Chapter

Perspective Chapter: Electric Reefs Enhance Coral Climate Change Adaptation

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Abstract

Survival of coral reefs from globally rising temperature, sea level, and pollution requires new regeneration methods that greatly increase coral growth rates, survival, and resistance to accelerating extreme environmental stresses. Electric ("Biorock") limestone reefs can be grown in any size or shape, get stronger with age, grow back if damaged, and increase settlement, growth, survival, and stress resistance of all marine organisms examined. Electrified corals survive repeated severe bleaching events when over 90% of corals on nearby reefs die. Electric reefs are open mesh frameworks with more vertical levels of holes and surfaces than natural reefs, which can be grown in places where natural reefs cannot grow due to lack of substrate or unsuitable physical and chemical conditions. They strongly enhance reef physical structure, wave absorption, ecological function, biodiversity, productivity, and habitat and ecosystem services including shore protection, sand generation, and fisheries habitat, even at severely degraded sites where no natural regeneration takes place. Electric reefs, optimized for local needs, provide superior cost-effective options for shore protection, conservation, sustainable mariculture, and regeneration of coastal ecosystems that grow to keep pace with sea level rise. They will provide an essential tool to develop sustainable "Blue Economies."

Keywords: coral reefs, structure and function, space frame structures, wave absorption, water throughflow, ecosystem services, climate change, adaptation, electrolysis, electric reefs, biorock, blue carbon

1. Introduction

Coral reef structure and function are imminently threatened with extinction from pollution, global warming, and pathogenic diseases, problems that began to affect coral reefs in the 1980s [1, 2].

Key parameters of coral reef structure and function based on interactions with water flow include the following: 1) how efficiently reefs absorb wave energy, 2) how reef water throughflow prevents scouring erosion in front from wave pressure buildup and reflection, and 3) how quickly water flows through the reef structure, providing food and removing wastes [1]. All are highly sensitive to three-dimensional solid reef structure [3] and also to what is defined here as "reef negative structure," the size, shape, and interconnections of empty water-filled spaces in the reef framework, commonly called holes, cracks, crevices, and caves that result in reef porosity and permeability to throughflow. Here, we discuss how structural benefits of reef throughflow can be greatly increased using Biorock electric reef technology to adapt to accelerating global warming and global sea level rise threats to coastal ecosystems and infrastructure.

Corals have evolved superb adaptation to wave forces and flow, so reef morphology at every scale elegantly recapitulates the wave forces on them. Charles Darwin realized this when he climbed Mount Orohena, Tahiti's highest ancient volcanic peak, to admire the smooth curves of coral reefs completely encircling the islands of Tahiti and Moorea, except for gaps wherever rivers poured freshwater and mud into the sea. Darwin recognized the key features of coral reefs: They were the most effective wave energy absorbers, built beaches, islands, and atolls, had the greatest marine biodiversity, needed warm, shallow, clear waters, and were damaged by freshwater and mud from land. There is no evidence Darwin ever went into the water himself, his insights came from studying Admiralty Nautical Charts (British Royal Navy maps of where ships could run aground, based on meticulous bottom soundings), from leaning over the boat railing when the water was calm and clear at anchor, and rare glimpses through an "underwater telescope," the bottom viewing glass sailors used to see if anchors set properly on the bottom. His focus was on coral as geological island builders, and he never looked at coral reefs closely enough to gain evolutionary insights from them. Darwin knew corals could be propagated by fragmentation on clean bottoms from information provided by a Jamaican geologist about reefs in Panama, and from a Scotsman in Madagascar, not from his own personal observations [4]. Although coral fragmentation and propagation have been routinely used by coral scientists ever since, it has recently been claimed as a "new discovery."

The other co-discoverer of evolution, Alfred Wallace, saw coral reefs of Ambon Bay in Indonesia by looking over the side of a boat at port and was mesmerized by the vast untouchable universe beneath the waves, which he could only glimpse ephemerally but never touch, with shapes and functions even more complex, varied, and intricate than the astonishing tropical jungle life he studied [5]. The blind seer of Ambon, Georg Eberhard Rumpf (Rumphius) described the skeletons of corals and shells by touch in the 1600s [6]. Now, those corals have vanished due to mud and pollution, and Biorock Indonesia electric reefs are growing the last corals in Ambon Bay (https://www.globalcoral.org/biorock-brings-corals-back-in-ambon/). After development of diving as a research tool at the 1947 Bikini Atoll Scientific Resurvey, scientists began to dive into reefs to learn how corals functioned as habitat builders from shallow to deep [1].

2. Collapse of coral reef structure and function

The priceless ecosystem services of coral reefs may soon be lost unless methods are found to regenerate reefs in the ocean that are more resistant to high temperature and pollution stresses. Coral reef ecosystem services per unit area are the most valuable of any ecosystem on earth: so valuable that economic losses caused by coral reef destruction alone make up nearly 60% of total global value of all of Earth's ecosystem service losses between 1997 and 2011 [7]. Those estimates of reef damage are obsolete because they were made before accelerated collapse of coral reefs from bleaching, diseases, and pollution, which happened in the record hotter years since that paper was written. Coral reefs occupy less than 0.1% of the ocean's surface, so all other ecosystems in the world, which cover more than 99.9% of the planet, contribute only 40% of all global economic losses from ecosystem deterioration. The economic losses per unit area in coral reefs are thousands of times greater than the global average, making clear the exceptional vulnerability of coral reefs to destruction, and resulting global economic impacts on shoreline protection, fisheries, tourism, and biodiversity.

Healthy coral reefs absorb up to 97% of incoming wave energy [8], and healthy corals grow back in years after being damaged, but only if water temperatures, sediments, nutrients, pollutants, pathogens, and wave energy are within the coral's tolerance range [1]. Dead reef structures are crumbling and collapsing from bioerosion by boring sponges, clams, worms, algae, fungi, and bacteria, which perforate dead coral skeletons and limestone with holes until seemingly solid reef rock eventually shatters and collapses in severe storm waves [1]. Once gone, shore protection dead coral reefs used to provide has to be replaced by concrete and stone walls costing tens of thousands of dollars per meter, which provide no ecosystem services such as fish habitat and sand production. Instead of generating sand like coral reefs do, concrete and rock walls cause scouring and sand erosion in front, and then underneath them, until they are undermined and collapse.

Spectacular elkhorn and staghorn coral reefs grew right up to the surface around Caribbean islands, so dense one could not swim over them [1]. These were dynamited in Bonaire and other places so divers could swim from the beach to reach the outer slope. Now, those reefs are almost entirely gone except for a few fragments of dead coral on the slopes below, and the beaches are washing away. There is urgent need worldwide to regenerate reef structures to prevent beach loss: Half the world's beaches are expected to vanish in this century [9], even if sea level rise, wave strength, and coral bleaching caused by global warming do not increase, as now seems certain to happen due to political failure to halt and reverse greenhouse gas emissions.

Unless coastal ecosystem collapse is reversed quickly, tropical coastal countries have little hope of developing sustainable Blue Economies. This will require active restoration with artificial structures where the reefs themselves have collapsed. All around the world dead reefs have disappeared, flattened, and pulverized to rubble by hurricanes, nearly barren of living corals and fish. Artificial reefs can regenerate some lost biomass, biodiversity, and ecosystem function in such places, but vary greatly in their effects depending on structural design and ambient conditions.

3. Types of artificial reefs

Artificial reefs can be classified by three generations of technological improvements. First-generation or "Indigenous" artificial reefs [10] are traditional fish habitats on the bottom or floating, constructed since ancient times by Indigenous Pacific Sea Peoples from natural rocks, bamboo, and coconut palm leaves to create Fish Aggregation Devices (FADs). Pacific fishermen know fish swarm beneath the shadow of floating tree trunks, so whenever they see a floating log, they head straight for it and fish under it as long as they can and still get back home. FADs anchored to rocks or deep moorings work so well that there is no point fishing elsewhere.

Indigenous bottom reefs can be astonishingly productive of fish and edible snails by creating habitat for desired species where there is little available. One such reef dismantled by fishermen in the Philippines yielded nearly a hundred rabbit fish and groupers in just a few square meters. These artificial reefs build up populations of some species, but do not restore habitat in the long run or on large scale because floating FADs made of coconut and bamboo rot and fall apart, and rock piles are deliberately dismantled to harvest fish and shellfish hiding inside, although usually reassembled for the next harvest a year or two later. In many places in Southeast Asia and the Pacific islands, you see ancient rock pile reefs along shores that had been regularly harvested for thousands of years, but which were abandoned after colonial administrators destroyed traditional resource use laws as a political threat to the new rulers.

Second-generation, or "modern" artificial reefs, are mostly made from massive exotic manufactured materials such as Portland Cement concrete, steel, ceramics, rubber, and plastics, and now, 3-D printing [10]. Larvae of coral reef organisms are particular about where they grow; they seek clean limestone surfaces on which to settle. Most coral reef organisms refuse to settle on exotic materials, so instead of hard corals found on limestone rock, artificial reef materials generate biological fouling communities dominated by slimy cyanobacteria, weedy algae, stinging hydroids, and bacteria eating sponges. These soft fouling communities are very different in structure, function, and biodiversity from true constructional coral reef communities. Fish will hide behind any structure where there are none, but artificial reefs made of exotic materials almost always fail to generate real coral reef ecosystems, and fish seem to prefer to aggregate in dead coral reefs than concrete. The individual modules from which these artificial reefs are constructed rust, corrode, collapse, crumble, and eventually fall apart, often leaving toxic materials behind. Or they are moved, removed, or destroyed by storm waves, making physical benefits temporary, and littering the sea floor with trash. Since hard coral settlement on their exotic surfaces is very sparse, second-generation artificial substrate reefs are based on propagation by coral fragmentation, which was well known to Charles Darwin, so we classify them as Pre-Darwinian reef restoration methods.

Pre-Darwinian artificial reefs have a very poor record of survival in storms and are often completely demolished, frequently without trace. After Hurricane Andrew hit South Florida, divers found all artificial reefs (mostly sunken ships) had moved from where they had been installed. The structures were ripped apart, with none, one, or many fragments being found far down-current. Despite lack of long-term structural stability, exotic material artificial reefs planted with fragmented coral clones are the fad of the moment with funding agencies, and hundreds of well-intentioned groups around the world are breaking corals and gluing them to concrete, rubber, plastic pipe, plastic fishing lines, and other underwater structures. These groups mean well, but have shown no long-term results because fragmented corals in these nurseries can grow in tanks with expensive pumps, lights, filters, and food with sufficient care and expense, but will die when put into the field as soon as the water gets too hot [11], muddy, polluted, or rough, and when disease strikes, these monoclonal coral plantations usually all die. Such methods are expensive and temporary solutions that typically last only until the first extreme stress event.

The well-known failures of these fragmentation reef regeneration methods in the face of global warming are reviewed elsewhere [11], so not repeated here. This chapter discusses optimization of Post-Darwinian reef structures to uniquely meet physical and biological challenges caused by anthropogenic stress to coral reef ecosystems from global climate change and pollution, which are increasing temperature, sea level, wave energy, nutrients, toxic pollution, and new epidemic diseases beyond the range corals glued to exotic material can tolerate.

Third-generation, or Post-Darwinian artificial reefs [10], grown in the sea by electrolysis [12], are a quantum leap ahead of all other artificial reefs, because they uniquely grow the natural limestone that coral reef organisms prefer to settle on [13–16]. Seawater electrolysis creates growing limestone reefs of any size or shape, which get stronger with age, and are self-repairing [15]. Electric reefs have survived category five hurricane impacts and severe coral bleaching events without damage [17]. Biorock reef structures show greatly increased settlement, growth, healing from damage, survival, resistance to severe environmental stress, and biodiversity of all marine organisms, preventing coral mortality from bleaching, absorbing wave energy, regenerating severely eroded beaches, and creating new habitats that allow selected valuable species to be grown at high density without added food, while absorbing CO_2 [14–16, 18].

The electrolysis process uses Safe Extra Low Voltage (SELV) direct current seawater electrolysis to grow limestone structures in the ocean, in any size or shape [12–16]. More than 600 electric reefs have been built since 1976 to ameliorate local marine ecosystem regeneration problems in some 45 countries around the world. All projects worked well if designed by a trained team, used the right materials and conditions, and were maintained. Untrained users of Biorock technology generally fail to get results shown in this chapter because of fundamental errors, reviewed in Ref. [15].

The principles of electric ecosystem regeneration have been learned by observation and experimentation, not derived from *a priori* physical principles or models. Indeed, the results were so unexpected that they could only have been learned from the observational natural history-based approach used by Rumphius, Linnaeus, Charles Darwin, Alfred Wallace, and Alexander Humboldt, and could not have been learned from conventional hypothesis-based research funding strategies.

4. Physical observations of electric reefs

There are no limits to the size or shape of reefs that can be grown in the ocean by electrolysis, and costs are far less than any Pre-Darwinian artificial reefs, while ecosystem service benefits are far greater [18]. The minerals produced by seawater electrolysis are the only marine construction materials that grow solid limestone structures, attach themselves solidly to the sea floor, “glue” or “cement” themselves to the bottom, and get stronger with age by growing new layers of limestone minerals from sea water. More remarkably, this material repairs itself, and the physically damaged areas grow back as long as they are electrically charged. Electrolysis produces solid materials at least 2–3 times harder than Portland Cement concrete that grow upward at rates of up to 2 centimeters per year, faster than global sea level rise, now about 0.3 centimeters per year [14]. Since they only grow while submerged, breakwaters made from this process match sea level rise and will not need to be constantly repaired, rebuilt, and re-topped to keep pace with rising waters like conventional marine construction. The oldest known rock breakwaters, built 7000 years ago to protect a village on the shores of the Eastern Mediterranean, failed when the ocean rose above it [19].

Electric reefs can be built in any form, as strong, porous, and permeable to water and sediment flow as desired. They are versatile and adaptive, and can evolve as needed by adding new modules to provide more wave absorption, or removing portions if more water flow is desired. For example, groynes can be made partially permeable to sand so they do not block longshore sand drift, causing erosion down-current like solid groynes. Sand permeability of such groynes can be adjusted as desired by adding or removing modules or segments when needed (https://blueregeneration.com/#).

Electric reefs are designed with interconnected open spaces and passages with high internal surface area that efficiently absorbs wave energy, while recycling nutrients on biological surfaces of organisms living on internal passage surfaces. Large open-framework structures have much higher negative space than massive reefs, allowing many times more water throughflow for their mass than real coral reefs. Open spaces are built into the structure at the start, while natural reefs are accretionary, adding on new corals only from the bottom up, until they fill the spaces between corals, so many holes are accidents of failure to grow or physical damage.

Because coral reefs grow from the bottom-up, they interact with water only by bottom friction. Once passages through the reef are filled in by solid massive corals and sediments, the reef is no longer porous and permeable to water flow, which is needed for efficient energy dissipation and internal carbon and nutrient recycling [1, 3]. As reef passages and pores fill in, reef structure negative space, porosity, and permeability decline, and so do biological growth, ecological function, and wave energy absorption capacity, as the reef reaches its upper vertical limits and transforms from an open growing structure to a solid eroding one. Blockage of holes through the reef prevents water throughflow and prevents wave pressures equilibrating across the reef structure, greatly increasing erosional forces on the reef front. Hole blockage causes wave reflection and sediment scour on the front surface, erosion that is minimized in reef frameworks with open passages. Conventional artificial reefs are usually made of solid rock and concrete, and so suffer severe scour erosion in front and underneath them in storm waves, while electric reefs nearby accumulate sand underneath them [17]. Some reinforced concrete structures have been designed with holes, but generally have poor water throughflow, and deteriorate as steel reinforcement rusts, expands, and cracks the concrete, the opposite of electric reefs that do not rust and gain strength with age.

Electric reefs are open cross-linked mesh frameworks that interact with water throughout their entire vertical height and cross section, not just the uppermost or outermost surfaces. Crucial design features of electric reefs are low surface area cross section perpendicular to flow, but high surface area parallel to flow, avoiding excessive drag stress forces that can tear solid structures apart, while providing internal surface area with tangential drag to efficiently slow down waves. They can be made with any number of layers of holes and passages, of any size or orientation, and so provide much more surface area and effective biological volume, with vastly less solid mass than a coral reef that accumulates solid material only from beneath. Different species of fishes, lobsters, octopus, oysters, giant clams, and other marine life are observed to prefer different size and shape holes for shelter and finding food, so structures can be designed to suit desired species. Biorock reef structures survived extreme hurricane waves that tore solid concrete structures apart (**Figure 1**, from [17]).

Mesh frame structures cover much more bottom area and volume with far less material than solid breakwaters, so they cost much less to build and install (**Figure 2**). A simple geodesic dome is shown in **Figure 2**. Despite low weight, these structures are extremely strong because of tensile interconnections and can be made in any shape to fit any bottom topography. Mesh frame structures are readily analyzed by finite element stress and strain analysis, which shows mesh structures made from varying length elements have superior mechanical properties to those made from uniformly sized elements [20]. Because such structures are largely open in their interiors, they allow flow of nutrients and food to marine organisms throughout the structure, and flushing of their wastes, resulting in elevated growth of all reef species throughout

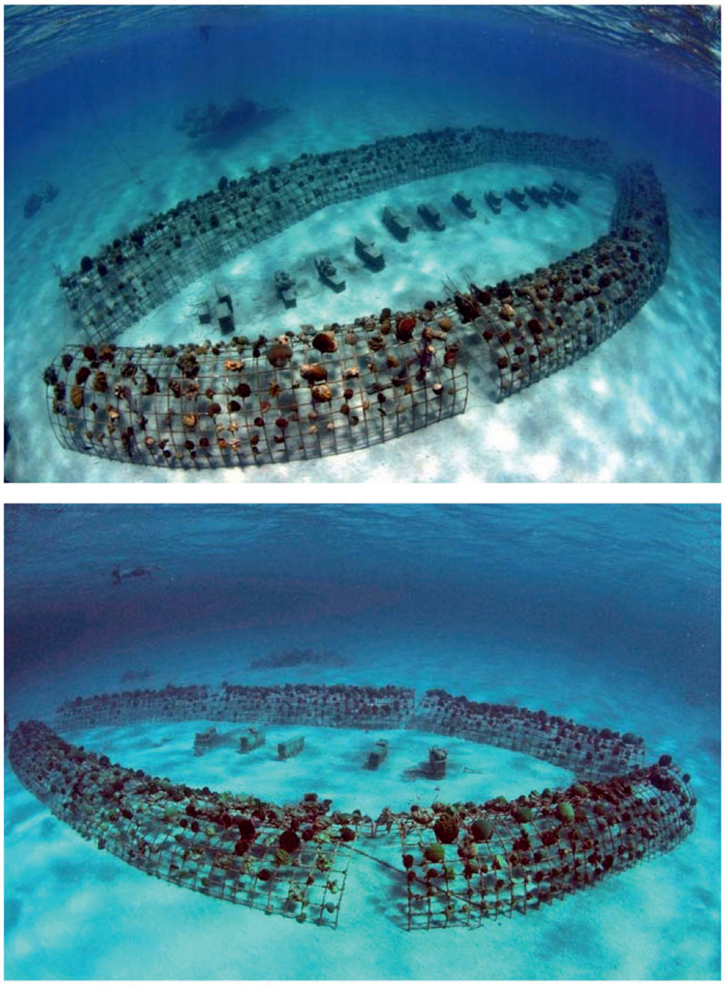

Figure 1.
Before and after the two worst hurricanes in Turks and Caicos Islands history. The biorock reef built up sand underneath, while most concrete artificial reefs were thrown out and concrete reef balls nearby suffered severe scour erosion and were buried beneath the sand (in background). Note swimmer for scale. Photographs by Lucy Wells.

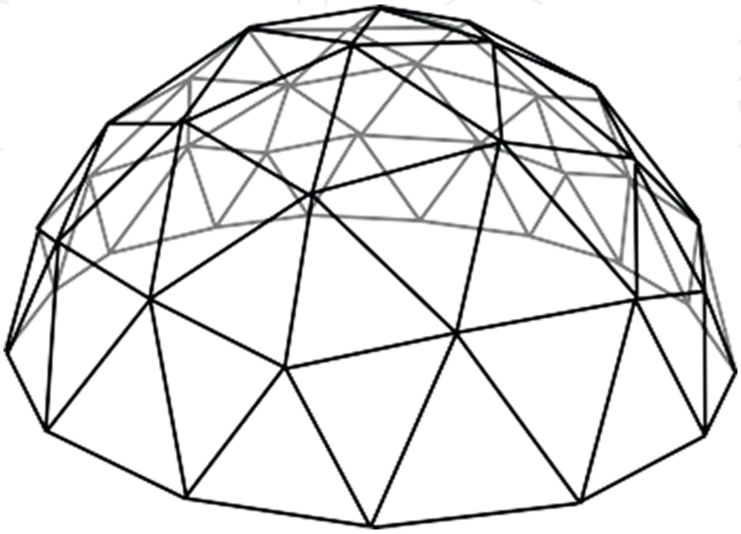

Figure 2.
A geodesic dome space frame structure shows the basic principle of biorock reefs. This is a simple geodesic dome, but they can be made in any size or shape.

the reefs negative space when compared with marine organisms living in cracks and crevices in solid frameworks, which are limited by slow transport of food and wastes. They provide much more biological surface area than breakwaters for wave energy absorption by friction and for food capture from the water by filter-feeding organisms such as corals and sponges.

Figures 3–5 show the ranges of shapes of a small portion of around 150 electric reefs built by Biorock Indonesia at Pemuteran, Bali. Electric reef structures built on sand created lush reefs in a few years on bare sand sites that had been barren of corals and fishes. Electric reef structures on the dead reef, which was almost entirely killed by bleaching in 1998, stimulated tremendous spontaneous settlement of corals that turned nearby areas from only a few percent coral cover to nearly 100% live coral in around 5 years [15]. It is especially noteworthy that diversity of corals and fishes were greater 10 years after electrical regeneration than before bleaching. Soft corals (stress indicators) had covered much of the bottom before bleaching, but were replaced by hard corals after electric regeneration. More complex internal spaces in electric reefs created hiding places for large schools of fish, whose populations and diversity soared [16].

Electric reef hurricane performance was compared with conventional concrete artificial reefs in Grand Turk [17]. The electric reef was sitting loose on the bottom, not anchored, and had not been welded, only hand-tied together with wire. Thousands of corals were rescued from a reef where they were being killed by propeller wash sand and turbidity from tourist cruise ships. The corals had been attached loosely to the structure only a week before the two worst hurricanes in the island's history hit, just 3 days apart. Almost all houses on land were destroyed or damaged, but there was essentially no damage to corals or structures, although the electrical cable powering it was ripped out by waves. During the hurricanes sand built up under the electric reef and buried the lowest portions [17]. In sharp contrast, most concrete block artificial reefs inside the electric reef were washed out, and concrete reef balls on the sand nearby caused so much scour and erosion around and underneath them that they were undermined, dug their own graves, and sank partly into the sand or vanished completely beneath it (**Figure 1**). Electric reefs have shown their effectiveness at wave energy absorption by growing back severely eroded beaches at record rates [14, 21].

Electric reefs must be heavy and strong enough, or sufficiently well attached to the bottom, which they do not move or get damaged in extreme storms before growing strong. They can be attached to the ocean floor by drilling or with sand anchors. Electric reefs that survived Category 5 hurricanes were neither welded nor attached to the bottom in any way, and they sat on the bottom under their own weight and cemented themselves to it with growing limestone [17]. There was no damage to corals or structures on an electric reef on Saint Barthelemy on top of the dead reef flat in 1 meter depth of water. This reef flat absorbed the major force of huge breaking waves from Category 5 Hurricane Irma, which damaged and destroyed all buildings in the bay behind the reef (see video at https://www.globalcoral.org/biorock-electric-coral-reefs-survive-severe-hurricanes-little-no-damage/). The first electric reef built in Jamaica in the 1980s has been off power for more than 30 years, but is so solidly attached to the sea floor that it has survived every hurricane in three decades, and many of the original corals are still growing on it, although it no longer has enhanced growth or self-repair [16].

Electric reefs are weakest when first built and get steadily stronger, the opposite to all other construction materials, which are strongest when installed and deteriorate from that moment until they fail and collapse. The electrolysis process cements

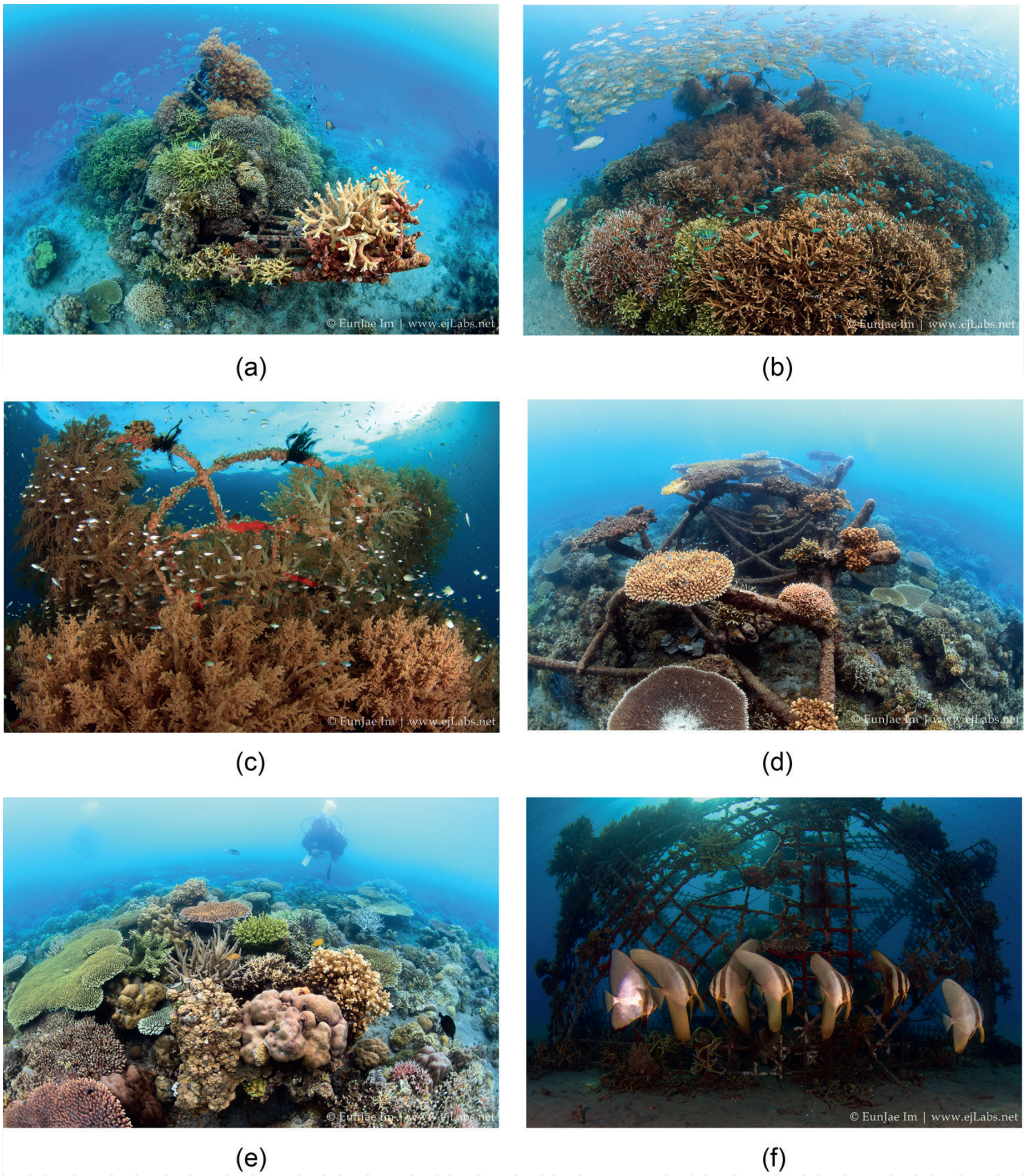

Figure 3.
A sample of the range of biorock coral habitats at the Karang Lestari project, Pemuteran, Bali, photographed in may 2012 by Euen Jae Im. These photos were all taken on 1 day, and they show only a small part of around 150 different biorock reefs at the site. Many reefs represent Balinese myths, designed by creative local artists. a) Four-year-old biorock reef on bare sand surrounded by a cloud of fish, zoned according to their preferred habitat. b) Four-year-old biorock reef on bare sand attracts schools of fishes. c) Biorock reefs attract spontaneous settlement by hard corals, soft corals, tunicates, sponges, crinoids, and juvenile fish, quickly building up highly biodiverse ecosystems. d) this biorock reef covers a lot of area with little material. By building up the height of the dead reef and attracting coral settlement, it has grown back a badly eroded beach on the shore behind it. e) Biorock mesh reefs stabilize loose rubble and can become quickly concealed under coral growth, armoring coastlines against erosion. f) a wide variety of fishes are attracted. Batfish are usually first to school around newly installed biorock reefs.

sediments below the water surface, so is ideal for sub-bottom structural foundations, such as in Venice [22]. The bases of collapsing cliffs can be armored against bioerosion and loose rubble cemented together. In Indonesia, the Philippines, and Tanzania, baby corals settle on dead coral rubble of dynamited reefs, but die when waves flip them over. Electrolytic mineral growth on meshes stabilizes shifting substrate, and

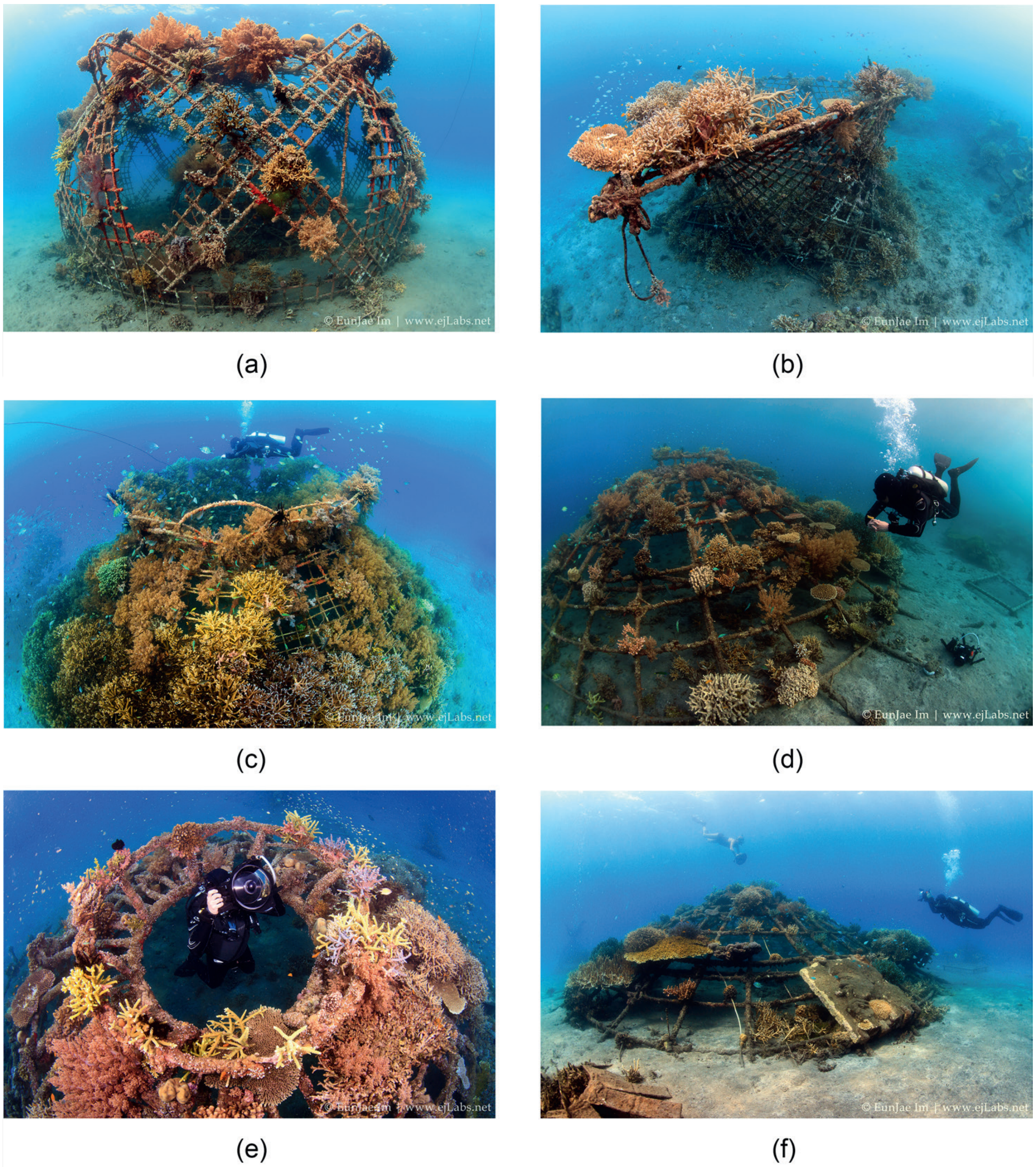

Figure 4.
A sample of the range of biorock coral habitats at the Karang Lestari project, Pemuteran, Bali, photographed in may 2012 by Euen Jae Im. These photos were all taken on one day, and they show only a small part of around 150 different biorock reefs at the site. Many reefs represent Balinese myths, designed by creative local artists. a) this biorock reef contains three concentric domes, the inner one creating a darker cave-like habitat. b) Biorock reefs quickly build up dense local fish populations in barren areas. c) Biorock reefs attract cleaning shrimp and cleaner fish and are excellent places to watch fish behavior close up. d) these reefs are located on barren sand in front of a reef that was killed by bleaching in 1998. e) They brought back spectacular life to an area that had looked like a barren moonscape. Larger fish, such as groupers, prefer the dark interiors. f) the entire economy of the town or Pemuteran is built around ecotourism. People come from around the world to see the projects.

coral fragments grow right up through it, allowing reefs to grow back in severely damaged sites where there had been no recovery.

Electrolysis can create reefs where there is no suitable bottom for reef growth, even in the deep sea. Floating electric reefs in a suburban Grand Bahama canal grew

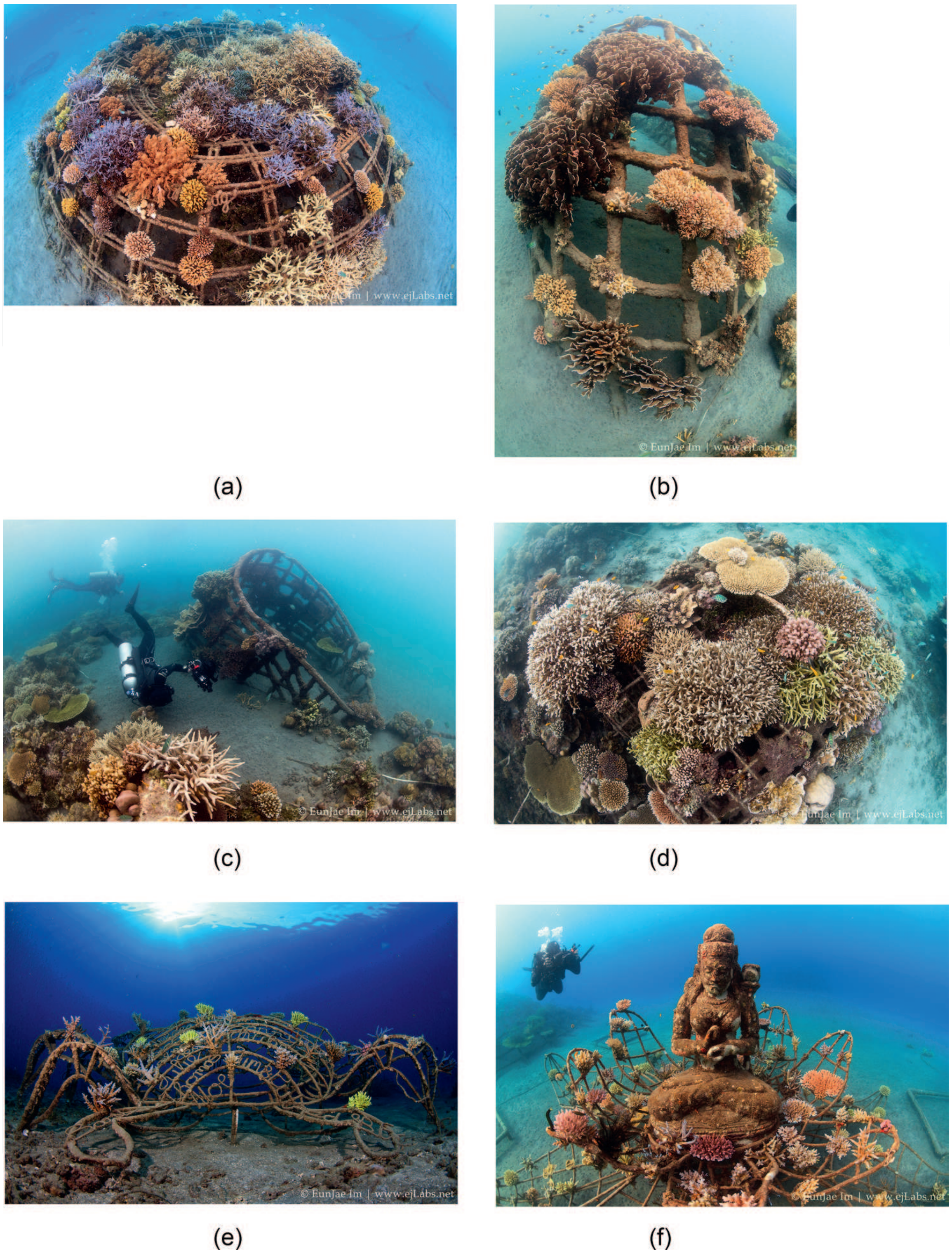

Figure 5.
A sample of the range of biorock coral habitats at the Karang Lestari project, Pemuteran, Bali, photographed in may 2012 by Euen Jae Im. These photos were all taken on 1 day, and they show only a small part of around 150 different biorock reefs at the site. Many reefs represent Balinese myths, designed by creative local artists. a) Biorock dome reef on sand. b) the first biorock reef, built in 2000, has spectacular growth of the blue coral, Heliopora coerula. Front side. c) Back of same reef, shaped like a Balinese fish trap called a Bumbung. It increased growth rate of corals on it 4.01 times more rapid than nearby controls, and stimulated massive spontaneous settlement of new corals all over the dead reef nearby that was killed by bleaching in 1998. d) Corals grow through and over biorock reefs, while fish swarm inside. e) Ingenious Balinese artists make spectacular reefs shaped like marine life, in this case a crab, in a new biorock reef just starting. f) Hybrid sculptures retell Balinese mythology.

filter feeding reef communities dominated by sponges, hydroids, oysters, mussels, tunicates, and corals that helped filter and clean turbid waters, a method that could be used to help clean-polluted harbor waters. Floating solar-powered electric reefs can serve as superior Fish Aggregating Devices and offshore wave absorbers, increasing pelagic fish populations by providing shelter, shade, and food. Electric reefs can be used for floating offshore port installations [23]. The United Nations Sustainable Floating Cities Initiative, launched in April 2022, plans to use electric reefs on the bottom as mooring anchors and bottom fisheries habitat regeneration, and floating electric reefs for wave protection, mariculture, and cleaning polluted harbor waters.

Safe Extra Low Voltage (SELV) direct electrical currents are the cause of all physical, chemical, and biological benefits of the electrolysis process [1]. Limestone does not naturally form in sea water unless marine organisms spend their own biochemical energy growing shells and skeletons. The need for a trickle charge of electricity is also the method's major limitation, requiring reliable, cost-effective sources of electricity at sites where projects are needed. Extremely low voltages like those used for seawater electrolysis cannot be transmitted long distances except through large-expensive electrical cables due to power losses from voltage drop, so they are best provided by local electrical sources. Electric reefs can be powered by any source of electricity transformed into low-voltage direct current; we have used conventional alternating current, photovoltaic panels, windmills, ocean current and tidal energy turbines, wave energy generators, and batteries. Fuel cells can be used too and will likely become the method of choice for remote sites such as on the bottom of the deep ocean floor. Which power source to use depends on the choices available at each site, and their costs, so is a site-specific local design issue.

Electrolysis allows whole islands to be grown on shallow banks that are now being submerged by sea level rise, potentially allowing low island nations that are now abandoning inhabited islands due to erosion to adapt to climate change. Hard electrically grown limestone materials are permanent (the same material as the pyramids), eliminating need for frequent and costly repairs, or concerns that sea defenses will be eventually overtopped by global sea level rise. No other coastal defense technology evolves to match global sea level rise.

5. Biological observations of electric reefs

The physical benefits of structural wave attenuation and shelter exist independently of any biological benefits, but are greatly enhanced by them [16]. Most wave absorption capacity of electric reefs is provided by prolific biological growth over the structure, whose surface area greatly exceeds that of limestone chemically produced by electrolysis (**Figures 3–5**). Electric reefs grow and protect coastlines fastest where there are the best water quality conditions for healthy marine life; however, they also work even in sterile and toxic environments where little or no marine life can grow, though not as well. Wave-absorbing reefs to protect shorelines from erosion can be grown in waters whose physical, chemical, and biological conditions are too extreme or lethal for reef building organisms, for example, in severely polluted and anoxic harbors, or in front of Fukushima (where it would help trap radioactive Strontium-90 emissions). Electrolysis allows offshore reefs to be built along shallow coasts whether a reef was there before or not. Such reefs could save beaches lacking protective reefs that are replenished regularly at great expense by sand dumping "renourishment" that vanishes after the first big storm, such as Cancun or Miami Beach.

Figures 3-**5** Examples of the huge variety of open framework electrolysis reefs. These photographs show only a small portion of around 150 electric reefs at the site, taken during a single day.

The electrolysis process provides direct biochemical energy benefits for health and resilience of marine organisms, empowering them to survive otherwise lethal conditions [14, 16]. Corals survive repeated severe bleaching on electric reefs, while corals away from them die, electrified intertidal saltmarsh grass grows deeper offshore than it could otherwise tolerate because of their prolific root growth, and sea grass has been grown on bare rock with no sediments, previously thought impossible [16]. Most seagrass, saltmarsh, and mangrove transplantation projects fail because plants are washed away by waves before roots can grow. Electrolysis regenerates natural coastal defenses and capability to adapt to sea level rise by accelerating plant growth both below and above ground, allowing marine plants to quickly establish themselves and proliferate by underground root growth. They can expand eroding coastal saltmarsh ecosystems seaward in places where they are now rapidly retreating inland because of increasing sea levels and storm strength, while increasing coastal "Blue Carbon" storage in living shorelines and sediment organic carbon in seagrasses, salt marshes, and mangroves [16].

Carrying capacities of reef species are determined by the size and shapes of holes available for their shelter and also for organisms they eat. Each species of octopus, lobster, crab, shrimp, and fish searches for holes of a certain shape to hide or searches for food. The number of suitable holes limits how many individuals fit any given area. Holes in a natural reef are not the result of systematic and abundant design, there may be only one suitable hole in a large area, and there is usually only one layer of holes on the bottom. Holes are often historical accidents limited to spaces not yet filled in by corals or sand, or cracks from structural failure where corals broke off and were washed out by extreme waves. Such holes are accidental, ephemeral, and temporary, filling in with coral, sand, or rubble as the reef grows. Electric frame mesh reefs have not just a few holes at the bottom like coral reefs do, but also have passages repeated up throughout the entire height of the structure, allowing larger populations of marine organisms to find shelter than possible on natural reefs, with better flow of water transporting food in and wastes out. Electric reefs of different shapes side by side build up populations of different fish species. Electric reefs can be designed for specific needs of desired species, once we learn what shape they prefer. Scores to hundreds of lobsters crowded into a few square meters of electric lobster habitat in Jamaica, Mexico, and Panama. Electric reefs have been completely overgrown with oysters, mussels, or corals that spontaneously settled [16]. High biodiversity of electric reefs allows the reef to internally generate its food supply for sustainable whole-ecosystem mariculture, without needing to add expensive manufactured food, avoiding most of the problems of monoclonal commercial mariculture [24]. A small sample of the range of electric reefs grown at one location, Pemuteran in Bali, is shown in **Figure 3**. They are more spectacular in video because of constant movement of fish schools around them, seen at: https://www.youtube.com/user/TheBiorockChannel.

Electrolysis not only amplifies reef physical and biological function, extending and regenerating them where it had been lost or degraded, it also allows shapes natural reefs do not have, and in locations where they cannot naturally exist. Floating electric reefs moored to the bottom can create upside down reefs in deep water, generating habitat for oceanic fish such as mahi-mahi and tuna. Electric reefs are predicted to be more effective than conventional Fish Aggregation Devices because they generate intense biological productivity and biodiversity, creating new food chains. Electrolysis has been shown to increase growth of the deep-sea cold-water coral Lophelia pertusa [25] and grow back eroded beaches [26]. Electric reefs could be grown on the deep-sea floor using batteries and fuel cells maintained by Remotely Operated Vehicles (ROVs) to repair deep cold-water reefs destroyed by trawlers, fossil fuel extraction, and deep-sea mining. Electrified enclosures in shallow atoll lagoons create intensely productive hatcheries and nurseries for juvenile sea cucumbers http://www.pacinternational.org/. Electric reefs therefore can be adapted to provide habitats from the surface of the ocean to the bottom, not only in shallow water.

6. Reef-wave interactions in time and space

The study of wave interactions with reefs languished because oceanographic research has been almost entirely funded by the military, which focused only on aspects related to military needs, such as whether waves would tip over military landing craft during invasions or detecting submarines [27], leaving fundamental coral reef research systematically unfunded. Research focused on large-scale oceanographic circulation around reefs [28] rather than understanding internal flows and processes, and what controls their variability. Because of the extreme complexity of reef structures, studies of wave-reef interactions can rarely be generalized beyond the reef that was measured. One focus has been to model impacts of extreme storm events that break corals to determine minimum forces to break corals [29]; however, corals vary enormously in morphology and internal strength, so the results rarely apply to more than one species.

Physical drag forces from water flow can be calculated from the Universal Drag Equation, $F_D = ½C_DdAU^2$, where F_D is the drag force on the object, C_D is the drag coefficient, d is the density of the water, A is the cross-sectional area of the object perpendicular to the flow, and U is the velocity [30]. The Drag Coefficient represents the fraction of flow toward the structure that is blocked, is extremely sensitive to shape, surface roughness, and turbulence, and can range for very low for wires oriented along the flow vector to very large for flat objects perpendicular to it. The equation applies for simple geometrical objects with known drag coefficients, which few corals have, and steady flow, something that rarely happens in rapidly fluctuating coral reefs.

After the 2004 Asian Tsunami, Thomas Sarkisian, VP of the Global Coral Reef Alliance, and I studied his videos of coral reefs in the Similan Islands, Thailand, 1 week before and 1 week after the tsunami. In some patches, there was total coral destruction, mingled with patches with no damage at all even to fragile branching species, interspersed with areas of intermediate damage. The worst damage occurred where waves ran up the shore and flowed back full of rocks, soils, trees, wrecked buildings, and bodies, especially where wave energy focused on convex surfaces such as headlands and reef promontories (buttresses). Concave areas between promontories were largely untouched, indicating incredible temporal and spatial variability of wave breaking forces in even the most severe events and the difficulty of predicting their impacts theoretically.

Despite these limitations, important work has been done applying these principles to flow in the spaces between coral branches [31] finding that flow inside densely branched colonies can be nearly stagnant. On the other hand, spiny coral skeletons induce micro-scale turbulent vortex flows that greatly reduce the thickness of stagnant surface boundary layers and increase flow of oxygen and nutrients, stimulated by organized patterns of directed surface flows by ciliary pumping on the coral epithelia [1]. Measurements show internal pores in reefs are an important sink for bacteria and source of nutrients [32], but this obviously varies enormously in time and space depending on the size of the pores, their surface area, degree of interconnectedness, and throughflow.

Flow measurements on reefs show even simple reef structures with low-living coral cover greatly increase turbulent drag forces on reefs [33], but these can clearly be much higher in well-developed reefs with high-living coral cover [3]. A major focus has been to measure wave energy dissipation in waves crossing coral reefs. Due to the great expense of arrays of long-term recording current meters, this has only been done comprehensively by Storlazzi and colleagues on the South Shore of Molokai, where the reef has been shown to absorb up to 97% of the incident wave energy [34]. Clearly, these results are highly sensitive to overall reef profile, live coral cover, and kinds of corals, so cannot be easily generalized [35–37]. However, the lessons learned have been applied to estimate costs of reef decline and benefits of reef restoration for beach tourism, diving, and fishing in Florida, Puerto Rico, and Hawaii [38–40].

Without real field data that reflect the unique topography, wave climate, and history of each reef, the results are difficult to generalize, but it is clear coral reefs provide vastly superior environmental services at greatly reduced cost compared with concrete and rock seawalls. The models also show what we have long learned by practice in the field and are intuitively obvious that the greatest benefits for shore protection and natural beach regeneration come from reefs as high and close to shore as possible, with the highest porosity, permeability, and water throughflow. Electric framework reefs can be made as complex and as tall as needed, as long as they are physically stable. They have much lower mass, much larger negative space internal volumes, much higher interconnectedness resulting in high porosity and permeability, much higher internal surface area exposed to flow, and therefore biological activity than any other kind of artificial reef material, so they quickly achieve high biomass and biodiversity, often exceeding that of the former reef at the site that was restored. As of now, there are no flow performance measurements that allow these physical and biological benefits of regeneration to be quantified, but they are clearly visible in **Figures 3–5**.

During the 1947 Bikini Atoll Scientific Resurvey, physical oceanographer Walter Munk realized that the outer reef formed a regular series of growing coral reefs at right angles to the reef crest, oriented outward into the waves, separated by sand channels, and called this spur and groove morphology [41]. The constant pressure of waves on the reef crest resulted in water flow orientation into distinct cells, with broad incoming flow separated by narrow bands of much more intense return flow capable of eroding the reef, similar to riptide currents on beaches. The concentrated outflow eroded grooves into the reef rock, filled with rounded and abraded boulders of corals that had been smashed off the reef, rolling around in the channels, and living corals were rare on channel walls. Spur and groove formations were only found on sides of the atoll most exposed to prevailing winds and currents, and were absent on leeward slopes.

Thomas F. Goreau, research diver on the 1947 Bikini Atoll Scientific Resurvey, working with Roger Revelle measuring ocean and reef pH, O_2, CO_2, and alkalinity, built rebreathers to dive on coral reefs in Jamaica and found that these reefs also showed areas of coral growth oriented into the waves separated by sand channels, but their origin was entirely different, and they were caused by the rapid upward growth of corals, with sand canyons up to 30 meters deep between them, allowing excess limestone sediments produced by the reef to drain out into deep water. Unlike Bikini Atoll spur and groove morphology, with clearly erosional channels carved out of rock, Jamaican reef channels were depositional and completely covered with living corals, so he named it buttress and canyon morphology to highlight the fundamental ontogenetic difference with spur and groove reef structures [1, 42].

Unfortunately, constructional reef channels have largely continued to be called spur and groove by coral researchers, thereby confusing their origin. The two represent entirely different phases of coral reef growth and wave interaction. During rapid vertical reef growth, sand channels allow flushing of wave-driven water into the reef and the much larger volume of sediments produced by the reef to drain out into deep water. If the reef is shallow behind the reef crest, or fringing land, sand will accumulate in the lee of the reef, reducing outward flushing of sediment into deep water until the reef reaches sea level, and no further vertical growth can take place. At this point, the reef fills in and becomes a solid wall, greatly increasing the force of erosion on the forereef, as waves are now reflected since they can no longer flow over and through the reef. Waves reflected from a vertical wall receive a horizontal force that is twice the energy of the wave, because the wave reverses direction but does not lose strength in perfect reflection [42].

Reefs go through an aging cycle, starting from porous permeable rapidly growing structures with high throughflow, transforming into mature impermeable structures receiving the full force of the waves on the outer perimeter. Few measurements of reef physical, chemical, or biological performance take maturity of the reef structure into account, and this varies so much between reefs that measurements of reef flow in one reef will not be representative of another reef with different morphology, history, or wave climate, or even the same reef at a different stage in its life history. As a reef matures, the volume of internal negative spaces, their interconnections, and their throughflow, along with the physical, chemical, and biological processes dependent on them, are greatly reduced. As they evolve, reefs alter internal permeability through space filling growth of organisms in crevices, and through active formation of new holes by bioerosion of boring sponges, worms, sea urchins, clams, algae, and bacteria that pump water through the holes to meet their food and waste needs [1]. Finally, there are submarine lithification and cementation effects that depend on local factors. In high, wet, limestone islands like in Jamaica, the flow of groundwater percolating through the reef cements the entire reef framework into solid limestone rock, filling voids so thoroughly that the rock requires dynamite to excavate [43]. In sharp contrast, atoll reefs around low islands that lack groundwater flow, such as the Maldives, have essentially no internal reef cementation, and the entire framework consists of loosely attached corals that can easily be pulled apart from the reef by hand. On the other hand, some younger atolls, such as in the Tuamoto Archipelago, have internal hydrothermal circulation generated by residual heat from the buried volcanic formations around which the atoll grew as the volcano subsided [4], which draws deep ocean waters into the base of the atoll and causes internal cementation of sediments [44].

7. Electromagnetic fields and energy

The electrolysis process depends on flow of electrical current through the water and is therefore clearly affected by water flow patterns. Even though it has been long known that marine larvae are electrically polarized and migrate to the negative terminal in a DC electrical field, little work seems to have been done on electrotaxis of marine larvae since the 1970s although the method is used by scientists to collect fish eggs, fish larvae, and zooplankton [45]. Sea water electrolysis greatly enhances settlement of sessile marine organisms, and motile organisms are attracted in large numbers, especially juvenile fishes, as well as zooplankton at night [16, 46]. The electrolysis process appears to create biophysical conditions that increase biochemical energy production in marine organisms [15, 16]. The benefits are seen in increased growth, settlement, survival, and resistance to extreme stresses in all taxonomic groups, both animals and plants. The last universal common ancestor evolved the enzymes to make ATP and NAD used by all living organisms billions of years ago, perhaps using natural direct electrical currents in the sea caused by water movement, possibly in hot volcanic sea floor springs.

Since water is an electrical conductor, flowing through the earth's magnetic field as it is stirred by surface and internal waves, water currents, refraction, diffraction, absorption, reflection, etc., both electric and magnetic fields are constantly being generated. The fields generated are highest where there are strong water currents, and where waves break on shores or are focused on reef promontories, and may also be generated by fine-scale flow interactions with coral surface morphology. The electric and magnetic fields generated by breaking waves extend high into the atmosphere where they can be measured by satellites and deep into the ocean (Dommermuth, 2022, personal communication). Breaking waves cause an inverse energy cascade from small to large-scale motion that Dommermuth calls "The Ocean's Heartbeat," which drives the ocean's Langmuir circulation and stirs both the ocean and the lower atmosphere [47]. These natural fields can generate electrical currents high enough to exceed the sensitivity of sharks [48, 49]. Measurements of coastal turbulence show that the inverse energy cascade from small- to large-scale motion is largely driven by wave reflection from coasts and propagates to the interior of the ocean, rather than generated by open ocean wave breaking [50], which is no surprise since breaking free waves lack physical reaction forces caused by wave reflection [42]. There appear to be no direct measurements of the electrical and magnetic fields generated in coastal ocean waters, apparently due its lack of military importance (too shallow for submarines to hide).

Electrical currents are the driving force for of all biological energy production, but almost nothing is known about their natural or stimulated effects on marine environmental health except for natural history observations (16). The amount of energy radiated by the induced electromagnetic fields is given by the Poynting Vector, E x B, where E is the induced electrical field vector, B is the induced magnetic field vector, and the x represents the vector cross-product operation [51]. We hypothesize here that natural wave generated electromagnetic fields have fundamental biological benefits that are further stimulated by actively impressed electrolytic fields. In addition to electromagnetic fields developed in the water, eddy currents should also be induced by wave turbulence in the conductive steel frame itself. Direct measurements of induced low-frequency electrical and magnetic fields in the water, whose ultralow-frequency electromagnetic energy spectrum is unknown due to lack of direct measurements, will provide fundamental insights into these physical processes, their biological consequences, and how to manage them most effectively to regenerate marine ecosystems for climate change adaptation.

8. Conclusions: electric reefs for climate change adaptation

Reef ecosystems, and their invaluable and irreplaceable ecosystem services, are collapsing worldwide. Electric reef technology offers the first real hope of not only slowing the decline, but reversing it, and of amplifying the structural benefits beyond what could happen naturally, in site-specific problem-solving strategies. Corals are sick to death of humans, and electrolysis gives them an energy recharge to survive severe stress. Electrolysis technology will be an irreplaceable tool for adapting to climate change that already exceeds anything in human experience. Electric Reef Technology provides the first hope of reversing deterioration, regenerating ecosystems on large scales, increasing ecosystem service benefits even beyond those of natural reefs, and in locations where natural reefs cannot grow. More basic research is needed to understand the biophysical and biochemical mechanisms behind the benefits seen, and optimize them for rapid large-scale climate change adaptation and marine ecosystem regeneration.

Electric reefs mimic all functions of real coral reefs, but are more versatile because they can be rapidly built at places where thousands of years would be needed for natural growth under the best conditions. Electric reefs can be built in zones that are dead due to extreme conditions, severe pollution, even dead zones. Electric reefs grow back severely eroded beaches at record rates [21, 26] at a small fraction of the cost of seawalls and breakwaters that increase erosion in front of them, and with vastly greater benefits than concrete and rock structures by restoring marine ecosystem services and fisheries habitats [18]. They are the only method known to protect corals from dying during extreme high temperature events, which are becoming more frequent and severe [2].

Electric reefs grow solid rock frameworks of any form upward at up to 2 centimeters per year or more, 2–3 times harder than concrete [14]. They provide the only shore protection that grows to match sea level rise and provide adaptive protection that will never be overtopped by sea level rise, like seawalls will, only by extreme wave events. Electrolysis provides superior, lower-cost alternatives to protect coasts and regenerate collapsing fisheries to create sustainable Blue Economies and Blue Carbon sinks than any known alternative.

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Conflicts of interest

The author has worked on applications of the Biorock seawater electrolysis process with the late Wolf Hilbertz since the 1980s and coined the phrase “Biorock” as the generally accepted synonym for electrolytic marine materials previously called “Seacrete,” “Seament,” “Mineral Accretion,” or “Electric Reefs” in order to emphasize its growing and auto-repairing nature, similar to corals. He has never made any money from this work; instead, it consumed all his very limited resources.

Web links

https://www.globalcoral.org/biorock-brings-corals-back-in-ambon/
https://blueregeneration.com/#.

https://www.globalcoral.org/biorock-electric-coral-reefs-survive-severe-hurricanes-little-no-damage/
https://www.youtube.com/user/TheBiorockChannel
http://www.pacinternational.org/
https://en.wikipedia.org/wiki/Extra-low_voltage

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