great Barrier Reef, Australia, greatly increase available coral reef habitat*, ICES Journal of Marine Science, Volume 70, Issue 2, March 2013, Pages 284-293; https://doi.org/10.1093/icesjms/fss165

improved coastal resilience (climate change adaptation), biodiversity preservation and creation, food security, and ecotourism, all of which create productive employment and sustainable economic growth. This initial investment required equates to 4.0% of the total direct revenue generated by the Great Barrier Reef over a 25-year period that would generate an estimated 10,000 new direct and indirect employment opportunities in Australia.

By rapidly deploying a combined Micro-Fragmentation and Fusion and Electrolytic Reef Restoration on an industrial scale, the Great Barrier Reef and other reefs worldwide might not only be spared certain death by 2050, they could avoid the corresponding adverse impact on associated revenues.

Introduction

Based on current estimates, shallow water coral reefs occupy somewhere between 284,000 and 512,000 km^2 of the planet. This area represents less than 0.015 percent (0.015%) of the ocean, yet coral reefs harbour more than 25 percent (25%) of the ocean's biodiversity. No other ecosystem occupies such a limited area with more life forms. The ecosystem service valuations[5] of coral reefs are immense and go far beyond the biodiversity narrative. The *Reefs At Risk Revisited*[6] report highlights a few of the important functions of coral reefs globally:

- Support more than 500 million people worldwide.
- Protect coastlines in more than 100 countries - helping defend against storms and erosion.
- Accounts for 15% of gross domestic product (GDP) in more than 20 countries.
- Hold the potential to fight disease - including treatments for cancer, HIV, malaria, and other diseases.

Australia's Great Barrier Reef "makes up about 10 per cent of the world's coral reef ecosystems"[7] and according to Australian government published information[8], "the Great Barrier Reef alone generates over [AUD] 6 billion dollars' worth of revenue per year".

On a global scale, 50% of coral reefs are estimated to have died and a total of 90% of the world's corals may die by 2050 as a direct consequence of human-caused global warming. Human causes result in ocean acidification, coral bleaching events and other environmental stress factors that are rapidly killing corals at alarming rates. It is therefore of no surprise that The *Great Barrier Reef Outlook Report 2019*[9] highlights the urgent need for accelerated action to improve the outlook of the Great Barrier Reef. Over the past 800,000 years, global CO_2 concentrations were never above 300 ppm. This threshold was breached due to human caused carbon emissions in 1950[10] and has been climbing exponentially since. For coral reef

[5] De Groot et al, *Ecosystem service valuations are the varied benefits that humans receive from properly functioning ecosystems and are used to assign economic value to these ecosystem functions*, 2012
[6] Lauretta Burke et al *Reefs at Risk Revisited*, World Resources Institute, 2011; https://doi.org/10.1016/j.ecoser.2012.07.005
[7] Great Barrier Mariner Park Authority [internet]; http://www.gbrmpa.gov.au/the-reef/reef-facts
[8] Great Barrier Reef [internet]; https://greatbarrierreef.com.au/
[9] Great Barrier Reef Marine Park Authority, *Great Barrier Reef Outlook Report 2019,* 2019; http://elibrary.gbrmpa.gov.au/jspui/handle/11017/3474
[10] Data: Luthi, D., et al.. 2008; Etheridge, D.M., et al. 2010; Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO_2 record; https://climate.nasa.gov/climate_resources/24/graphic-the-relentless-rise-of-carbon-dioxide/

declines to be reversed, reef scientists advocate that atmospheric CO_2 concentrations need to be reduced from the current 414 ppm to under 350 ppm, a level that was last observed in 1990. Thus, if net zero CO_2 emissions are attained on a global scale and CO_2 from both the atmosphere and the ocean is actively sequestered, this <350 ppm goal will be achievable.

Since 2016, half of all corals in the Great Barrier Reef have died [11]-- a direct result of back-to-back unprecedented marine heat waves in 2016 and 2017 causing prolonged coral bleaching events. A post-mortem report[12] written by leading marine scientists and published in the journal *Nature* in 2018 attributes the causes as "human-caused global warming." According to the *New York Times*, "Australia relies on the Great Barrier Reef for about 70,000 jobs and billions of dollars annually in tourism revenue, and it is not yet clear how that economy will be affected by the reef's deterioration"[13].

Corals are animals that secrete a skeleton of calcium carbonate ($CaCO_3$) and source their food in a unique way. Tiny, photosynthetic algae called zooxanthellae live in coral tissues, that, simply put, turn sunlight into food for corals and corals give them a place to live in return. Scientists estimate that over 50% of the oxygen in the atmosphere, i.e. the air we breathe, comes from the ocean[14]. Algae and phytoplankton produce this oxygen and corals are an intricate part of this globally complex ecosystem by hosting many of these photosynthetic algae, named zooxanthellae, in their skeletons. The coral gives the zooxanthellae a home. In return, the zooxanthellae provide the coral with food. This symbiotic relationship between coral and algae is the foundation of the tropical coral polyp and elevated water temperatures suspend this symbiosis. When corals are exposed to elevated temperatures, they expel the zooxanthellae from their tissue as a survival mechanism. To human eyes, this causes them to lose their colour—they "bleach"—but it also removes their biggest food source. When temperatures do not soon return to safe levels, the corals simply starve and die. Minor changes in water temperature, i.e., less than 2 degrees Celsius, cause bleaching in a manner analogous to the effects of a 2-degree Celsius fever in humans. With a loss of coral and coral complexity the food chain dynamics change. This can significantly alter the natural ecosystem and can have profound socio-ecological effects in the form of fisheries productivity.

Ocean acidification is another severe existential threat to corals. Approximately 25% of total global CO_2 emissions are absorbed by the oceans[15]. Without this natural carbon sink, greenhouse gas concentrations in the atmosphere would be significantly higher, the planet much warmer and acidity in the ocean much higher.

Since the beginning of the Industrial Revolution, the oceans have experienced approximately a 30 percent increase in acidity due to human caused emissions of CO_2 and other green-house gases. Increasing ocean acidification has been shown to significantly reduce the ability of

[11] Meyer, R., *Since 2016, Half of All Coral in the Great Barrier Reef Has Died,* The Atlantic, 2018 Apr 18; https://www.theatlantic.com/science/archive/2018/04/since-2016-half-the-coral-in-the-great-barrier-reef-has-perished/558302/

[12] Hughes, T. et al, *Global warming transforms coral reef assemblages*, Nature, Volume 556 Pages 492-496, 2018 Apr 18; https://doi.org/10.1038/s41586-018-0041-2

[13] Cave, D and Gillis, J, *Large Sections of Australia's Great Reef Are Now Dead, Scientists Find* The New York Times 2017 Mar 15; https://www.nytimes.com/2017/03/15/science/great-barrier-reef-coral-climate-change-dieoff.html

[14] NOAA Ocean Exploration and Research [internet]; https://oceanexplorer.noaa.gov/facts/oceanproduction.html

[15] NOAA Science on a Sphere [internet]; https://sos.noaa.gov/datasets/ocean-atmosphere-co2-exchange/

reef-building corals to produce their skeletons. In a paper[16] published in 2010, coral biologists reported that ocean acidification compromised the successful fertilization, larval settlement and survivorship of Elkhorn coral, an endangered species. These research results suggest that ocean acidification could severely impact the ability of coral reefs to recover from disturbance. Other research indicates that, by the end of this century, coral reefs may dissolve faster than they can be rebuilt due to the increasingly acidic oceans.

According to the *Reefs At Risk Revisited* report, "reef scientists recommend not only a stabilization of CO_2 and other greenhouse gas concentrations, but also a slight reduction from our current level of 388 ppm (2010) to 350 ppm, if large-scale degradation of reefs is to be avoided." Atmospheric CO_2 concentrations reached a peak of 414.7 ppm in May 2019[17] and continue to increase unabated at alarming rates of around 2 ppm per year, which presents an existential threat to reefs. In the long term, atmospheric CO_2 concentrations must be drawn down to 350 ppm or less. A long-term solution is to achieve global net zero emissions and deploy carbon sequestering technologies, with a 20 year lifespan, that remove up to 50 gigatons (50 billion tons) of CO_2 per year from the atmosphere[18] - a total of 1 trillion tons.

For coral reef restoration and protection to have a meaningful impact, new technologies, methods and business models need to be combined and applied on industrial scales in order to avert predictable catastrophe. The *Great Barrier Reef Outlook Report 2019*[19] itself states that "to protect and restore habitats, species and heritage values, management agencies must complement proven techniques with innovative approaches that are targeted, science-based and risk-managed".

There are two existing coral restoration methods and technologies that complement each other, that, when combined, correctly applied and upscaled to industrial levels, have the potential to 1) significantly accelerate restoration of coral reefs and 2) provide these corals with enhanced resilience against environmental stress factors:

1. *Micro-fragmentation and fusion* ("**MFF**") of corals, and;
2. *Electrolytic Reef Restoration* ("**ERR**")

To-date, there is no record of any research having been conducted on combining these two complementary methodologies in one single research project. By combining these methodologies and deploying them on industrial levels at the Great Barrier Reef and other locations such as the Ningaloo Reef in Western Australia, the potential exists to regenerate declining reefs and boost coral growth rates to counteract environmental stressors that are threatening to wipe them out.

Micro-Fragmentation and Fusion

[16] Albright, R, et al, *Ocean acidification compromises recruitment success of the threatened Caribbean coral Acropora palmata*, Proceedings of the National Academy of Sciences 2010 Nov, 107 (47) 20400-20404 https://www.pnas.org/content/107/47/20400

[17] NOAA Research News [internet] 2019 Jun 4; https://research.noaa.gov/article/ArtMID/587/ArticleID/2461/Carbon-dioxide-levels-hit-record-peak-in-May

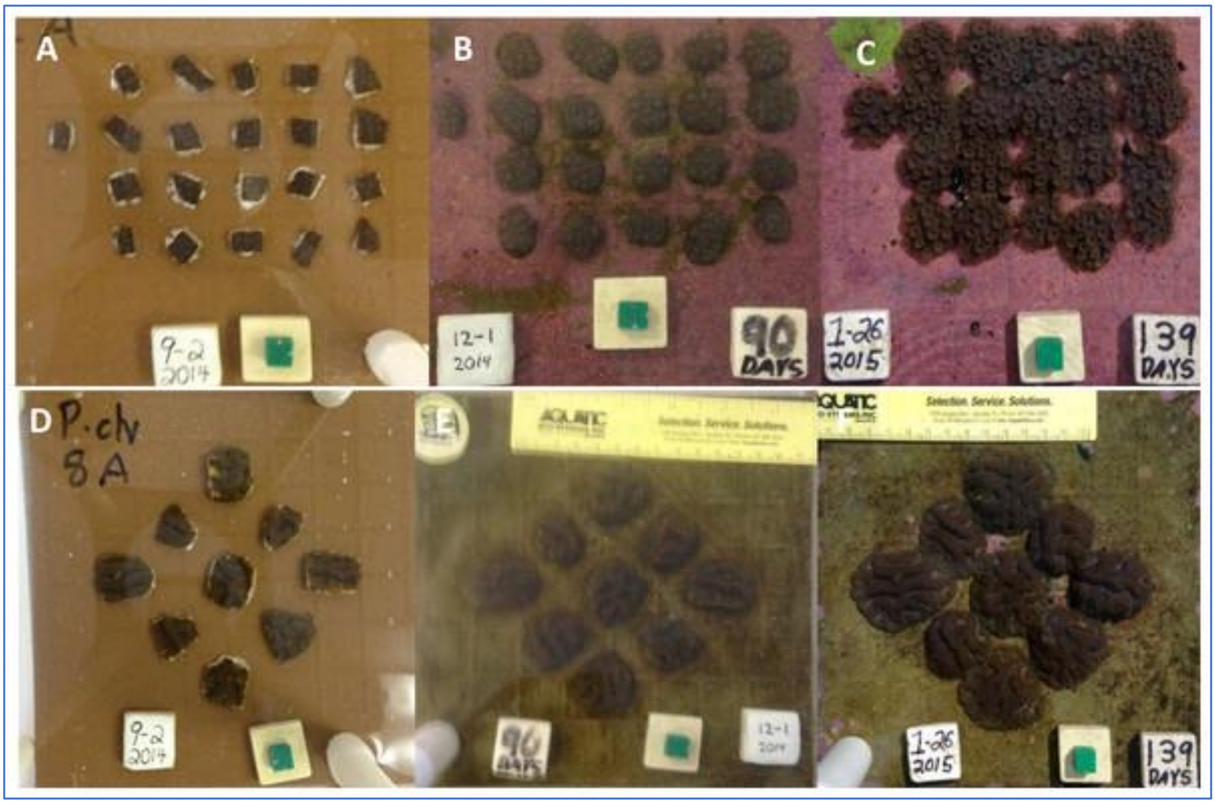
[18] Millison, Dan, (2019) *Commercial Prospects to Combat Ocean Acidification*, Regional Workshop on Blue Economy, Disaster Risk Financing and Ocean Infrastructure, Fiji, 2019 May 01

[19] Great Barrier Reef Marine Park Authority, *Great Barrier Reef Outlook Report 2019,* 2019; http://elibrary.gbrmpa.gov.au/jspui/handle/11017/3474

Micro-Fragmentation and Fusion of corals, originally developed by *Mote Marine Laboratory & Aquarium* in Florida, USA, is elegantly summarised as follows:

> “Micro-fragmentation is a proven scientific technique that consists of breaking the corals into smaller pieces of 1 to 5 polyps, using a specialised saw. This stimulates the coral tissue to grow, allowing them to grow into clones at 25 to 50 times the normal growth rate. The fragments are then placed in their shallow water tanks at 22–26 degrees Celsius. With careful management, after 4-12 months the fully-grown corals are ready to be planted back into the ocean or fragmented again to restart the process.
>
> Using this technique, laboratories can fragment, grow and recombine corals in under 2 years to a size which would normally take 100 years, enabling much faster restoration of reefs. Furthermore, the recombined colonies become sexually mature, which would usually take up to 75 years.”[20]

Figure 1 and Figure 2 below are examples of some of the scientific research of MFF conducted at the *Mote Marine Laboratory & Aquarium*. These results demonstrate that MFF is particularly effective to speed the growth of slow growing brain, boulder and star corals that are crucial reef-building species. Upscaling of MFF to industrial proportions is straightforward, provided that adequate financial resources are made available. The science and methodology are proven, and upscaling laboratories requires a combination of appropriate funding and qualified marine scientists.



[20] Wilson, A., *Microfragmentation: a breakthrough for coral reef restoration* [internet], 2018 Sep 18; https://medium.com/@amykwilson/microfragmentation-a-breakthough-for-coral-reef-restoration-6a2e862c4e2

Figure 1 - ***Orbicella faveolata and Pseudodiploria clivosa fusion experiments.***[21]

(A) Initial fragments of O. faveolata; (B) the fragmented colonies after 90 days; (C) the fragmented colonies at 139 days as colonies begin to fuse; (D) initial fragments of P. clivosa; (E) the same fragmented colonies after 90 days; (F) the fragmented colonies after 139 days as fusion between colonies begins.

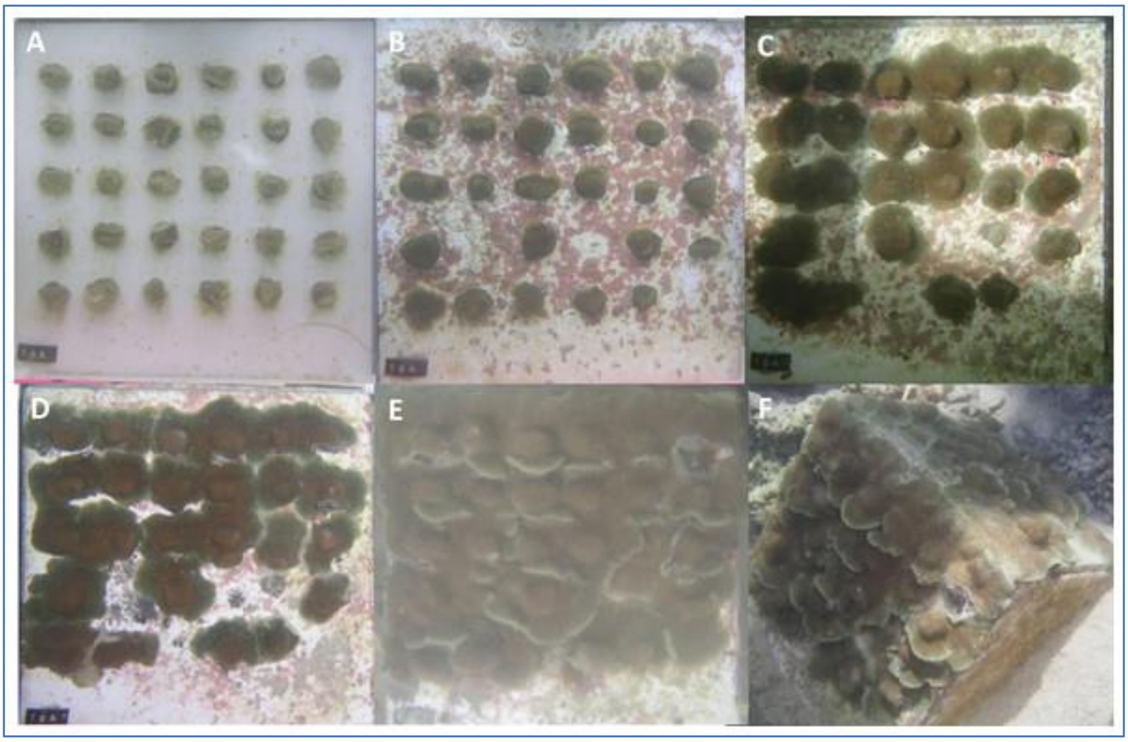


Figure 2 - ***Porites lobata fragments fusing over ceramic tiles***[22]***.***

(A) Thirty fragments were epoxied to ceramic tiles on 6/25/2006, yielding 23 cm^2 of area covered by coral tissue; (B) after 38 days of growth, tissue begins to attach and 3 fragments are lost; (C) after 125 days of growth, tissue begins to come in contact with other colonies; (D) after 205 days of growth, most fragments are fused and area covered by tissue is 178 cm^2; (E) after 368 days of growth the substrate is completely covered; (F) the resulting colony is approximately a half meter in diameter after one year.

Nevertheless, MFF on its own leaves these new laboratory-grown corals just as vulnerable as existing corals to environmental stresses once they are out-planted in the ocean environment. With the application of a complementary technology named Electrolytic Reef Restoration, enhanced resilience to coral bleaching events as well as additional long-term accelerated growth rates may be achieved.

Electrolytic Reef Restoration

Electrolytic Reef Restoration ("**ERR**") is a process of electrolytic deposition of calcium carbonate ($CaCO_3$) from seawater that was pioneered by the late Wolf Hilbertz in the 1970s. He developed the process, called it *Biorock* and patented it in 1979[23]. His original idea was to make sustainable building materials from seawater, which in itself is a very viable

[21] Forsman ZH, Page CA, Toonen RJ, Vaughan D. 2015 Oct 20. *Growing coral larger and faster: micro-colony-fusion as a strategy for accelerating coral cover*. *PeerJ* 3:e1313; 10.7717/peerj.1313/fig-1
[22] Forsman ZH, Page CA, Toonen RJ, Vaughan D. 2015 Oct 20. *Growing coral larger and faster: micro-colony-fusion as a strategy for accelerating coral cover*. *PeerJ* 3:e1313; 10.7717/peerj.1313/fig-1
[23] Patent is now expired

business proposition[24]. The process was inspired by and derived from cathodic protection systems used on offshore oil and gas facilities, where a source of low voltage DC electric current would help to drive the protective electrochemical reaction. It was observed that coral reefs spawned and thrived on the offshore facilities at a rate that seemed higher than normal measured coral growth rates[25]. It is postulated that the enhanced skeletal growth rates occur through an increase in available electrons and enhanced metabolic efficiency of the coral polyps[26]. We use the term *Electrolytic Reef Restoration* as this is a more general term for the application, which includes advances made to the technique by independent practitioners.

There is now over 40 years of ample empirical evidence, mostly obtained by trial and error during in-field experiments, to suggest that with the correct application of ERR, coral reefs grow at a rate 3-4x faster than normal. Whilst active, ERR have demonstrated a 95% survival rate of corals during bleaching events, disease outbreaks and other disturbances[27]. Moreover, higher survival rates of coral transplants grown in the presence of the Electrolytic Reef Restoration have been reported[28]. The principles of ERR are fairly uncomplicated and consist of passing a low-voltage and direct electric current through a cathode and an anode to induce electrolysis through seawater around coral reef habitats as depicted in Figure 3 below.

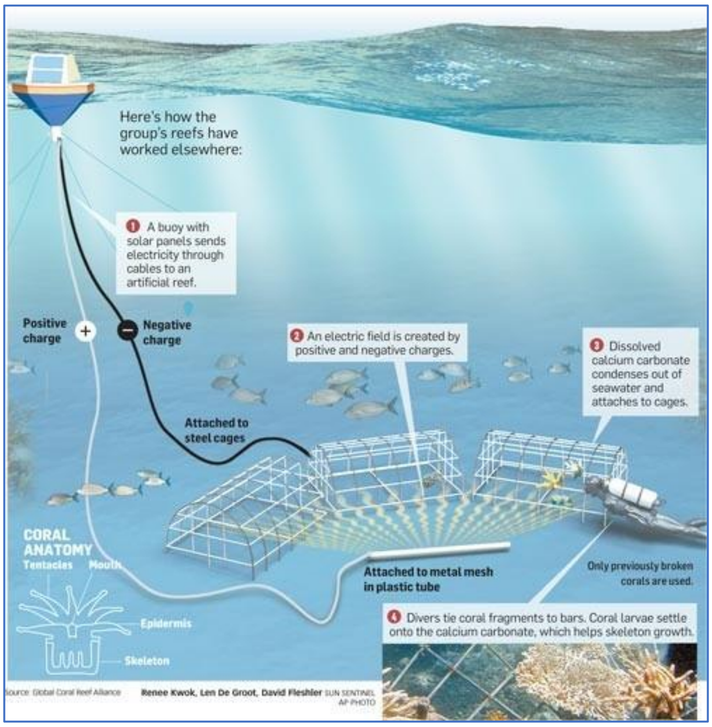


Figure 3 - Overview of Electrolytic Reef Restoration Set Up[29]

[24] Millison, Dan, (2019) *Commercial Prospects to Combat Ocean Acidification*, Regional Workshop on Blue Economy, Disaster Risk Financing and Ocean Infrastructure, Fiji, 2019 May 01

[25] Koster, J., 2017. Electrolysis, halogen oxidizing agents and reef restoration. DO 10.13140/RG.2.2.11469.74725

[26] Hilbertz WH, Goreau TJ (1996) A method for enhancing the growth of aquatic organisms and structure created thereby. http://www.uspto.gov, US Patent # 5,543,034

[27] (Goreau, 2012), Romatzki (2014), Natasasmita *et al.* (2016)

[28] van Treeck and Schuhmacher 1997; Schuhmacher et al. 2000; Sabater and Yap 2002, 2004; Eisinger 2005; Eisinger et al. 2009

[29] Image made with source material from *Global Coral Reef Alliance*, https://www.globalcoral.org/

The electric field will cause a chemical reaction that will allow calcium carbonate ($CaCO_3$, limestone) to form using dissolved calcium and mineral ions from the seawater, that then accumulate onto pre-made metallic structures that function as the cathode. Through this electrolytic mineral accretion, the structures become more massive and capable of surviving storms and other damage. Moreover, the electric power protects the metallic frames from corrosion. The low-volt electric field is harmless to marine life itself and scuba divers. The theoretical yield of ERR is about 1 US ton $CaCO_3$ per megawatt-hour (MWh) of electricity. However, empirical data shows that, on average, actual yields are 50-60% of the theoretical yield.

Calcium carbonate ($CaCO_3$) is the basic compound of coral reefs and other key marine organisms such as molluscs. Using the *Electrolytic Reef Restoration* for accelerated reef restoration by following the common method of coral gardening[30] involves 2 key steps:

(i) Growing $CaCO_3$ on metal frames in seawater using an electric field; and

(ii) propagate broken off but still living coral fragments ("Corals of Opportunity") onto this continued depositing $CaCO_3$ substrate, onto which the coral pieces will accrete and fuse.

Figure 4, Figure 5 and Figure 6 are examples from a project in the Maldives where "Corals of Opportunity" have been propagated onto a ERR cathode using the coral gardening method.

Figure 4 - Examples of accelerated coral growth and enhanced resilience[31]

[30] Coral gardening, or asexual coral propagation, methods use fragments of corals that are generated by disturbances ('corals of opportunity') and may include fragments broken from storms, anchoring, or vessel grounding. Fragments are transported to a nursery where they are grown for several months and can then be replanted.
[31] Image courtesy of Coralive.org; https://coralive.org/

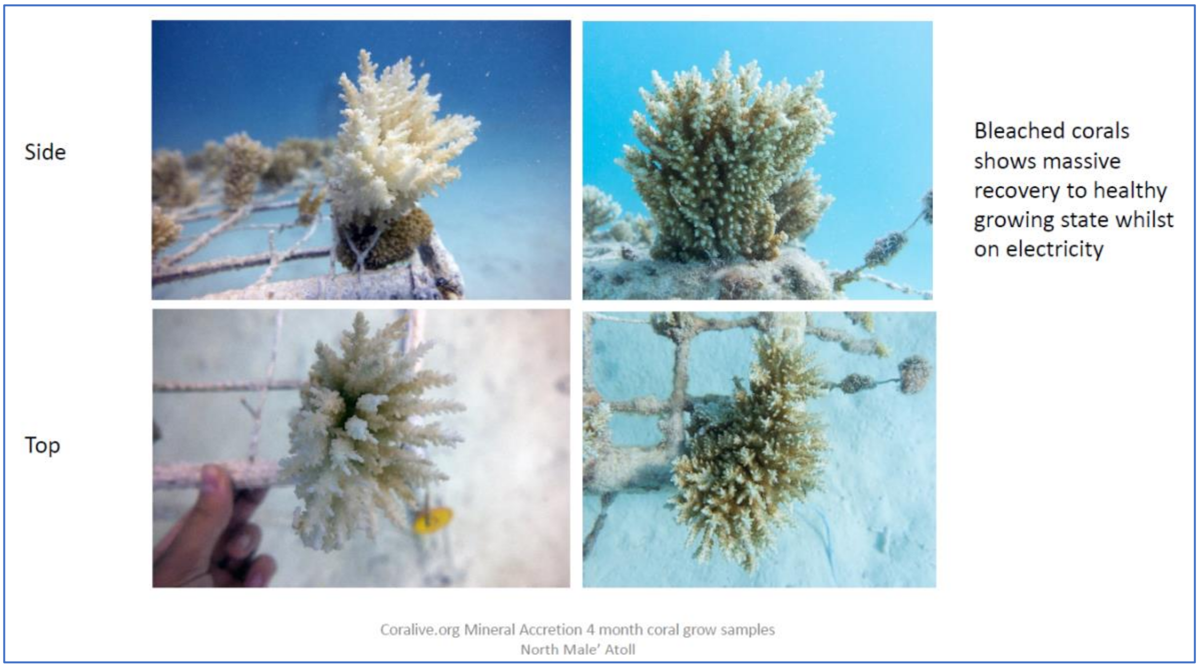


Figure 5 - Examples of accelerated coral growth and enhanced resilience[32]

Figure 6 - Example of electrically stimulated Corals of Opportunity out planted over bleached reef [33]

[32] Image courtesy of Coralive.org; https://coralive.org/

[33] Image courtesy of Coralive.org; https://coralive.org/

The challenge: upscaling Micro-Fragmentation and Fusion and Electrolytic Reef Restoration to Industrial Levels

There are several challenges that need to be addressed prior to justifying the capital investments required for upscaling accelerated reef cultivation using ERR to industrial levels, all of which are readily achieved provided sufficient resources are made available:

1. Mostly empirical data and insufficient long-term comprehensive scientific data

   Based on empirical data, if the electric field is present and correctly applied, corals benefit from a 3-4x accelerated growth rate (depending on species) for at least the first 2-3 years, with limitations on available data. The absence of long-term scientifically obtained data causes the longer-term effects to be unquantified beyond this initial early phase. Although ample empirical data demonstrates the viability of the ERR method to enhance resilience to coral bleaching events, insufficient scientific research has been conducted with few peer-reviewed publications[34,35,36] to consider the technology to be "proven" and supported by the global marine science community. As a result, many coral restoration scientists are sceptical of the long-term viability and benefits of the technology. There are also marine scientists that actively discredit ERR as a viable method for coral reef restoration.

   This can be addressed by initiating a long-term research project with leading international research institutes and using proper and statistically sound field methodologies, to gather scientific data that is subjected to peer review. This new scientifically verified data will 1) provide the scientific evidence of what the longer-term potential of ERR can be (of a subset of coral species at a specific location within the reef tract), 2) provide enough quantitative data that a simple correlation between coral growth rate and resilience to elevated water temperatures and energy provided (kWh) can be extrapolated. From this data, a scientifically supported cost-benefit ratio for industrial scale deployment of MFF & ERR can be deduced.

2. Constant, reliable, cost effective, renewable power at the coral reef sites

   Providing the necessary regulated power offshore in remote areas over long periods is not surprisingly very challenging due to the harsh ocean operating environment. Fluctuation and spikes in electrical currents and voltages, or applying altogether incorrect voltages, have proven to kill the corals. Efforts to-date have been predominantly done by adapting standard off-the-shelf onshore solar panels for offshore use. Naturally, given the harsh conditions encountered offshore, these systems only last for a limited period of time and limited funding is often insufficient for longer term research. In other instances, power has been provided by onshore (fossil fuel) generation with a cable to the offshore sites, which method only adds greenhouse gases to the atmosphere and further aggravates the situation for the corals. Coral restoration using ERR can be achieved using very cost-effective solar

[34] Romatzki, S. B. C. (2014). Influence of electrical fields on the performance of Acropora coral transplants on two different designs of structures. *Marine Biology Research*, *10*(5), 449-459.
[35] Munandar, Mahendra, Rizal, Rani, Faizal, 2018. The escalation of coral growth by biorock technology applied in Sabang marine ecotourism. AACL Bioflux, 2018, Volume 11, Issue 5. http://www.bioflux.com.ro/aacl
[36] van Treeck, P., & Schuhmacher, H. (1999). Artificial reefs created by electrolysis and coral transplantation: an approach ensuring the compatibility of environmental protection and diving tourism. *Estuarine, Coastal and Shelf Science*, *49*, 75-81.

panels on land, but this would only be practical in those areas where reefs are very close to the shoreline and not feasible for the Great Barrier Reef.

The challenge of providing reliable, affordable renewable energy in saltwater environments is being addressed by a number of commercial companies that are now offering commercially available systems, as well as other new systems being developed that are currently in early stage development. Systems have been developed specifically for remote and harsh offshore environments that can be deployed in any global location and based on wave tank testing can withstand up to 13-meter waves. With mooring systems adapted from the offshore oil and gas industry, these systems are designed to withstand the extreme forces of hurricane and typhoon conditions. These systems are small, robust, modular, transportable and once mass produced on industrial scales will be very cost effective, with a predicted cost all-in installed and operational under USD 0.10/kWh.

3. Labour intensive propagation of corals onto metal frames

The ERR method causes limestone to grow on metal structures that in the current established methodology are made of reinforcement bars ("rebar") which are commonly used for cast-in-place concrete. Currently, applied methodology for coral reef restoration using ERR entails having scuba divers attach coral recruits to metal structures (typically dome-shaped) made of rebar, as depicted in Figure 3 above. This process is cumbersome in the underwater environment, time consuming, costly and challenging to scale up to industrial proportions.

There are several conceptual solutions to design ERR reefs and scale them for functional, aesthetic and streamlined process. Perhaps it is beneficial to integrate other materials that would allow for reduction in metal and electrification, offer more surface area and diversity in design and biodiverse organism recruitment.

To reduce the time spend under water, perhaps MMF-grown coral recruits can be attached to rebar-domes onshore and then transported and installed in the ERR area, eliminating the complexity of requiring this to be done underwater. A step further would be to develop a methodology whereby rebar domes are replaced with wire mesh structures, the coral fragments attached to these metal wire mesh structures in an onshore laboratory and the entire mesh rolled up, transferred and positioned on the seabed in the ERR electrified area. The challenge is to develop a scalable method in which the corals survive the process from shore-base to the ocean environment. Finally, it is worth investigating whether there is a need for cathodic metal structures at all, and whether just creating an electrical field is in itself enough to enhance coral growth rates.

All solutions proposed will need to be field-trialled to determine whether they are realistic and cost-effective.

4. Adequate funding and Political Will

Coral ecosystems are capital assets that provide benefit in the form of goods and services. Therefore, if managed, they yield flows of vital services and should be treated like other assets of material value and accounted for in their essential contribution to current and future economic well-being[37]. Global environmental needs and the commercial importance of the Great Barrier Reef to Australia are well established. Two of the more significant existential threats to the Great Barrier Reef, ocean acidification and coral bleaching due to rising sea water temperature, are a direct result of human-caused global warming, predominantly caused by the most developed and industrialized nations. In August 2019, there was a swift response by the G7 countries to the fires in the Amazon rainforest with immediate logistical and financial assistance[38]. Coral bleaching, in effect, is the same as the Amazon fires, though below the surface of the water the destruction is not immediately apparent. Similarly, the rapid response of the G7 countries in August 2019 to these Amazon rainforest fires, with a proven methodology of deploying coral reef restoration and protection on an industrial level, necessary funding could be provided by G7 & G20 countries to augment the funding commitment of the Australian government. Given the momentum that is being gained globally in addressing climate change related issues, it is envisaged that with proven scientific evidence and a cost-effective industrial scale solution, the political support and funding will be obtainable. Like any political support, this will not be without challenges and will require intensive lobbying with the support of the marine science community and the general population.

Nevertheless, a business case needs to be developed that demonstrates that investing annually at a steady rate in accelerated coral reef restoration and protection makes economic sense due to the extensive impact on tourism, fishery and other directly related economic activities. In countries where 15% of GDP is directly related to coral reefs, the need and desire is likely going to be even greater.

The Potential: integrating MFF & ERR for super-charged coral growth rates on industrial levels

MFF and ERR each show results for corals to grow at substantially increased rates. Combining the two methodologies could potentially have a compounding effect for greater growth rates, but needs to be scientifically researched. The process, conceptually, entails growing micro-fragmented corals on metal structures, designed to integrate into nature, in water tanks in a laboratory environment that are subjected to a ERR electrical field. Once the coral recruits are fused and grown sufficiently, the entire metal frame can be transferred to the seabed in a predetermined location subject to a ERR electrical field. This logistical step alone would eliminate the cumbersome underwater out-planting of MFF and coral fragment attachments in the ERR methodology. Even though as this point still a hypothesis that needs to be tested and proven to be a certainty, the out-planted metal frames and the laboratory-grown corals potentially could sustain continued accelerated growth rates over extended periods as well as benefitting from significant resilience during coral bleaching events. We predict in less than two years the metal frames would be completely overgrown and invisibly blend in with the coral ecosystem.

[37] Barbier, E. B. *Wealth accounting, ecological capital and ecosystem services*. Environment and Development Economics (2013), *18*(2), 133–161; https://doi.org/10.1017/S1355770X12000551
[38] BBC News [internet], 2019 Aug 26; https://www.bbc.co.uk/news/world-latin-america-49469476

To achieve industrial level deployments of corals for coral reef restoration, where several Hectares (1 Hectare = 100 m x 100m ≅ 2.5 acres ≅ 2 football fields) of corals are out-planted in the ocean daily, significant investment will need to be made in the following:

(i) Large-scale dedicated coral larvae growing laboratories using MFF;

(ii) manufacturing facility for the offshore floating solar platforms as close to the reef sites as possible; and

(iii) dedicated installation vessels for installation of ERR systems that could simultaneously deploy the offshore floating platforms, the mooring systems and the metal frames with the MFF grown coral recruits.

There are several other initiatives that could complement and further increase the effectiveness of the combined MMF & ERR, such as “LarvalBot”, which is an underwater robot that collects coral larvae and redistributes it to areas in need of restoration[39]. Releasing mass quantities of coral larvae across fields of MMF & ERR grown corals possibly would allow these coral larvae to settle on the ERR structures and grow 3-4x more rapidly and reach sexual maturity much faster.

Using MMF & ERR on industrial scale is one of a number of coral interventions for restoring and protecting coral reefs. A growing body of research on "coral interventions" aims to increase the ability of coral reefs to persist in rapidly degrading environmental conditions. Those interventions include activities that affect the genetics, reproduction, physiology, ecology, or local environment of corals or coral populations. A first report[40] reviewed the current state of the science for 23 novel interventions. This report provides a decision framework to help managers assess and implement interventions that are suitable for their region and goals. MFF & ERR in combination with a number of additional proven a new methodologies has the potential to help corals adapt to climate change conditions with enhanced growth and survival rates.

The next step: scientific research to validate benefits of combined MFF & ERR

As a first step to developing industrial scale combined MFF & ERR for deployment on the Great Barrier Reef, an initial 5-year research study to scientifically document and quantify the effects of combined MFF & ERR on coral reef growth and protection is required. Such a study would need to be a collaboration between universities, NGOs, private companies and a consortium of funding partners. Such a study would require a commitment budget of around USD 10 million for the total duration of five years and an initial capital investment of USD 2.5 million for the technology and USD 1.5 million annual research & operating costs.

This funding would cover 2-4 simultaneous research projects, with similar objectives, one in East Australia for the Great Barrier Reef, the other in Western Australia for the Ningaloo Reef. This would allow each of the research projects to focus on the most successful, future-proof (read: fastest growing and most temperature resilient) coral species that are specific to each

[39] Queensland University of Technology [internet], 2018 Nov 1; https://www.qut.edu.au/science-engineering/about/news?id=137694

[40] The National Academies of Sciences, Engineering, and Medicine, *A Decision Framework for Interventions to Increase the Persistence and Resilience of Coral Reefs*, 2019; http://dels.nas.edu/Report/Decision-Framework-Interventions/25424

particular reef province and would provide additional scientific data for correlation. Additional research projects could then be rolled out on each of the largest reef tracts in the world as listed in Table 1 below.

	Coral Reefs	Length	Location
1	Great Barrier Reef	1,553 miles	Coral Sea, North East Australia
2	Red Sea Coral Reef	1,180 miles	Red Sea, Israel/Egypt/Djibouti
3	New Caledonia Barrier Reef	932 miles	Pacific Ocean, New Caledonia
4	Mesoamerican Barrier Reef	585 miles	Caribbean Sea, Mexico/Belize/Guatemala/Honduras
5	Great Chagos Bank	310 miles	Indian Ocean, The Maldives
6	Florida Reef	200 miles	Gulf of Mexico, Florida Keys
7	Ningaloo Reef	162 miles	Indian Ocean, Western Australia
8	Andros Coral Reef	124 miles	Atlantic Ocean, Bahamas
9	SE Asia Coral triangle	100's of miles	Indonesia, Malaysia, Papua New Guinea, Philippines, Solomon Islands, Timor-Leste (e.g. Takabonerate atoll South Sulawesi; Raja Ampat Islands, Indonesia)

Table 1 – List of Large Coral Reef Tracts in the World[41]

Comparison of growth rates in laboratory conditions and in-field observed conditions, with the necessary control groups, would present conclusive data that would be a prerequisite in order to start lobbying to obtain the associated significant capital investments for upscaling the combined methodologies to industrial levels.

Conceptually, a consortium of several if not all of the following entities could collaborate to undertake the initial research projects:

Entity	**Envisaged Role**
Australian government	Funding, permits, approvals
G7/G20 countries	Funding
Ocean Life Foundation	Funding
Greater Barrier Reef Marine Park Authority	Project co-ordination, supervision, monitoring & execution
Asian Development Bank	Funding partner and/or coordinator
Commercial offshore solar EPC providers	Research partner & technology supplier

[41] Adapted from Sheth, Khushboo. *The Longest Coral Reefs In The World*, WorldAtlas, 2017 Apr 25; https://www.worldatlas.com/articles/the-longest-coral-reefs-in-the-world.html

Australian Institute of Marine Science	Research partner
Centre for Marine Science, Queensland University	Research partner
James Cook University	Research partner
University of West Australia	Research partner
Mote Marine Laboratory, Florida	Research partner
Rosenstiel School of Marine and Atmospheric Sciences, University of Miami	Research partner
Hawaii Institute of Marine Biology	Research partner
Rice University	Research partner
Florida Institute of Technology	Research partner
Bermuda Institute of Ocean Sciences	Research Partner
International Coral Reef Initiative	Observer, global awareness of project
National Coral Reef Institute	Observer, global awareness of the project
Coral Reef Alliance	Observer, global awareness of the project
Sir David Attenborough	Documentary, global awareness
Sylvia Earle, National Geographic Society	Documentary, global awareness

Table 2 - MFF & ERR Potential Research Consortium Participants

The goal: industrial level restoration and protection of the Great Barrier Reef

The Great Barrier Reef is an area of 344,400 km^2, approximately half the size of Texas. The average depth is 35 meters, but the continental shelf on the east slopes down to 2,000 meters. According to the Great Barrier Reef Marine Park Authority, coral reefs account for only 7% of the area[42], approximately 24,108 km^2. Different corals species grow at different depths. According to marine scientist studies[43], near-sea-surface coral reefs ("**NSS**") cover a total area of 20,679 km^2 in the Great Barrier Reef with a mean depth of 14.9 m. These NSS shallow reefs account for 85% of the coral reefs in the Great Barrier Reef and most likely account for most of the tourism related activities as they are easily accessible for swimmers, snorkelers and scuba divers. Due to their shallowness, these NSS coral reefs are also at greatest risk of warm water induced coral bleaching. It can be concluded that approximately 50% has died during the back-to-back coral bleaching events of 2016 and 2017[44].

Industrial scale deployment of combined *Micro-Fragmentation and Fusion* and *Electrolytic Reef Restoration* can make meaningful impact on restoring and protecting these immense

[42] Great Barrier Reef Marine Park Authority [internet]; http://www.gbrmpa.gov.au/the-reef/reef-facts
[43] Harris, P. et al, *Submerged banks in the Great Barrier Reef, Australia, greatly increase available coral reef habitat*, ICES Journal of Marine Science, Volume 70, Issue 2, March 2013, Pages 284-293; https://doi.org/10.1093/icesjms/fss165
[44] Hughes. T et al., *Global warming transforms coral reef assemblages.* Nature 556, 492-496 (2018). https://www.nature.com/articles/s41586-018-0041-2

coral reefs in the Great Barrier Reef. The cost of industrial scale ERR[45] is a total one-time capital investment of USD 0.99/m^2 for a 25-year project, of which the energy system accounts for approximately two-third and the rebar cages about one-third. Due to the extensive areal extent of the Great Barrier Reef, this results in large capital investment requirements. If twenty percent (4,136 km^2) of the NSS area of the Great Barrier Reef were to be restored and protected with ERR, it would require a total of 1,034 MW_p of power to be installed and coupled to rebar structures, with a corresponding approximate total investment of USD 4.1 billion (€3.7 billion). This initial investment required equates to 4.0% of the total direct revenue generated by the Great Barrier Reef over a 25-year period.

It is estimated that this investment for industrial scale deployment of combined *Micro-Fragmentation and Fusion* and *Electrolytic Reef Restoration* will create around 2,000 direct jobs and 8,000 indirect jobs in Queensland in manufacturing, installation, monitoring, research and all the support services required. Once the added economic benefits that healthy resilient coral reefs bring to the economy as well as helping to preserve the significant tourism-related income of the Great Barrier Reef, it demonstrates a significantly compelling value proposition.

Coral Reefs and the Blue Carbon Budget

Industrial scale MFF & ERR will actively grow corals at an accelerated pace and provide resilience against future coral bleaching events. They also create Megatons of calcium carbonate annually, sequestering a total of 0.4 Megaton of CO_2 annually for every Megaton of calcium carbonate in the process[46], at least as long as pH stays above 7.9. If this sequestering of CO_2 by corals is permanent in the same manner as mangroves, seagrasses and saltmarshes do, this would contribute to the so-called 'blue carbon' budget[47] (carbon sequestered in coastal ecosystems). Coral reefs are not currently included in the blue carbon budget, as it is unclear what their carbon-sequestering properties are [48]. However, global estimates of the coastal ocean CO_2 uptake and release (including coral ecosystems) contain large uncertainties[49]. CO_2 fluxes can vary pronouncedly both spatially and temporally, where the system sometimes act as a net source[50], sometimes as a net sink[51]. If indeed coral ecosystems are important for the global storage of carbon, then theoretically, for each US ton of limestone created by ERR, 0.44 US ton of CO_2 is permanently sequestered directly out of the seawater.

[45] Details of assumptions and calculations are provided in Appendices 3, 4 & 5
[46] 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.
[47] Howard, J., Hoyt, S., Isensee, K., Pidgeon, E., & Telszewski, M. (2014). Coastal blue carbon. Conservation International, 36(1), 180.
[48] Suzuki & Kawahata, 2003. Carbon budget of coral reef systems: An overview of observations in fringing reefs, barrier reefs and atolls in the Indo-Pacific regions. Tellus B 55(2):428 - 444 · May 2003. DOI: 10.1034/j.1600-0889.2003.01442.x
[49] Regnier, P., et al., 2013. Anthropogenic perturbation of the carbon fluxes from land to ocean. Nat. Geosci. 6 (8), 597–607
[50] Suzuki, A., Kawahata, H., Ayukai, T., Goto, K., 2001. The oceanic CO2 system and carbon budget in the great barrier reef, Australia. Geophys. Res. Lett. 28 (7), 1243–1246. Takahashi, T., Olafsson, J., Goddard, J.G., Chipman, D.W., Sutherland, S.C., 1993.
[51] Shaw, E.C., McNeil, B.I., 2014. Seasonal variability in carbonate chemistry and air–sea CO2 fluxes in the southern great barrier reef. Mar. Chem. 158, 49–58.

Summary

Combining the complementary methodologies of *Micro-Fragmentation and Fusion* and *Electrolytic Reef Restoration* and deployed on an industrial scale, coral reefs might be able to grow at a rate faster than climate change events is killing them. With underlying scientific data obtained from a collaborative international research project, it would be envisaged that the proven effective combination of the MFF & ERR methodologies could be deployed not only on the Great Barrier Reef, but also at all of the large reef tracts in the world and the countless small islands in South East Asia, the Pacific and the Caribbean.

In order to prevent the terminal decline of the Great Barrier Reef and coral reefs globally, reduction of atmospheric CO_2 concentrations from our current level of 414 ppm (2019) to 350 ppm needs to be achieved. The long-term solution is not only to get to global net zero emissions, but to also deploy CO_2 sequestering technologies that could remove up to 50 billion tons (50 gigaton) of CO_2 per year from the atmosphere and the ocean for around 20 years.

Powered by offshore floating solar systems, industrial scale deployment of Micro-Fragmentation and Fusion in combination with Electrolytic Reef Restoration on the Great Barrier Reef is cost effective and only a fraction of the revenue generated by economic activities directly associated with the Great Barrier Reef. The global benefits for the planet's future health are not only unquantifiable, they are essential.

In order to achieve these ambitious objectives, a relatively small initial investment (USD 10 million) needs to be made now to obtain the scientific data to validate the sustainable accelerated coral growth rates. This is a fraction of the AUD 700 million (USD 481 million) that the Australian government has committed to The Reef Trust[52] for improving coastal habitat and water quality of the Great Barrier Reef. With the scientific evidence, the political will needs to be obtained to invest significantly in MFF & ERR over extended periods of time. Without it, the Great Barrier Reef may likely face certain death by 2050.

[52] Department of the Environment and Energy, Australian Government [internet] https://www.environment.gov.au/marine/gbr/protecting-the-reef

Appendix 1

Great Barrier Reef Facts & Figures[53]:

- The Great Barrier Reef is classed as the single largest living organism in the world, spanning a total distance of over 2,300km from the Torres Strait in the North to Bundaberg in the South
- The Great Barrier Reef is comprised of over 900 individual islands
- The widest sections of the Great Barrier Reef reaches over 65 kilometres
- Over 1,500 species of tropical fish, 400 different types of coral, 200 types of birds and 20 types of reptiles are just some of the lifeforms which inhabit the reef
- The Great Barrier Reef is one of the few Australian features that can be seen from space
- The Great Barrier Reef is a UNESCO World Heritage area and listed as one of the "Seven Natural Wonders of the World"
- The Great Barrier Reef covers an overall area that is larger than the size of Italy
- The Great Barrier Reef draws over a million international visitors each year
- In terms of the Australian economy, the Great Barrier Reef alone generates over AU$ 6 billion dollars' worth of revenue per year
- The depth of the reef ranges from 35 metres inshore to 2,000 metres depth on the outer reef.
- Around 10 percent of the world's total fish species can be found just within the Great Barrier Reef

[53] (https://greatbarrierreef.com.au/information/great-barrier-reef-facts/)

Appendix 2

About the Authors

Harald VAN HOEKEN, BSc

Harald van Hoeken obtained Bachelor's of Science degrees in both Aerospace Engineering and Ocean Engineering (1993, Florida Institute of Technology) and has 25 years' experience in West Africa in oil & gas investments, oil field exploration and production services and mining. He is the founder and CEO of Precision Energy Group, a natural resources and renewable energy advisory company. He is the Co-Founder of the Ocean Life Foundation, a newly established foundation that is dedicated to the research and development of new technologies for the restoration and protection of coral reefs.

Brigitte VLASWINKEL, PhD

Brigitte Vlaswinkel is Research Director at Oceans of Energy. She holds a PhD in Marine Geology and Geophysics (2007, University of Miami) and has extensive experience in the academic, corporate, consulting and not-for-profit sectors. She is responsible for searching out strategic R&D projects and partners worldwide, as well as developing in-house research and environmental monitoring programs around offshore floating solar technology. She is a UNESCO chair (IGCP) and Marine Spatial Planning Expert of the IOC (Intergovernmental Oceanographic Commission).

Dan MILLISON, MSc

Dan Millison is the Manager of Transcendergy L.L.C., a private consultancy established in 2008 to provide sustainable infrastructure solutions. He holds a M.S. in Civil Engineering (1986) and a B.A. in Geological Sciences (1981), both from Northwestern University in Evanston, Illinois. He has helped mobilize well over $10 billion investment in energy and transport infrastructure in developing countries in the Asia-Pacific region, including more than $1 billion of co-financing from the Clean Technology Fund, the Scaling Up Renewable Energy Program, and the Green Climate Fund. He was formerly a senior energy specialist at Asian Development Bank, and previously worked in the environmental services and oil and gas industries.

About the Contributing Authors

Francesco RICCIARDI, PhD

Francesco is an environmental scientist with work experience in academy, NGOs, consultancy companies and multilateral financial institutions. Actually based in Manila with the Asian Development Bank, he is working to fill the gap between scientists and policy and decision makers, pushing new technologies and innovative ideas to make a difference in the development world.

John W. KOSTER, Msc

John Koster is a Research Fellow at the Ocean Sciences Department of the University of California, Santa Cruz. This came about from a decision to return to his academic roots after a 31 year career as an officer of the U.S. Coast Guard, where he served in various mission areas including as a helicopter Aircraft Commander, Chief of the Pacific Area Environmental

Response Branch, and as Commanding Officer of both of the USCG's overseas regional offices. He also recently got underway for two legs of 50' motorsailer catamaran ORV ALGUITA's oceanographic expedition to the South Pacific Gyre, documenting the problem of plastics in the ocean. His interests in coral reef ecology date from service as a Peace Corps Volunteer marine biologist in East Africa during the late 1970s, and his current studies are concentrated upon applications of weak DC seawater electrolysis to mariculture, reef restoration, coast protection and alternative energy processes.

Dr. Geoffrey SWAIN, PhD

Dr. Geoff Swain is Professor of Oceanography and Ocean Engineering and the Director of the Center for Corrosion and Biofouling Control at the Florida Institute of Technology (FIT). He started his career at the University of Southampton, UK to develop novel methods for corrosion and biofouling control for the Royal Navy and the Department of Energy. In the early 1980’s he moved to Aberdeen, Scotland where he joined a company that conducted corrosion and biofouling surveys on offshore structures in the North Sea. He joined FIT in 1984 and established the Center for Corrosion and Biofouling Control. The Center is fully staffed, has a laboratory on campus, static and dynamic seawater test facilities at Port Canaveral, two research boats and has active research grants with the Office of Naval Research and the shipping and coatings Industries. Notable accomplishments include the design of the cathodic protection system for the Living Seas at Disney World, developing an ASTM method for evaluating fouling release coatings, establishing a quality control procedure for dry docking and fouling control coatings for Royal Caribbean International, and pioneering the development of in-water grooming to maintain ship hulls in a smooth and fouling free condition. He has published over 50 refereed articles on the subject. He is a member of the National Association of Corrosion Engineers, the Society of Naval Architects and Marine Engineers, the American Society for Testing and Materials and the Marine Biological Association of the U.K.

Ahmad ALLAHGHOLI, Msc

Ahmad Allahgholi, “Aki”, has dedicated his energy and talents to marine conservation initiatives around the globe since 2011, from serving as Program Manager for marine conservation NGO, Reefdoctor in Madagascar, to Project Manager for a Philippine-based NGO working on coral reef restoration, MPA management, and alternative livelihood solutions. Armed with a master’s degree in “Sustainable Natural Resource Management” and a thesis in “Coral Reef Restoration” from the United Nations mandated University for Peace in Costa Rica, he is always searching for new knowledge and learning best practices to share. Over the past years, Coralive.org have successfully restored (over 5000m^2 of) corals in Jamaica, Maldives, Seychelles and the Philippines using the Electrolytic Reef Restoration Technique.

Chris HAVER, Bsc

Chris Haver is based in Los Angeles, has a BSc in Finance, attended the University of Southern California and San Diego State University. He is the founder of H4 Capital Partners, a U.S. based private equity firm that invest in sustainable projects in the developing world, specifically focused on South East Asia and Africa. H4 Capital Partners has investments numerous clean energy companies seeking to reduce the cost of electricity, food and forestry products. Chris arranged a USD 20 million Concessional Loan from ADB to the benefit of a small start-up from Thailand to provide solar power to under-served areas of the Philippines and subsequently from other investors an additional USD 400 million in debt and equity. H4 Capital is currently working to provide 1 million families in Mozambique with electricity using PV/Charger/Battery on a PAYGO model to address the nearly 75% of the population lacking grid connectivity. He is the Co-Founder of the Ocean Life Foundation, a newly established foundation that is dedicated to the research and development of new technologies for the restoration and protection of coral reefs

Mike MCDOWELL, Msc

Mike was born & educated in Australia. He obtained a BSc in Economics from Australia National University and a MSc in Astronomy and Astrophysics from Swinburn University. His career began on MacQuarie Island as a geophysicist with an Australian expedition in 1971. He would go on to found Quark Expeditions and pioneer tourism transit to the polar regions with Russian icebreakers. In the late 1990s, he sold Quark in order to focus on new ventures in space travel and deep ocean exploration. He currently serves on the board of Space Adventures which offers space travel to the general public and operates Deep Ocean Expeditions which has coordinated dive expeditions to the Titanic, the Bismarck, and the Mariana Trench.

Appendix 3

List of Conversions & Assumptions Used in Calculations

Conversions

- 1 US Ton = 0.907 Tonne
- 1 billion US Ton = 1,000 US MegaTon = 1,000,000,000 US Ton
- 1 km^2 = 100 Hectare
- 1 Hectare (Ha) = 10,000 m^2= 100m x 100m ≅ 2 football fields
- 1 Hectare (Ha) = 2.47 acres

Assumptions

- 1 AU Dollar = 0.7 US Dollar (as at 09 September 2019)
- 1 Euro = 1.1 US Dollar (as at 09 September 2019)
- 1 kW_p installed solar power generates 1,700 kWh of usable electricity per year offshore at the Great Barrier Reef[54]
- Based on ERR requiring 1 Amp/m^2 of metal exposed area at 6V DC, 1 kW_p installed solar power can cover 4,000 m^2 (~63m x 63 m; or 50m x 80m the area of a small football field) using 125 5m x 5m rebar domed structures
- 1 offshore solar platform has 4.2 kW_p power installed
- Cost of 1 offshore solar platform mass produced and installed on industrial scale is €10,000 per platform all-in installed and operational – effectively €2,381 (US $2,620) per kW_p installed
- Cost of rebar is USD 425 per US Ton; based on 8 rebars of 5.6m each, each dome-shape cathode occupies 25 m^2 (5m x 5m) which equates to USD 0.33/m^2

[54] https://globalsolaratlas.info/?c=-19.626015,148.162968,8&s=-19.089617,147.967229

Appendix 4

Summary of Calculations

Inputs	Value	Units
Theoretical yield of MAP	1.0	US Ton CaC03/MWh
CO2 sequestration by MAP	0.44	US Ton CO2/US Ton CaCO3
Empirical observed MAP yield	50%	of theoretical
Annual energy yield from solar	1,700	kWh/kWp/year
Power per OOE platform	4.2	kWp/platform
Cost of OOE platform installed & operational	€ 10,000	€/platform
Cost of OOE platform installed & operational	€ 2,381	€/kWp
Coral reef area restored with MAP	4,000	m2/kWp
Cost of rebar#3 for MAP dome-cathodes & anode	USD 0.33	USD/m2
System operational design life	25	years
Total surface area of the Great Barrier Reef	344,400	km2
Total area of coral reefs in the Great Barrier Reef	24,108	km2
Total surface area of Near Sea Surface Reefs in the Great Barrier Reef	20,679	km2
Euro to USD exchange rate	1.11	USD/Euro
AUD to USD exchange rate	1.45	AUD/USD
Cost of MAP		
Cost of Energy requirement	€ 0.60	€/m2
Cost of anodes & cathodes	€ 0.30	€/m2
Total cost of MAP - Euro	€ 0.89	€/m2
Total cost of MAP - USD	€ 0.99	USD/m2
Total cost of MAP - AUD	€ 1.44	AUD/m2
Investment		
Required Area of NNS in GBR with MAP	20.0%	percent of total GBR NSS
Required Area of NNS in GBR with MAP	4,136	km2
Required Area of NNS in GBR with MAP	4,135,800,000	m2
Required power for MAP area	1,033,950	kWp
Required power for MAP area	1,034	MWp
Total Investment required - Euro	EUR 3,691,347,876	Euro
Total Investment required - USD	USD 4,097,396,143	USD
Total Investment required - AUD	AUD 5,941,224,407	AUD
Investment as % of 25-year GBR revenues	4.0%	percent
Carbon Sequestering Yields (US Ton)		
Annual energy yield	1,757,715,000	kWh/year
Annual energy yield	1,757,715	MWh/year
Annual theoretical CaCO3 yield	1,757,715	US Ton/year
Empirical adjusted anticipated annual CaCO3 yield	878,858	US Ton/year
Annual anticipated annual CO2 sequestration	386,697	US Ton/year
Total anticipated CO2 sequestration	9,667,433	US Ton CO2
Effective cost of CO2 sequestration	USD 424	USD/US Ton CO2
Carbon Sequestering Yields (Metric Tonne)		
Annual energy yield	1,757,715,000	kWh/year
Annual energy yield	1,757,715	MWh/year
Annual theoretical CaCO3 yield	1,594,248	Tonne/year
Empirical adjusted anticipated annual CaCO3 yield	797,124	Tonne/year
Annual anticipated annual CO2 sequestration	350,734	Tonne/year
Total anticipated CO2 sequestration	8,768,361	Tonne CO2
Effective cost of CO2 sequestration	EUR 421	EUR/Tonne CO2

Appendix 5

Conceptual ERR Configuration Options

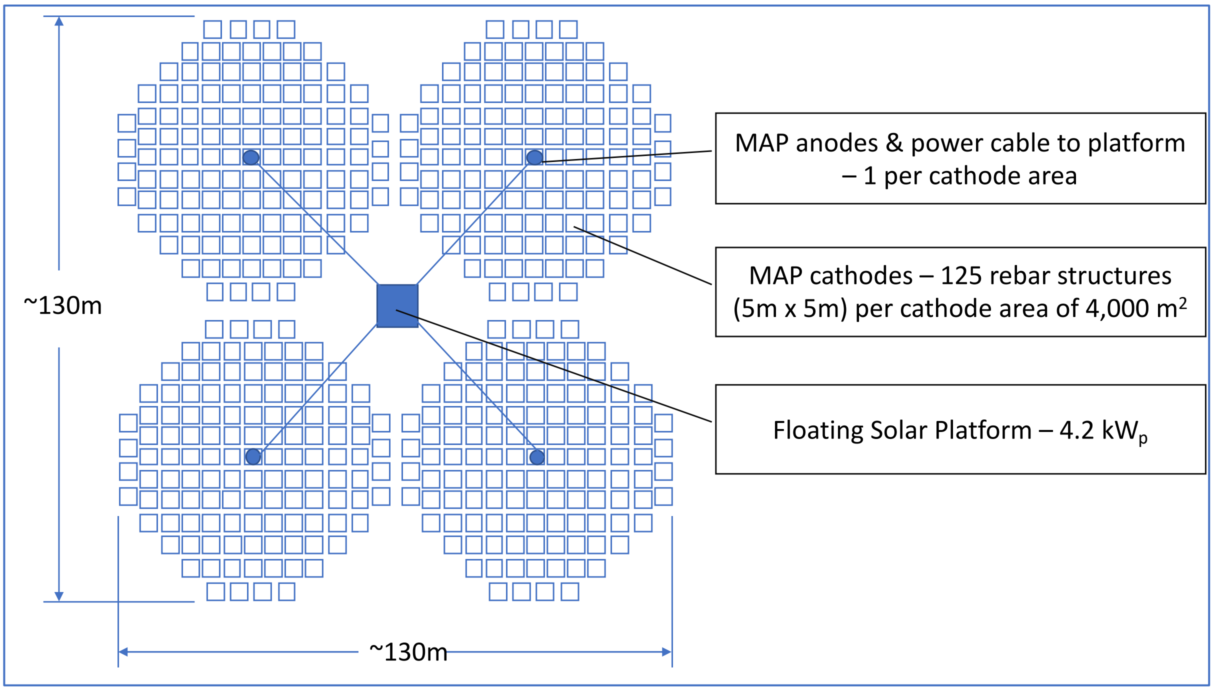


Figure 6 - Conceptual lay-out of 125 rebar domed cathodes; 4-group configuration

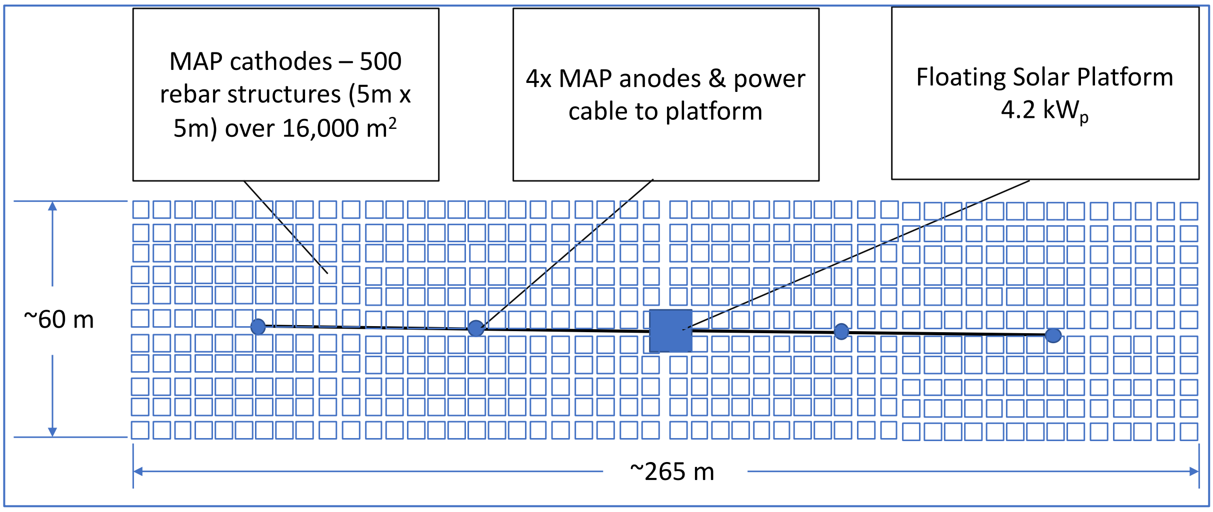


Figure 7 - Conceptual lay-out of 125 rebar domed cathodes – 1 rectangle configuration

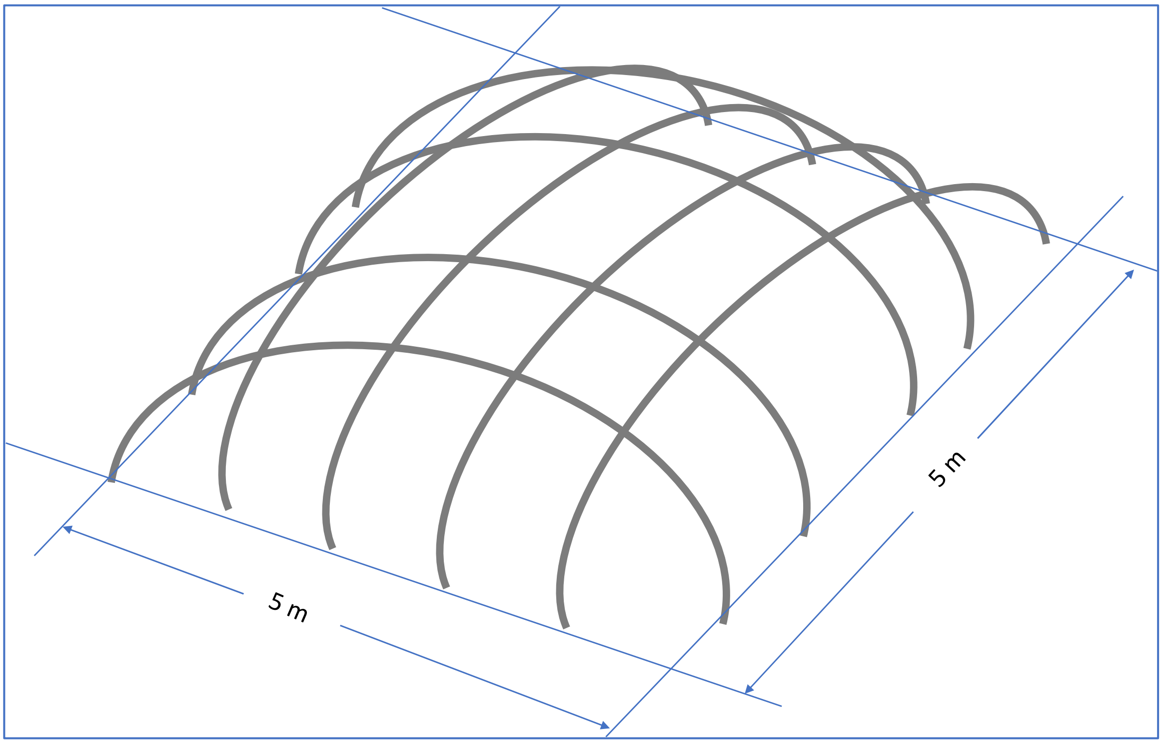


Figure 8 - Schematic of cathode - 5m x 5m rebar domed structure