Electrically stimulated artificial mussel (Mytilus edulis) reefs to create shoreline protection and coastal habitat in St. Margaret's Bay, Nova Scotia.

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Abstract

Infrastructure designed to protect coastal environments, such as seawalls, can have adverse effects on the area they are supposed to protect. Hard shore armouring can be expensive, disrupt hydrodynamic processes, eventually rebuilding, and impact the surrounding marine environment. Artificial reef structures built with mineral accretion technology (MAT) grow stronger over time and improve corals' and other reef-forming organisms such as blue mussels, growth, and survival. MAT reef structures develop through the seawater electrolysis reaction. By adding a current to a sacrificial anode, an electrical field envelops a cathode (the steel artificial reef structure), causing dissolved minerals to accrete. Seeding MAT installations with shellfish such as blue mussels add ecosystem services such as improved water quality through filtration and complex habitat creation to the reef structure. A literature review was conducted to determine the feasibility of a proposed MAT installation in St. Margaret's Bay, Nova Scotia, an atypical cold-water region with low dissolved carbonate mineral levels, to benefit blue mussel habitat construction. The ability to grow engineered living breakwaters with little electrical input and locally accessible materials presents a sustainable, cost-effective solution for coastal communities that require shoreline protection and marine habitat reconstruction.

Keywords: *Biorock™, Blue Mussel, Reef, Living Shoreline, Shoreline Protection, Marine Habitat Reconstruction, Mineral Accretion Technology, Engineered Living Breakwater*

Chapter 1 Climate Context

According to NOAA's historical records, the steady rise of annual atmospheric CO2 coincides with the industrial revolution that spanned from 1750-1860 and has continued to the present day. Specifically, the atmospheric concentrations of naturally occurring greenhouse gases—carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) - have significantly increased since 1750 (Bernstein et al., 2008). The concentration of these greenhouse gases has caused a scenario where the planet has not effectively expelled enough solar energy than the pre-1750 period, thus increasing overall retention of energy, which has caused the planet to warm up incrementally dangerously from a natural environment and human systems standpoint.

While the planet as a whole is warming, individual biospheres are absorbing the heat more than others. The ocean has absorbed over 90% of the extra energy retained by the Earth in the last 50 years (Zanna et al., 2019), resulting in increases in temperature in the water column. Much like the differences in the Earth's biospheres, the warming of the Earth's oceans is also heterogeneous. Certain areas, such as the Arctic and the East Coast of North America, are warming faster than others (Post et al., 2019; Saba et al., 2016). Increased sea-surface temperatures can be the driver for a wide range of environmental issues that can negatively impact the coastal environments, regions relied upon by a significant portion of the human population (UNESCO, 2017). Situations such as the shift in the spatial range of environmentally and commercially important marine species, increased vulnerability of marine species to disease, and increased severity of dangerous climatic events (e.g., hurricanes) will have grave consequences. However, these are only some of the numerous impacts humans face and will continue to face as this warming trend continues.

Since at least the year 1900, the global mean sea level (GMSL) has been driven by three principal factors. Terrestrial water storage, melting ice caps, and thermal expansion of seawater have caused fluctuations in the rise of GMSL (Frederikse et al., 2020). Added to this have been local changes (such as subsidence in Halifax, Nova Scotia) in the height/depth of the crust to the relative sea-level rise (RSLR). In concert, these drivers have begun to shift global climate processes, raise sea levels across the globe, increase destructive storm activity, and much more (Mann et al., 2017). The impacts on the ecosystems we depend on and socio-economic and health effects on humans are never-ending. Many climatic simulations and models predict the ocean's encroachment upon coastlines as significant and of dire importance. For example, over 40% of the global population lives within 100 km of the coast (UNESCO, 2017). More importantly, 10% of the world's population lives in low-lying coastal cities at threat of rising seas and dangerous storm activity (McGranahan et al., 2016; Wahl et al., 2018). Countries such as Guyana, Maldives, the Pacific Island Nations such as Tuvalu and Kiribati, Thailand, and Mauritania have all or most of their population living in low-level coastal zones (Colenbrander et al., 2019). Even 77% of the Netherlands' population is in low-elevation coastal zones, with a significant portion below sea-level.

Chapter 2 The Coastal Impacts

The capacity to protect the coast, and the methods proposed, vary widely from policies, hard and soft armouring, retreat (physically move populations back from the coast), accommodation (allowing for some flooding/damage), and even abandonment. The Netherlands has the Maeslantkering, a floodgate the size of two Eiffel Towers (The Dutch Solution to Rising Seas, 2018). The structure is a marvelous feat of engineering that may be beneficial for many countries. However, its construction is costly and relatively inaccessible to many coastal countries that could benefit the most. Additionally, the Netherlands has taken an approach that seeks to work with the elements rather than fighting against them by allowing waterways to expand when large volumes of water enter the country. The solution works with the threat rather than against it. The idea is that lakes, gardens, basketball courts, open-air theatres, parks, and plazas could also double as enormous reservoirs when the seas and rivers spill over (The Dutch Solution to Rising Seas, 2018). Of course, this is not practical for every coastal region. Many more countries fear rising sea-levels and the increase in destructive storm activity linked to warming oceans. More and more individual extreme and increasingly routine weather events cause billions of dollars’ worth of damage. As humans increase, investments, development, and populations near the coast, the risk and cost of damaging storms become greater (IPCC, 2018).

Protecting these investments and populations should be of great importance; great may well be an understatement. Nevertheless, the actions of some countries, states, and municipalities may well be slow or minimal relative to the risks and costs. There are several barriers to responding, reacting, or being proactive in the face of such daunting issues. The interests of stakeholders often dictate whether or not a project is seen as cost-prohibitive, a threat to the environment, sustainable in the long term, or socially and culturally acceptable, which is especially apparent in large coastal cities where such a large number of diverse stakeholders use, depend on or own property in the coastal space. Additionally, it becomes more complex to plan in such a way as to ensure coastal spaces are retained for the generations ahead. The reality of coasts giving people a sense of place is sometimes ignored, but it is central to protecting the coastal environments beyond quantitative measures.

It is becoming increasingly important for communities and multiple government levels to start managing coastlines in the context of the above. Without a sound strategy, citizens and infrastructure are increasingly susceptible to coastal erosion and flooding due to altering sea levels. Failure to act can have severe economic and social effects, especially along coastlines used for tourism and industry. Management of coastlines is also vital to help protect natural habitats; however, governments generally do not engage in coastal management when there are risks of adverse economic impacts as effective coastal management is costly to implement and may well cause economic activities to decline. When considering coastal defence, there are five available options (Figure 1):

1. Hold the line: Where existing coastal defences are maintained and improved, but no new defences are set up.
2. Advance the line: New defences are built further out in the sea to reduce the stress on current defences and possibly extend the coastline slightly.
3. Limited intervention: An action taken whereby the management only addresses the problem to a certain extent, usually in areas of low economic significance.

Limited intervention often includes the succession of haloseres, including salt marshes and sand dunes.

4. Retreat the line (surrender): Move people out of danger zones and let the elements unleash and take control.
5. Do nothing: The easy option, deal with the effects of flooding and erosion as they come or ignore them. Taking no action is what typically happens in areas where there are no people and nothing of "value" (to the government) to protect.

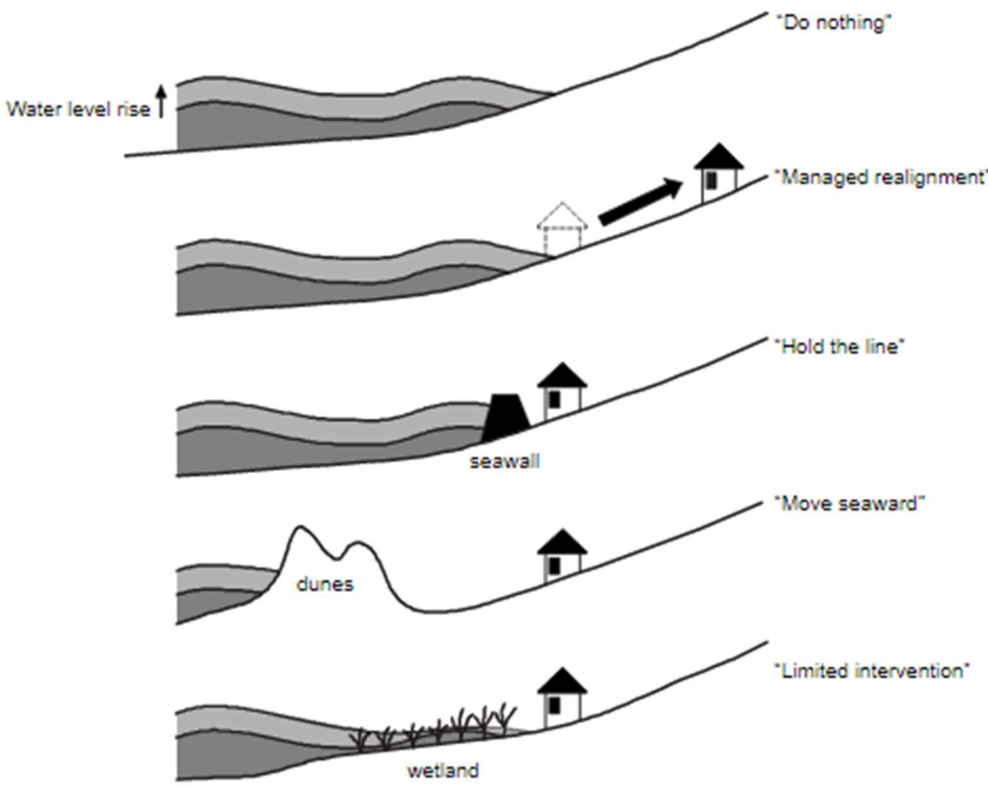


Figure 1 Five Coastal Policy Options (Five Policies, n.d.).

Chapter 3 Hard and Soft Solutions

When discussing coastal defence methods, there is a spectrum between hard and soft armouring options. As usual, hard engineering techniques such as seawalls, groins, and detached breakwaters, artefacts borrowed from port design and construction are high technology, high cost, human-made solutions. There are no structures or techniques that stand a chance in lasting the test of time against the ocean's never-ending erosive and destructive power. They tend to be invasive, produce lots of emissions with the required construction materials, and alter natural processes, despite their initial signs of perceived success (Goudas et al., 2003). A hard shore protection structure's function is to resist and deflect the ocean's impact rather than dissipate and remain resilient over time. They are a terrestrial solution to a marine problem. Figure 2 illustrates the effects of seawalls using the Vancouver seawall as an example. Over the sea wall's lifetime, the waves crashing against the solid flat surface have eroded the beach by pulling the sand back into the ocean.

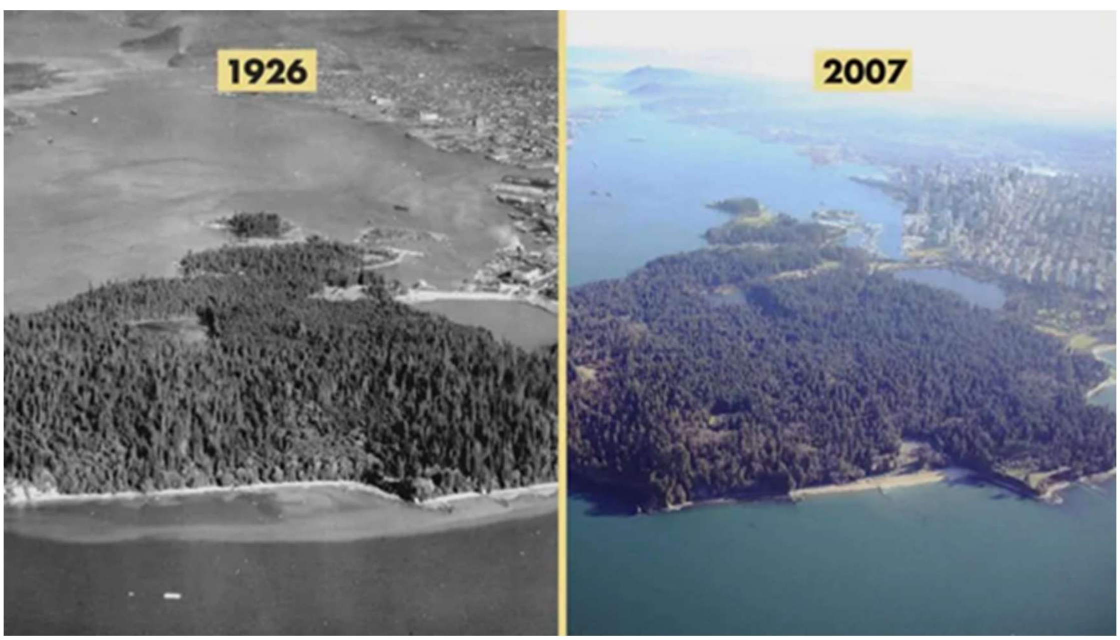


Figure 2. Beach erosion at the Vancouver Seawall 1926-2007 (Uytae Lee/About Here).

Soft shore protection techniques such as beach nourishment, submerged breakwaters, artificial reefs (AR), gravity drain systems, floating breakwaters, plantations of mangroves and seagrasses are low-tech, low-cost solutions, relative to hard shore protection methods, that work to reduce erosion by being more resilient. It is worth noting the difference between artificial techniques (i.e., using only human-made materials) and techniques described as living-shoreline protection methods. Living shorelines emphasize the restoration and enhancement of ecosystems that contribute to shore protection as an ecosystem service (Gittman et al., 2016). Living shorelines can be combined with a variety of human-made coastal protection techniques as well. Another benefit of incorporating living elements into a shoreline protection plan is creating new habitat and the continuity it provides by connecting habitats between land and sea, rather than fragmenting them (Munsch et al., 2017). Instead of statically resisting the ocean's forces, these techniques offer slight resistance by moving with the forces and creating drag or are porous like a reef structure and dissipate wave energy. They are nowhere near as immediately effective as hard engineering techniques, but they tend to be far more sustainable and are intended to improve over time (MacDonald, 2018). Combining an array of soft shore protection methods may offer better results than a single method, especially when using living shoreline techniques (Figure 3). Like in nature, landscapes are variable and composed of several biotic and abiotic layers contributing to their structural integrity and resilience.

Figure 3 Before, during and after a Living Shoreline installation ("Helping Nature Heal", 2017).

Chapter 4 One Potential Defensive Solution

The proposed solution to address the management problem of implementing a coastal defence strategy that is effective and sustainable is mineral accretion technology (MAT), or formerly patented and protected under the Biorock™ technology. Originally invented by the late Dr. Wolf Hilbertz and adapted to marine reefs by Dr. Tom Goreau, Biorock™ technology takes advantage of electrolysis reactions in seawater. By injecting a weak current into a positively charged anode, using seawater as a conductor, and steel as a negatively charged cathode, the reaction creates a localized environment that attracts calcium carbonate to precipitates to the cathode. The aggregate material that accretes on the steel cathode acts as an extremely strong sea-based 'concrete' derived from the calcium and carbonate ions freely available in seawater. With continued weak electrical stimulation, the accreted material grows and increases in strength over time. Through this seawater electrolysis process, the inventors and other researchers have demonstrated the technology's ability to enhance several marine species' growth and survival. These include habitat-forming species such as stony skeleton reef-forming corals, reef-forming oysters, meadow-forming seagrasses, and saltmarsh plants such as spartinas (Goreau, 2012a). It has been demonstrated that when a Biorock™ structure is damaged, the damaged area grows back first, before any additional growth in other parts of the structure. This feature makes it a self-healing marine construction material that promotes the rebuilding of marine habitat rather than destroying it. To support more uptake, the developers founded the Global Coral Reef Alliance (GCRA) to pursue research and development of the technology and understanding of uses and impacts. Moreover, since the patent's expiration, new research from new organizations have spurred innovative progress towards the evolution of the technology to make it more effective.

Chapter 4.1 The invention of Biorock

In a time of rising seas, increased storm activity, and accelerated erosion, there is a need for a superior material to protect the coast. MAT can grow a rust-proof material on-site using calcium ions floating around in seawater. When active, it becomes self-repairing and self-adhering, which means it costs less than typical coastal defence materials like steel, concrete, or reinforced rubber mats. The late Professor Wolf Hilbertz invented the original sea-based concrete material that he called Biorock. Inspired by the mechanisms with which some marine animals, such as corals and shellfish, could transform seawater's dissolved minerals into consistently intricate calcareous shells and skeletons, Hilbertz described the Ocean as the World's largest mine. By placing structures made of a conductive material, such as steel, and given a small electrical charge, Hilbertz catalyzed a seawater's electrolysis reaction. In this process, a direct low voltage current is applied to two metal pieces submerged in water. At one end of the circuit, called the anode, electrons flow from the wire into the water and cause water molecules to disassociate and oxygen to form. The water's pH surrounding this area lowers and becomes more acidic relative to seawater. For this reason, the anodes are much smaller than the cathode and are encased. At the negative end of the circuit, also known as the cathode, electrons flow back from the water into the metal, causing water molecules to split up and release hydrogen bubbles into the water. At the cathode, the surrounding water's pH rises and becomes more alkaline than seawater. In these conditions, calcium, magnesium, and other minerals become insoluble in the water. The reaction and localized conditions attract calcium and magnesium minerals that dissolve in seawater to crystallize on the metal surface of the cathode as long as the system is powered, no matter the shape or size (Figure 4) (Hilbertz 1979). If the charging rate is kept sufficiently low, and the rock is grown at rates of less than about 2 cm per year, they are predominantly composed of calcium carbonate or limestone. Some of the most notable long-standing limestone structures include the Great Sphinx, the Parthenon, and the Great Pyramids. Engineering tests of mature accreted minerals show that they have a compressive (or load-bearing) strength of about 80 MPa, nearly twice as strong as the 41 MPa of Portland cement, the most widely used building material in the World (Goreau et al., 2013).

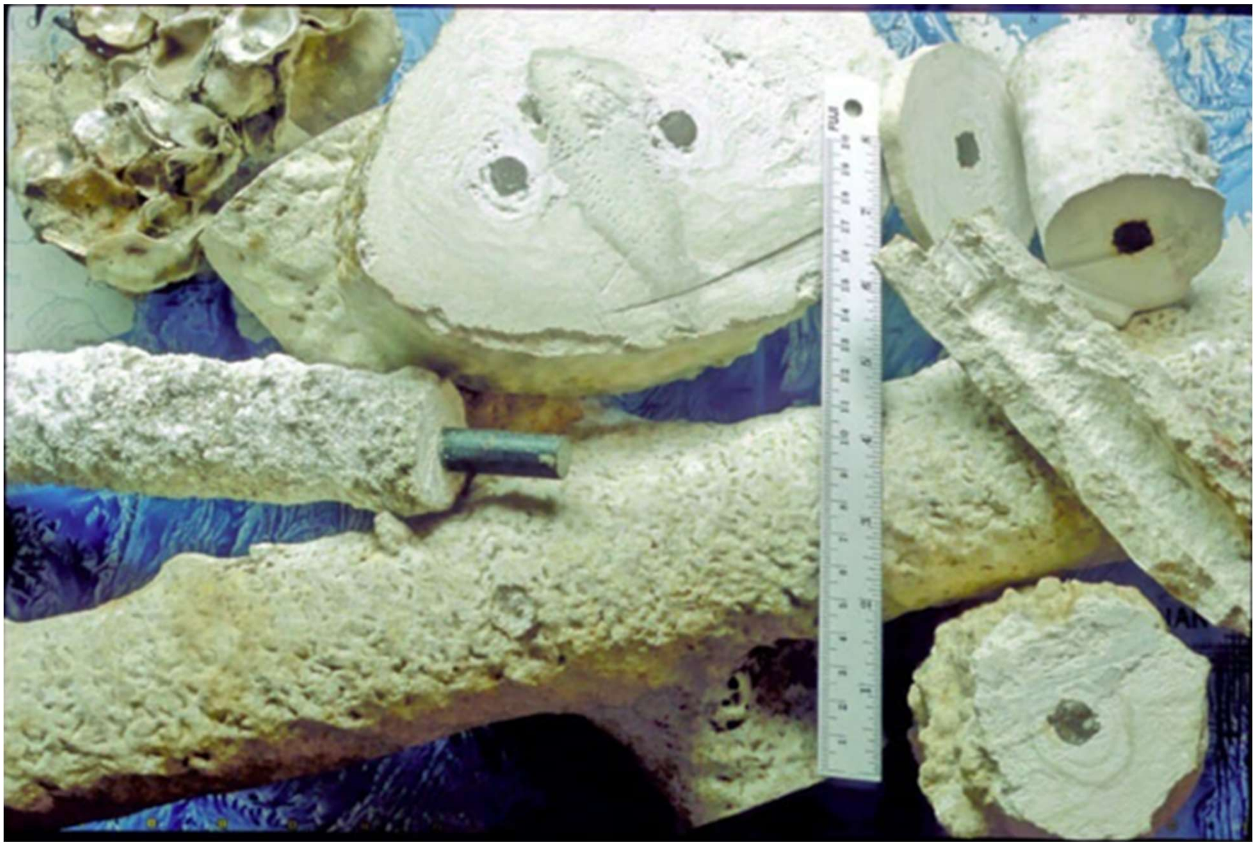


Figure 4. Biorock material grown in the Maldives. Photo by Wolf Hilbertz (mtessis, 2018).

This project aims to determine the feasibility of MAT in the Northwest Atlantic's cold waters as a method of coastal protection and habitat reconstruction. The feasibility was determined by conducting a literature review of MAT using Biorock™ as a search term and expanded upon by proposing an MAT reef installation based on the review and additional research. Specifically, the proposed installation of a MAT blue mussel reef at a coastal residential property in St. Margaret's Bay, Nova Scotia. During the preparation of the experiment, a series of steel reef structures, three experimental and one control, to test the efficacy of MAT in St. Margaret's Bay. The structures will have mussels hung within them to test the technology's effect on growth and survival. The proposed experimental installation aims to answer: 1) Which distance and power from the anode, and what amount of power is optimal for accreted mineral growth? 2) Which of the reefs will exhibit the best growth and survival? 3) If any, which of the reefs will exhibit the most spontaneous settlement of marine organisms.

Chapter 4.2 Potential impacts of the technology

The minute amount of electricity needed to grow Biorock™ from seawater makes it an intriguing material to investigate further since it could reduce costs, labour, transport, and emissions. As a critical input into concrete, the most widely used construction material globally, cement is a significant contributor to climate change. The chemical and thermal combustion processes involved in cement production play a key role in the major industries and processes that are responsible for CO2 emissions. According to Lehne & Preston, 2018, more than 4 billion tons of cement are produced each year, accounting for around 8 percent of global CO2 emissions.

A unique feature of MAT reefs is the technology's ability to promote the impressive growth of corals and other marine organisms (Figure 5). There are instances where observed growth was two to eight times faster than average, depending on the species and the conditions. They can rapidly create and recover ecosystems formed by habitat-forming species such as corals, oysters, and seagrasses. Corals growing on MAT reefs have, in some cases, 16–50 times higher survival from severe high temperatures and polluted waters than corals in surrounding reefs. The potential for increased survival means that coral reefs, some of nature's best shore protection, can be kept alive where they would die and restored in a few years in places where no natural recovery is taking place. There are also many non-coral organisms including coralline algae, sponges, stromatolites, archaeocyathids, bryozoans, rudists, and oysters that have formed reefs over millennia and still are today (Fox, 2005). "These communities are, in part, structurally and functionally similar to the terrestrial forests, with the main difference that they are dominated by animals instead of plants." (Rossi et al., 2017, p. 1). It makes them not only shore-protection devices but also highly valued fisheries habitat and ecotourism resources in front of the beaches they protect (Hilbertz and Goreau 1996; Goreau and Hilbertz 2005). MAT reefs can help construct habitat and provide shore protection without reef-forming organisms in places where they do not naturally occur or where environmental conditions are poor. Meta-analyses by (Ferrario et al., 2014) demonstrate that coral reefs are a substantial coastal defence asset by reducing wave energy by an average of 97%, and reef crests alone disperse most of this energy (86%).

Figure 5. Coral growth after 24 months with MAT (left) and without (right) (The Basics, n.d.).

Chapter 5 Methods

Chapter 5.1 Literature Review

A literature review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Figure 6). A literature search was conducted using a combination of search terms, including 'Biorock AND mineral accretion,' to identify papers that contained these within titles, keywords, or abstracts. An initial search of the online databases Scopus and Google Scholar identified 119 records. An expanded search to include entire articles using the above terms was performed on Scopus and Google Scholar to reveal an additional 46 records. Once duplicates from these results were removed, the search garnered 153 unique results. An additional screening step was taken to quickly remove unrelated records with titles including repeating words such as leachate, clogging, and modelling identified 32 ineligible records for removal. There is a method of processing sewage with the name “BioRock” that came up in many of the searches. The relevance of Biorock™ or mineral accretion technology regarding habitat restoration, coastal protection, and social impacts was reviewed for the 94 articles assessed for eligibility. Assessing the 94 articles' full text helped identify 37 records to exclude, leaving 57 studies included for quantitative synthesis. From each study, the following information was recorded: publication date, field study location, study purpose, and research topic. The information recorded from these studies was then sorted and analyzed to help draw more general conclusions about the application and effects of Biorock™ and mineral accretion technology for habitat restoration, coastal protection, mineral accretion, and social impacts.

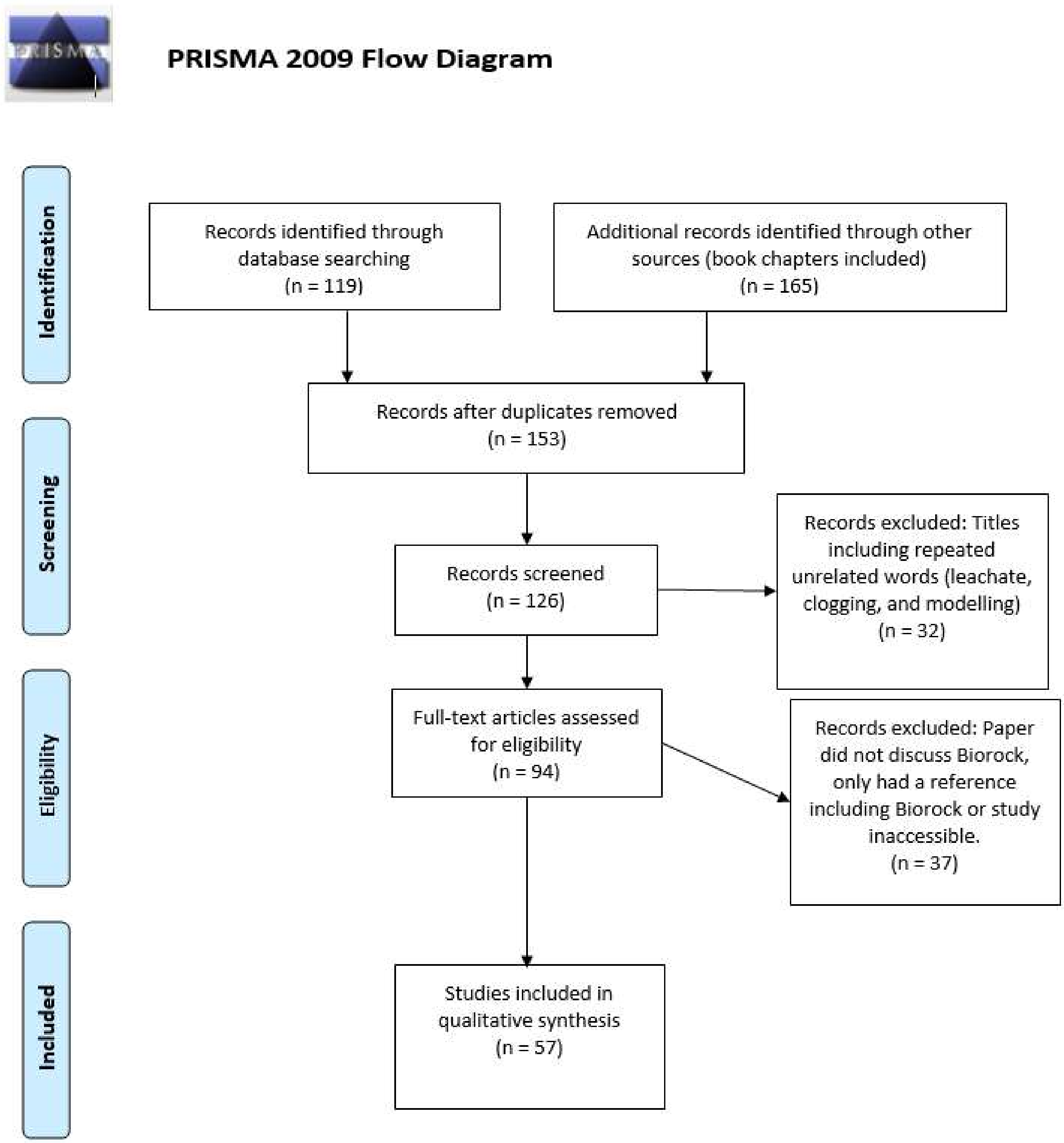


Figure 6. PRISMA framework used to guide Biorock literature search.

Chapter 5.1.1 Locations

Study locations were mapped worldwide to illustrate where MAT projects were implemented and field-tested. Providing the locations of field studies identified in the literature review provides an understanding of the variety of places MAT has been tested and implemented and helps to identify environments where the technology has not been tested. Other MAT project locations were identified from sources outside the reviewed records.

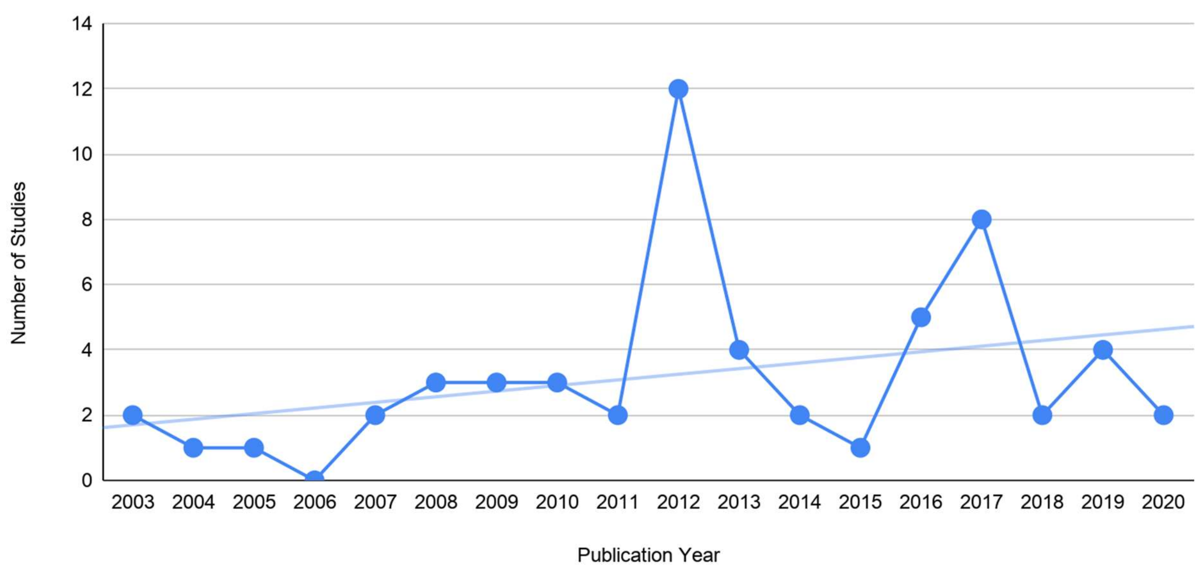
Chapter 5.1.2 Purposes

The purpose of each study was identified within the introduction section of the papers and recorded. Purposes were grouped using commonly stated objectives to determine general trends. Given the criteria for selecting review papers, all studies were sorted based on the purpose of the study being the field testing, implementation, lab testing, reviewing, the social impacts, or theoretical application of Biorock™ and MAT. The study purposes were developed based on the trends that surfaced while assessing the 51 included articles. It is important to note that not all records exclusively discuss Biorock™ and MAT. Some records that had sections dedicated to either were included as well.

Chapter 6 Literature Review Results

Chapter 6.1 Publication Dates

The search for primary literature that discussed Biorock™ and mineral accretion technology for coastal protection, habitat restoration, and social impacts yielded 57 studies. In general, there was an increase in the number of studies that have tested or discussed Biorock™ and mineral accretion technology for coastal protection, habitat restoration, and social impacts over the last 17 years; the earliest being published in 2003 (Figure 7). It is important to note that the book Innovative Methods of Marine Ecosystem Restoration by Dr. Tom Goreau was released in 2012, the year with the most publication. The book is dedicated to studies using MAT, which positively contribute to the overall trend. It is also important to note that these studies are only found in the book and do not appear in peer-reviewed journals.



Chapter 6.2 Distribution of Research Topics

The goal of the review process for this paper was to identify records that investigated the impacts of Biorock™ and MAT on coastal protection, habitat construction, mineral accretion, and the social dimensions of coastal communities. Figure 8 shows the distribution of study topics across the 57 records that were included in the review. The most present topic was the use of the technology in the context of rebuilding coastal habitat. 88% of the reviewed records tested or discussed the impacts of the technology on the growth, survival, and settlement of marine species, or as an AR to rebuild lost or destroyed coastal habitat. 66% of the records included experiments or discussions regarding the mechanism and use of the technology's mineral accretion properties. Some were related to building coastal habitat, while others discussed using the encrusted rebar as sustainable building materials and the best materials for optimal mineral accretion quality and rates. Social impacts were not originally part of the study topic; however, several records discuss the impacts of MAT projects post-installation and operational or the potential social benefits associated with implementing the technology as a community project. Several records investigated social impacts at a particular site in Pemuteran, Bali, Indonesia, home to the world's largest continuous aggregation of MAT structures, measuring over half a kilometer wide.

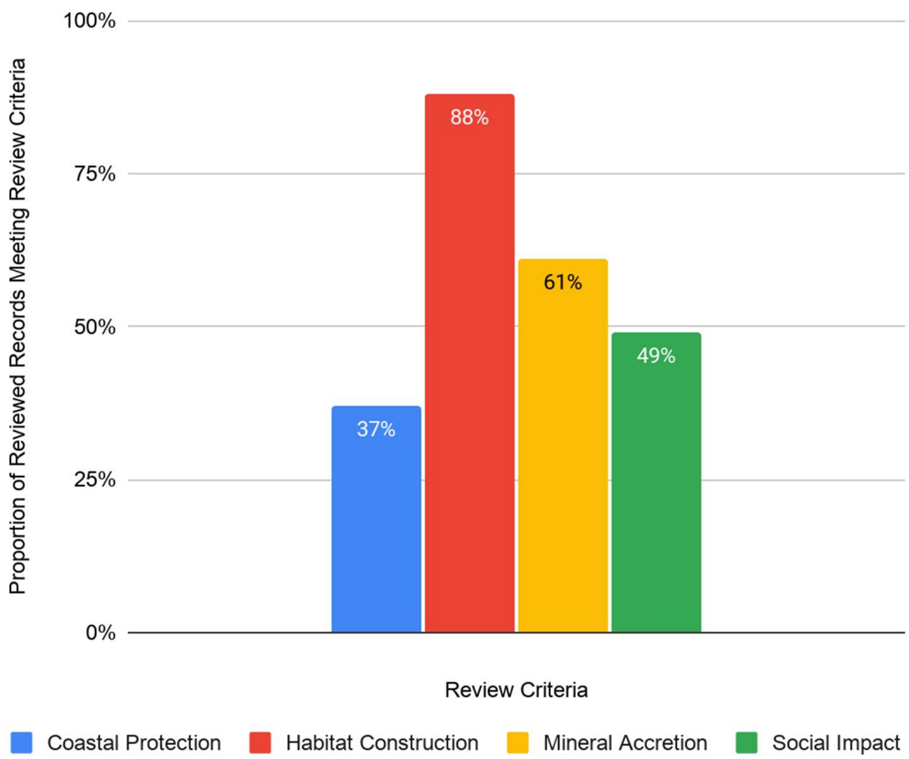


Figure 8. Distribution of study topics.

Chapter 6.3 Distribution of Study Purposes

The 57 studies' purposes were organized into five categories that were created based on observed patterns amongst the records (Figure 9). The identified categories are studies or book chapters whose primary objective was to investigate lab testing, field testing, review, theoretical applications, and social impacts of MAT installations. Studies that reported the findings from field testing and discussed the social impacts of MAT installations were the most common in the literature review with 20 and 11 studies, respectively. Field testing and social impacts accounted for 31 of the 57 of the reviewed literature, over half of the studies. Some of the records classified as field testing included a lab testing component but were classified as such since the field testing was the article's primary concern. Lab testing was limited to studies with lab experiments that did not include a field component. Nine studies fit within the lab testing category. Within the records that discussed the social impacts of MAT installations, nine of the 11 were linked to the technology's impact on tourism. The theoretical application category was defined by studies that discussed potential uses of the technology without carrying out any physical testing or implementation of MAT. Please note that social impacts and theoretical applications were, in some capacity, present in records that were categorized as field tests, lab tests, and reviews. However, they were not the primary focus of the article.

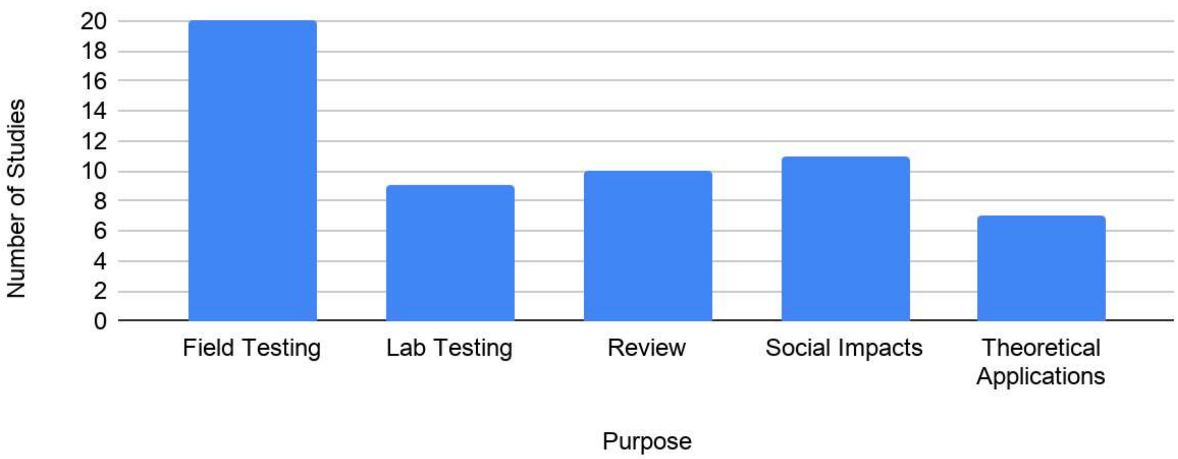


Figure 9. Distribution Study Purposes

Chapter 6.4 Field Study Location Distribution

The locations of the 19 MAT installation field studies identified in the literature review were recorded to display the variety of locations where the technology has been applied. Note that other MAT structures exist other than those identified in the literature review. MAT installations have been deployed for over 25 years at over 100 sites in over 20 countries ("Biorock," 2020). The Java Sea holds the most MAT field studies (n = 6). Otherwise, there are studies in the West coast of the North Atlantic (n = 3), near the Caribbean Sea (n = 4), the North Sea (n = 2), the Adriatic Sea (n = 1), the Celebes Sea (n = 1), the East China Sea (n = 1), the Gulf of Thailand (n = 1). Note that there has not been a study in Atlantic Canada; therefore, the build associated with this project will be the first in the region.

Chapter 7 Case Studies

The purpose of this research was to evaluate the feasibility of creating a mussel reef using mineral accretion technology in St. Margaret's Bay, Nova Scotia while identifying potential barriers and opportunities to realizing a project of this kind. The reviewed literature concerning MAT in the context of mineral accretion capacity, habitat reconstruction, coastal protection, and social impacts provided information useful for determining the feasibility of implementing the technology in St. Margaret's Bay given various opportunities and barriers. The analysis of the successes and failures of two case studies, identifying the benefits and barriers of implementing MAT in St. Margaret's Bay.

Chapter 7.1 Biorock® Indonesia:

In Indonesia, coral reefs cover an estimated 51'000 km^2. Approximately 36% (18.315 km^2) of coral reefs have been destroyed, and the numbers have struggled to improve over the last several years despite the efforts of various coral reef restoration (Yudiarso, 2019). For nearly three decades, Indonesia's mangrove coastline has declined due to coastal developments such as shrimp aquaculture. Shrimp aquaculture is a rapidly growing industry in Indonesia, and it is now the 2nd largest cultured shrimp producer in the world behind China. Environmental impacts such as the destruction of critical habitats, the effluent of wastewater, disease outbreaks, mangrove deforestation, and escapees of non-endemic species occur. Statistics show that Indonesia has lost 40 percent of its mangrove forests, mainly due to mangrove areas' aquaculture occupation, which is also consistent with the increasing agricultural coastline trend in these statistics (Sui et al., 2020). These coastal activities' impacts also affect coral reefs and seagrass meadows, both interdependent ecosystems with mangroves that are major blue carbon sinks (Watanabe & Nakamura, 2019). Upon coral reefs, blast fishing with dynamite and cyanide poison is also used for both food and aquarium trade (Halim, 2002). The cost of destructive fishing methods in Indonesia negatively impacts reefs at an estimated opportunity cost of more than $300,000 per km2 of coral (Pet-Soede et al., 1999). The Marine Recreation Park Gili Matra, on the north-west side of Lombok Island in Indonesia, is one of the areas that has been affected by these damaging activities.

One of the most critical efforts in rehabilitating and conserving coral reef ecosystems in Gili Matra was establishing a MAT project with the Biorock™ Company in 2004 by the Gilli Eco Trust (GET) initiative. The initiative was called the Biorock™ Coral Reef Restoration Program, and it was implemented in 2006. Funding for the program comes from a "reef tax" paid by each person that dives in the area. The program was a critical measure for ecotourism purposes and benefited damaged reefs that cannot recover naturally. It has gradually developed into a robust reef system that supports a complex diversity of marine life in the waters of the Gilis and helps prevent the increasing issue of erosion. The harmless electric current catalyzes electrolysis and precipitates calcareous material upon the underwater structures. These have prevented unwanted rust that would weaken the structure, and due to the reaction, provide an optimal substrate and water chemistry for corals to grow resiliently. There are three types of MAT structures installed around Gili islands:

1. MAT reefs to grow corals and provide new fish habitats
    a. There are over 90 structures dedicated to regenerate Pemuteran's coral reefs (Erapartiwi, 2019).
2. Anti-erosion reefs to grow corals and provide fish nurseries as well as breaking the wave's energy
3. Wave breakers to stop the erosion and get our beach back

At the time, the former Biorock™ technology was a revolutionary technology used to grow and preserve marine ecosystems cost-effectively and sustainably, particularly in areas where environmental stress has affected existing reefs. MAT reefs have already been installed on the coast of several islands worldwide and have been shown to increase coral growth rates from 3 to 5 times their average rate. It increases coral survival and accelerates coral growth under higher water temperatures and pollution 16 to 50 times. So far, the rehabilitation process is still going on and has shown some progress in terms of coral recovery. However, it needs a long time to recover fully.

Some other programs that were also promoted by GET in collaboration with SATGAS (local security on the Gili Islands), BKSDA, and Mataram University are to study the rate of bleaching coral in natural conditions and on MAT reefs. In 2010, another structure called "juvenile grouper structure" for fishermen in the Gili Air area to culture their own fish was proposed. Another important program is managing existing mooring buoys and prohibiting boat mooring, especially in shallow reefs and reef gardening. Collaborating with the Biorock™ company to implement MAT reef projects in MWTA-GM has been very strategic to rehabilitate and conserve coral reefs faster because Fox et al. (2003) found that in Komodo National Park and Bunaken National Park, Indonesia showed that within nine sites monitored since 1998, there was no significant natural recovery. They recommended better comprehending the prognosis for coral recovery to assess the long-term impacts of blast fishing and improve management decisions about protecting intact reefs and potential restoration of damaged areas.

Officially established in 2015, Biorock® Indonesia (BI) is an organization that assists in the implementation and monitoring of MAT projects in Indonesia with effective practices. With 20 years of experience, Biorock® Indonesia works directly with more than 1000 local communities in 14 villages in 6 provinces of Indonesia, including Bali, North Sulawesi, Maluku, West Nusa Tenggara, East Nusa Tenggara, and DKI Jakarta. It has reached several national and international governmental level milestones ("Pemuteran, Bali," n.d.). The efforts of BI have contributed to restoring an estimated 200 km^2 of coral reefs and 5 km^2 of shoreline. One of the most significant and earliest projects that started in 2000 is a chain of over 115 MAT reef structures that stretch over half a kilometer wide in Pemuteran, a region in Bali ("Pemuteran, Bali," n.d.). The site remains the largest MAT reef project in the world. Valuations by Trialfhianty & Suadi, 2017 reported a five-fold increase in diving at the reef restoration site valued at USD$ 62,932, and Suadi, from Gadjah Mada University, estimated an economic yield value of USD$ 115,158/year (equal to 1,532 Billion Rp.) with a 70% of participation rate of villagers in the project ("Pemuteran, Bali," n.d.). The cost of building and installing a MAT reef to grow corals has an approximate cost of Rp. 30 million, or USD$ 2,140. A coral reef adoption strategy was implemented to finance efforts to develop coral reefs. Tourists who visit or other communities can donate Rp. 400'000 (Approximately USD$ 30) for the development of one coral reef and their names would later be pinned on the reef (Erapartiwi, 2019). Today, Pemuteran village is a highly sought-after destination for beaches, well maintained coral reefs, and a slow-paced lifestyle. Pemuteran village's success can be attributed to community-based tourism they have implemented and have acquired international praise and awards on their coral reef conservation, assisted by local communities, and modern technology (Satyarini et al., 2017). Trialfhianty & Suadi, 2017 reported that the community's participation was linked to its proximity to the sea or the project area (Figure 10).

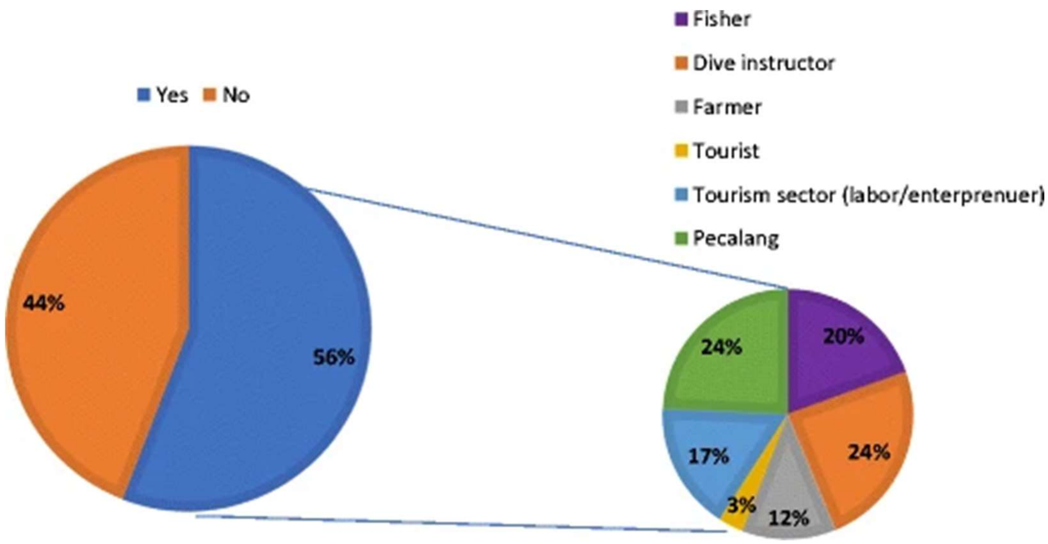


Figure 10. Pemuteran community participation distribution (Trialfhianty & Suadi, 2017).

Many factors have contributed to the success in growing the eco-tourism sector in Pemuteran. Once a poor village, it is now an excellent example of community-based co-management. Various marine space users have come together to involve themselves within a goal whose sum is greater than its parts, and each player has benefited from working collaboratively. By investing in the environment through the 2000 investment in MAT reefs, Pemuteran village successfully restored its reefs to a level that attracted visitors worldwide. Serving as a base, the positive results of coral growth and survival from the newly implemented MAT technology gained the village publicity, awards in the tourism and environmental sector, and community empowerment in economic activity. The Balinese individuals who have managed the Biorock® Indonesia projects are a core component of the project's success. By gaining the trust of the Pemuteran villagers, who had been one of the most impoverished villages at the time, Balinese conservationists translated and actualized local beliefs and philosophy, the Tri Hita Karana (three primary causes of goodness. The Tri Hita Karana creed emphasises the balanced and harmonious relationship between man, the environment, and the creator (pawongan/human, palemahan/environment, and parahyangan/God) (Trialfhianty & Suadi, 2017). By connecting with the villagers on a spiritual level (Figure 11), the Biorock® Indonesia group solidified the bond with the village of Pemuteran that assured them that investing in the coral reefs' health and survival would be the best investment the village could make. The case is interesting because the Biorock® Indonesia group succeeded in lifting the village out of poverty, something the government and other NGO's were unable to do previously. Over the past two decades, Biorock® Indonesia's growth and impact has saved several corals from dying and helped several corals grow resiliently and rebuild the necessary habitat for an array of marine life. The positive impacts have also lifted several communities to invest in eco-tourism and become stewards of coral reefs, just like Pemuteran village.

Figure 11. Community members praying before deploying their MAT structure (Trialfhianty & Suadi, 2017)

Chapter 7.2 Biorock® Technology Thailand:

Compared to Indonesia, the adoption of MAT has taken a different path. The Biorock™ Company had engaged in starting a chapter in Thailand, similar to the one that is thriving in Indonesia's Gili Islands. According to the Biorock® Technology Thailand website, the organization was created in 2005 and primarily operates as a non-profit group conducting community-based efforts, educational activities, and environmental awareness programs at a grass-roots level (Biorock Technology Thailand, n.d.). The website states that the organization offers several marine-based solutions ranging from shoreline protection to ecological tourist attraction sites upon request. However, the website is dated compared to its Indonesian counterpart, having no references for content past 2006. It is not easy to find exact information linked to the Biorock® Technology Thailand group and its recent projects.

The literature review did reveal some records that refer to the Biorock® Technology Thailand group. A study investigating the influence of mineral accretion induced on the settlement of the larvae and growth of the juvenile coral Pocillopoa damicornis Chavanich et al., 2013 explain in their methods that their study's experimental structures were built with the assistance of Biorock® Technology Thailand. Through further research within the grey literature, there are mentions of the group's activity in blog posts, articles, and travel websites, but nothing that genuinely confirms the status of the group's recent activities. The group may choose to position its focus on actions and projects and not marketing and documentation.

Another record that came to light through more in-depth research of the references of other Biorock™ related records was an internship report by Terlouw, 2012 studying coral reef rehabilitation on Koh Tao, a small island in the Gulf of Thailand primarily dedicated to diving tourism. The subtitle of the paper is "Assessing the success of a Biorock™ artificial reef." The report was written based on the research of Terlouw during two months of volunteer work at New Heaven Dive School Reef Conservation Program (NHRCP), and to write a literature thesis for her Masters in Chemistry at the Vrije Universiteit Amsterdam. NHRCP is a for-profit organization whose goal is to protect and reconstruct coral reefs while hosting educational internships for young career scientists to gain experience in marine management, coastal protection, and reef ecology. NHRCP offers instructional courses to assist interns in realizing their academic research and directly contributes to the conservation of Thailand's coral reefs through research and monitoring, reporting, mitigation, as well as active and passive restoration around the island of Koh Tao (About Us, n.d.). More importantly, NHRCP offers courses on mineral accretion technology (MAT). The course web page explains the history of the technology under the Biorock™ name and the positive effects the technology can have on coral growth and survival, much of which has been described earlier in this paper. The article explains that despite the technology being invented in the 1970s, few advancements in the efficacy and ease of use of the technology have been made, which is consistent with the findings of the literature review up until recent years. One of the main reasons for the lack of progress is the Biorock™ Company's patent protectiveness, their high fees for installation and maintenance, and lack of transparency concerning their system design (Mineral Accretion, n.d.; C. Scott, personal communication, November 17, 2020).

During personal communications with Chad Scott, the founder of NHRCP and the Conservation Diver program, it was brought to light that the Biorock™ Company had used outdated technology under the guise that their methods were proprietary and protected during a collaborative project in 2008. In only two years, the project, which was the largest MAT structure in the Gulf of Thailand and the most expensive project the NHRCP has undertaken, had lost power as a result of the quality of materials used during construction and the inability to monitor the status of the system's underwater transformer (Mineral Accretion, n.d.). Due to the lack of communication concerning the resources required for maintenance and high assessment and repair quotes from the Biorock™ Company, NHRCP was forced to leave the large Koh Tao structure sporadically powered until 2016 (C. Scott, personal communication, November 17, 2020). NHRCP continued to monitor and maintain the site in hopes of one day reestablishing its connection to a power source.

However, with the recent expiry of the original Biorock™ patent (U.S. Patent No. 5543034, 1996), new iterations of the technology have rendered MAT accessible through open-source sharing, making it easier to build and maintain and more cost-effective. An example of the benefits of the technology being open to the masses is the invention of a mineral accretion device (MAD) called corailAID. The first version of the device was designed in 2016 by Robert Sevenster, a dutch electrical engineer who attended one of the NHRCP MAT courses in 2015. Today, Sevenster is completing the 6th version of the coralAID MAD. The NetV6 CoralAID can automatically adapt to changing circumstances, like water flow, water resistance, temperature, and substrate conductivity (Sevenster, n.d.). The device can also be powered by solar energy and adjust the current applied to the reef based on light conditions (Sevenster, n.d.). Sevenster's innovations are a significant leap forward in MAT for marine habitat conservation and construction. The smart technology Sevenster is creating opens the possibility of using MAT in more environmentally variable and remote locations. Adding and removing MAT reefs to an existing coralAID device also improves projects' scalability, allowing testing in new locations to start small and grow sustainably. The coralAID devices can also send recorded data wirelessly to smart devices or computers anywhere in the world. The device does so by using a data monitor that connects to an application called ThingSpeak™ (Figure 12), an Internet of Things (IoT) analytics platform service that allows a user to compile, visualize and analyze live data streams in the cloud (Learn More - ThingSpeak IoT, n.d.). The option to monitor system data and environmental data could be an incentive to establish more AR habitats and track their impacts on important indicators such as water quality, hydrodynamics, and biodiversity. The active MAT reefs currently being managed by NHRCP now thrive and continue to improve due to conservation programs, community co-management, and the innovations of the instructors and students of the program C. Scott, personal communication, November 17, 2020).

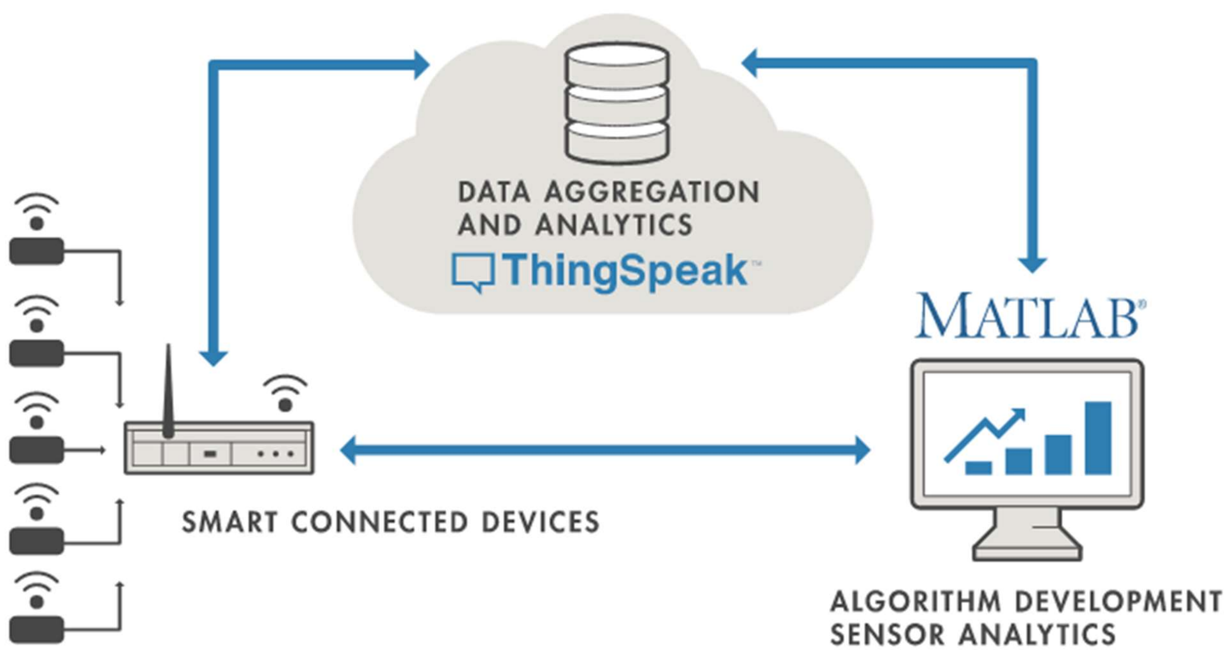


Figure 12. ThingSpeak data flow (Learn More - ThingSpeak IoT, n.d.).

While Biorock® Technology Thailand may not have a presence anymore, and the partnership between the Biorock™ Company and the NHRCP has failed, the general application of MAT reefs in some Thailand regions has been successful. The NHRCP has employed some of the factors of success used by Biorock® Indonesia. By working with the community, exchanging knowledge at the local level with their staff and volunteers, and providing hands-on experience to students from around the world, MAT has progressed more than it ever has. It is good to reiterate that the use of MAT is not intended as a silver bullet solution for reef habitat conservation and reconstruction, but rather a tool that can contribute to reef ecosystems' resiliency. Implementing MAT and coralAID devices to add to coral nurseries, aquaculture, habitat connectivity efforts, and living shoreline projects could produce positive results. However, more research is required to understand the technology's effects better and to standardize its use.

Chapter 8 Proposed St. Margaret's Bay MAT Reef Installation

The initial goal of this project was to build a MAT reef for field testing. Specifically, four steel AR structures were to be installed at a residential property at Mason's Point in St. Margaret's Bay, Nova Scotia, to create a MAT mussel reef (Figure 13). Due to several logistical changes related to the COVID-19 pandemic, the structures' installation was delayed and moved this portion of the project out of the Dalhousie Master's of Marine Management program's applicable timeline. Despite not being able to collect data within the timeframe of this project, the intent remains to install and test the effectiveness of a MAT mussel reef in St. Margaret's Bay. For this reason, the following includes the methods proposed to collect data to measure the effectiveness of a MAT reef in St. Margaret's Bay, Nova Scotia, its effectiveness to enhance the growth and survival of blue mussels, and whether the technology will induce spontaneous settlement. Furthermore, the proposed MAT reef's predicted performance will be provided based on the reviewed literature and personal communications with experienced users.

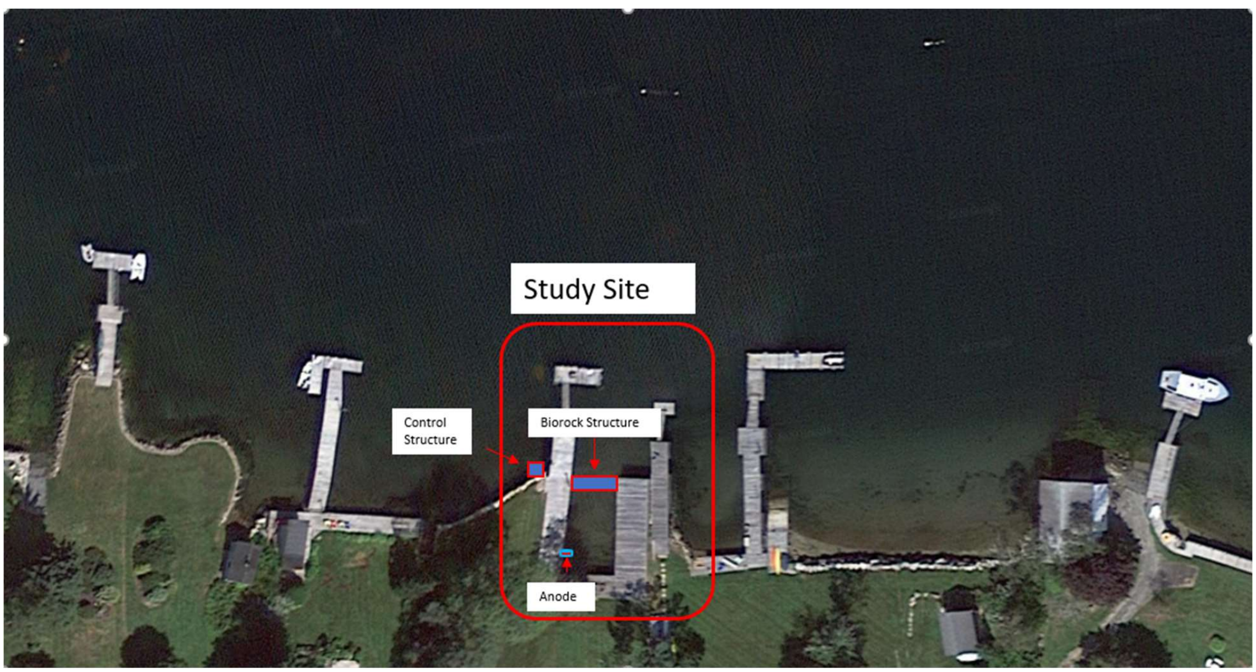


Figure 13. Study site at Mason's Point in St. Margaret's Bay, Nova Scotia (retrieved from Google Earth).

Chapter 8.1 Proposed Installation Strategy

The most common material for building MAT reef structures is steel. Leftover 20-foot steel rebar (10mm) were sourced for free from a marine construction project to build four AR structures. The rebar pieces were welded in a triangular prism shape for rigidity. Three of the structures will serve as the system's cathodes in the experiment, and one is reserved as a control. The three experimental steel cathodes, where the mineral accretion would occur, would connect in series to the negative wire connected to a variable power supply that can limit the amount of power entering the system. The control structure, which would not connect to the powered system, would sit on the left-hand side of the wharf with the power supply (Figure 14). The wires that would connect the whole system would be insulated underground cables that are waterproof. The MAT system would receive power from a standard grid-tied variable power supply installed on the site's left facing wharf (Figure 14). The power supply, housed in a waterproof electrical box, would be mounted on the post that is labeled power source for ease of access. The variable supply would make it possible to adjust the system's power to find the most optimal voltage, given the total surface to volume ratio of steel. The positive wires would be fed from the power supply and connected to the system's anode. The anode would be placed near the lower part of the tide range (low tide) to ensure it always remains submerged. The anode would also be attached to the left facing wharf to ensure it does get displaced by the tides. Once the system would be installed, the current would flow through the anode, conducted through seawater, and returned through the steel reef structures. The operational system would catalyze the seawater electrolysis reaction, and thus the mineral accretion on the surface of the reef structure would occur in theory.

Despite not being able to collect data within this project's timeframe, the proposed installation of the MAT reef in St. Margaret's Bay is planned to be carried out in the Spring of 2021. For this reason, the following includes the projected results for the installation project based on the literature that was reviewed for this study and the guidance of contacts that have previous experience with MAT for coastal habitat restoration.

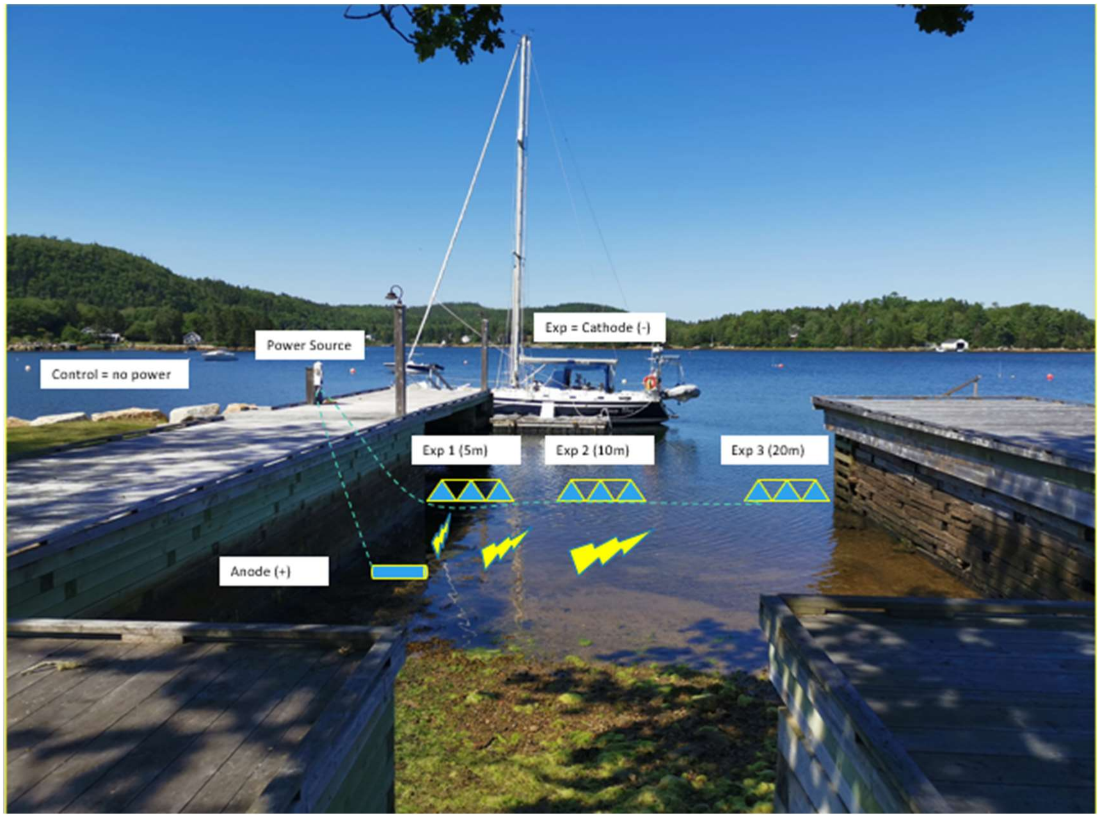


Figure 14. Diagram of proposed installation at Mason's Point study site.

Chapter 8.1.1 Proposed Experiment 1: Use of electricity to catalyze carbonate accretion to AR structure

The diameter of the four corners of each structure would be measured over time in order to quantify the growth of calcium carbonate or decay of steel rebar. Digital callipers would be used to measure the diameter of the steel rebar. Doing so would help determine three things:

1. Determine the efficacy of MAT in Northern Atlantic coastal waters.
2. Calculate the accumulation rate of calcium carbonate on the experimental MAT structures.
    a. The growth rate of the experimental structures would be compared in order to determine the effects of the distance between the anode and the cathode.
3. Determine if the control would decay over time without the added current.

Chapter 8.1.2 Proposed Experiment 2: Use of electricity to stimulate blue mussel growth and survival

Blue mussels would be collected on-site and measured before the experiment to determine the average size of each group before introducing them to the charged structures and the control. The mussels would be put into durable wire mesh bags and attached to the three experimental structures and the single control structure. The bags would be fastened on all sides to ensure a secure fit and reduce excessive movement. The open structure of the AR and mussel containment bags would allow the free flow of water through the setup from all directions, allowing the mussels to feed and rid of their feces and pseudofeces. Periodically, mussel length and height would be measured to compare mussels' growth rates on the electrified cages and the control cage with no electric power before, during, and after the growing seasons. The bags would be removed to sort live mussels from dead mussels. The dead mussels would be removed and counted, and the live ones returned to the bag. Mussel growth would be recorded using callipers, and an image would be taken of all the measured mussels with the callipers for scale for future analysis. Measurements can be taken at the end of the growing season, at the beginning of the following growing season, and for the duration of the project. Moreover, the experimental structures' effect on mussel growth and survival would be compared to determine the optimal distance between the anode and the cathode, given the site's conditions.

Chapter 8.1.3 Proposed Experiment 3: Use of electricity to encourage settlement

The settlement is defined as the density of organisms settled on the steel structures. The number of species and individuals would be assessed over time through observation, photography, and counting individuals. This experiment aims to determine whether marine organisms would settle or occupy the structures. Organisms can be algal, sessile, motile, including blue mussel spat that may settle on the structure from nearby colonies or the colony added to the structure. Moreover, the settlement upon the experimental structures and control would be compared to determine the effects of the distance between the anode and the cathode.

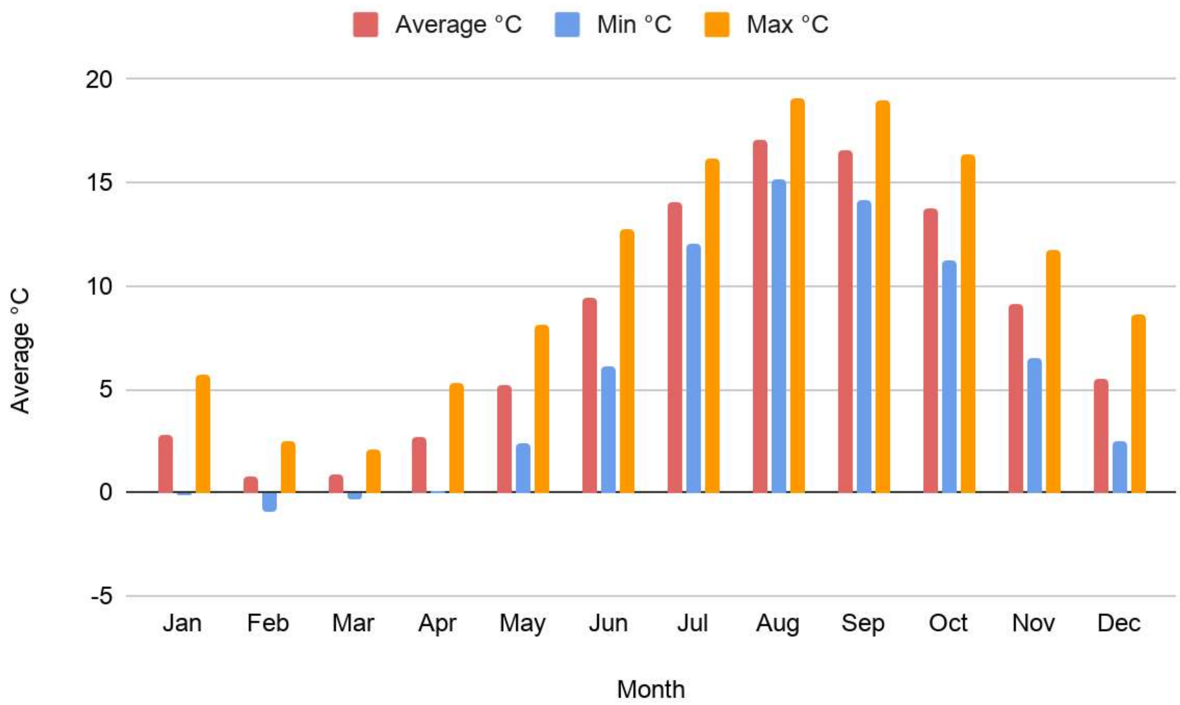
Chapter 8.2 Desired Results of the Proposed Installation

Chapter 8.2.1 Desired Results Experiment 1: Use of electricity to catalyze carbonate accretion to AR structure

Accretion of dissolved seawater minerals on steel structures has been suggested as a sustainable method for producing construction materials. The deposited material has similar mechanical properties as concrete, and the material is continuously deposited if the current is applied (Goreau, 2012c). As current is applied to the steel structure, it is not prone to corrosion, although it is placed in corrosive seawater. The method of putting a charge through steel to prevent corrosion is a common technique on oil platforms that need the structural fortitude of a steel-framed megastructure that can withstand the ocean's impacts over time. Given the numerous examples of oil platforms showing steel will not corrode if a current is applied, it is likely that the experimental structures for the future experiment will not either. Conversely, the proposed experiment's control structure will likely corrode without being exposed to an electrical field.

The mineral accretion process of MAT can be quite variable. Several literature review records discuss three different kinds of materials that precipitate upon charged steel structure: aragonite and brucite, and calcite. Aragonite and calcite are polymorphs of $CaCO_3$, aragonite being the most common of the two in the mineral accretion process. Aragonite is the desired material to be grown on the MAT structures between aragonite and brucite since it is a far superior material in terms of hardness compared to brucite (Mohs scale hardness: 3.5-4 vs. 2.5 to 3) (Goreau, 2012c). Higher current densities result in faster growth, but weaker material dominated by brucite. In comparison, lower current densities produce slower deposition dominated by harder aragonite (W. H. Hilbertz, 1992). If a surface pH <9.2 can be maintained on the cathode with a lower current density, there will be a higher chance of dominant aragonite deposition since the deposition of brucite takes place when the pH of the surface of the electrode reaches 9.2 (Deslouis et al., 2000). Applying this concept will ensure the experimental structures grow stronger over time.

Another factor contributing to a MAT structure's long-term success is the anode's material and the applied current. The anode material can dictate the accretion rate on the cathode and the anode's decay rate, which can ultimately dictate the anode's life and the system's performance. For example, if the applied current is too high, the anode will corrode quickly and negatively impact the electrical field (Hilbertz and Goreau, 1996). A study by Zamani et al., 2010 compared the accretion and decay rates of Titanium (Ti) with two other potential anode materials (Magnesium-Mg, and Aluminum (Al). The laboratory study was carried out for 48 hours with the stagnant seawater in aquariums. Four aquarium tanks were subject to different electric current treatments (1 Ampere, 2 Ampere, 3 Ampere, and 5 Ampere, respectively). The experiments revealed that Titanium is the best anode material as it produced the highest rate of mineral accretion, the hardness level of solid minerals (known from the ratio of Ca/Mg), the lowest anode decay rate, and the lowest oxide production. Another study by Margheritini et al., 2019, tested the effects of temperature (7 & 22 degrees Celsius), seawater composition (two different concentrations of Mg^{2+} and Ca^{2+}), anode material (titanium plate covered with; mixed metal oxides and platinum), and applied electrical current (0.22 A, 0.25 A, and 0.31 A) on the process of the mineral deposition over a cathode after seawater electrolysis. The results showed four things: more aragonite is deposited at lower temperatures (7 °C) than in room temperature water (22 °C); the percentage of aragonite is approximately the same for both water treatments; a lower amount of applied current makes it more likely for aragonite to be deposited at the cathode surface; the platinum-coated anode produced material with a slightly higher percentage of aragonite compared to the one covered in mixed metal oxides. The results from both studies indicate that a low and slow method is ideal for creating a long-lasting MAT structure. The continued production of aragonite using MAT at low temperatures is an essential feature since the area's water temperature can go below zero during the winter. The study area can have yearly average seawater ranging from 5.6 degrees Celsius to 10.6 (Figure 15), which is close to the most optimal temperature range of 7 degrees Celsius observed by Margheritini et al., 2019.



Chapter 8.2.2 Desired Results Experiment 2: Use of electricity to stimulate blue mussel growth and survival

An additional benefit observed throughout many MAT marine habitat installations is the improved growth and survival of organisms within systems' electrical fields. Researchers, NGOs, and community organizations have built MAT structures and reported improved resilience with coral species, seagrasses, shellfish, and salt marsh plants. The exact mechanisms behind MAT's beneficial effect on calcareous marine animals and marine plants are not yet specified, and likely vary amongst organisms. Nevertheless, despite the need for more testing to further explain the processes at play, the results of some experiments are difficult to ignore. Table 1 shows the results of several experiments testing the effects of MAT on the growth and survival of various taxonomic groups that can be found in Nova Scotia. Some species, such as those mentioned by Vaccarella & Goreau, 2012, and Fitri & Rachman, 2012, are not found in Nova Scotia.

Table 1. Results of studies testing the effects of MAT on the growth and survival of various taxonomic groups that can be found in Nova Scotia.

Title	**Experiment**	**Result**	**Reference**
Gorgonian Soft Coral Have Higher Growth and Survival in Electrical Fields	These experiments were conducted at Barrang Lompo Island Marine Field Station of Hasanuddin University, Makassar, South Sulawesi, Indonesia. Three colonies of the gorgonian (I. hippuris) were collected from their natural habitats, at a depth of 6 m on the reef of Bonetambung, western Barrang Lompo Island, and transported in containers of seawater to the islands of Barrang Lompo.	The electrical fields from MAT lead to 2.68 times increased gorgonian soft-coral growth compared to controls in the raceway tank conditions. The controls had 1.88 times higher mortality than electrified corals.	(Fitri & Rachman, 2012)
Suitability of Mineral Accretion as a Rehabilitation Method for Cold-Water Coral Reefs	At the marine research station in Tjärnö (Department of Biological and Environmental Sciences, University of Gothenburg), twenty-four aquarium tanks were set up in a constant temperature room with the inflowing water temperature set at 8°C to imitate the in situ conditions for local *Lophelia pertusa* populations (natural range: 4–10°C). A control and five experimental treatments at different current densities were compared.	The zero mortality and the overall performance of the corals in the lowest applied current density (LI) brings the authors to the conclusion that mineral accretion is a suitable method for the target species *L. pertusa*. Although there was no significant gain in the growth rate compared to the controls, the increased budding and firm attachment of coral transplants offer sufficient benefits, and the method is considered worth testing in a field study.	(Strömberg et al., 2010)
Increased Oyster Growth and Survival Using Biorock™Technology	Over the course of approximately three months, a subset of 90 oysters in each of the control and the experimental tank, both containing 600 oysters, were measured from the hinge to the farthest point (height) approximately every two weeks.	Oysters in the experimental tank grew statistically significantly faster, 2.75 and 1.62 times faster than oysters in the control tank during the course of both studies (2007 and 2008).	(Berger et al., 2012)
Electrical Fields Increase Salt Marsh Survival and Growth and Speed Restoration in	In one quadrat without electrical current, S. alterniflora was planted in June 2010l. Quadrat 2, with low electrical current, is S. alterniflora planted in June 2010. The S. alterniflora in Quadrat 3, planted in June 2010,	The *Spartina alterniflora* that received electrical stimulus had faster growth and greater height than the control *Spartina*, the leaves appeared distinctly darker green, and the roots appeared darker and thicker at the holdfast. Electrically charged	(Cervino et al., 2012)

Adverse Conditions	was grown under higher electrical current. The current was supplied from photovoltaic modules, which supplied electricity to metal grids at ground level with Spartina growing in 6 inch (15 cm) square spaces.	*Spartina* had high survival under conditions of high metal pollution and deeper in the intertidal than the species could otherwise survive, under which the controls all died. This implies greatly improved root and rhizome growth. Near the end of the experiment, a hard layer of calcium carbonate had formed over the grid.	
Restoration of Seagrass Mats (Posidonia oceanica) with Electrical Stimulation	Seagrass transplantation projects using electrified mesh substrates were carried out from June to September 2008 at two quite different locations, Giovinazzo, and Torre Guaceto. At each site, three or four pieces of metal mesh, 50 cm on each side, were nailed to hard substrate or laid over soft substrate. Mesh spacing was 4 cm, and seagrass plants with roots were planted in the spaces, attached by ties to the mesh to secure them against wave surge until established	MATmeshes grown at a low charging rate were able to produce healthy and rapid growth of *Posidonia oceanica* on hardground where they normally could not attach. Meshes that were overcharged grew too fast and overgrow the seagrass. In all cases, the minerals hardened, cemented themselves to the substrate, and attracted colonization by a wide variety of local marine life.	(Vaccarella & Goreau, 2012)
Electrical Stimulation Increases Oyster Growth and Survival in Restoration Projects	About 600 oysters were used in the spring for growth experiments in the 2010 growing season, another batch in the 2011 growing season, and a third larger-sized batch for survival measurements overwinter 2010–2011. Oyster size was measured periodically to compare growth rates of oysters on electrified helices and a control helix with no electric power during the 2010 and 2011 growing seasons. The bags were emptied into a tray, sorting live from dead oysters, and photographed with a scale. The dead oysters were removed, and the live ones returned to the bag. Measurements were made from the images using the Photoshop measuring tool.	Results obtained from the experiments that were performed at the College Point MATsite showed that the electrical field had positive effects, increasing both growth rate and survival of C. virginica oysters. While all oyster groups that received electrical stimulation responded with increased growth and survival, the oysters given the highest amount of electrical stimulation had the fastest growth and highest survival rates.	(Shorr et al., 2012)

The studies listed in Table 1 provide an overview of the research conducted concerning MAT to improve the growth and survival of habitat-forming organisms like those found in Nova Scotia. In different parts of the province, habitats such as eelgrass meadows, oysters flat/reefs, salt marshes, and coral communities can be found. However, many of these habitats can be challenging to find or are declining due to anthropogenic pressures, disease, and invasive species (Environment, 2009; Garbary et al., 2014; Poirier et al., 2017). Having a tool such as MAT could help improve the success of these declining species' rehabilitation efforts. The original intent of this project was to create an artificial oyster reef instead of a mussel reef. There were a few aquaculture leases for oysters and mussels on the eastern side of the Bay, but they are gone now due to an overwhelming increase in the size of its shellfish closures (Barrington et al., 2003). Because of the declining water quality due to chemical and bacterial contamination from point and nonpoint source pollution that led to the closures, it would have been challenging to find enough oysters for a long-term experiment. Also, the permitting required to introduce oysters that are non-local to the Bay was too extensive for this project's scope. For these reasons, the future project will use blue mussels, a habitat-forming species commonly found at the project site. Moreover, based on the literature review and further research, it seems the effectiveness of MAT has never been tested on blue mussels, meaning the experiments could be a world first. Given the technology's performance with cold water organisms in Table 1, the prevalence of blue mussels in the area, and the positive results of mineral accretion in cold water, the desired positive effect on the growth and survival of blue mussels may be attainable.

Chapter 8.2.3 Desired Results Experiment 3: Use of electricity to encourage settlement

Spontaneous settlement of organisms on MAT structures was reported in several papers reviewed in the literature. However, few studies have directly measured the difference of settlement rates of the larval stages of marine organisms on MAT structures compared to a reef structure outside the electrical field. A comparison of juvenile coral settlement rates revealed that some MAT structures had higher rates than reported in other non-MAT coral recruitment studies (Goreau, 2012a). As seen in Table 2, the rates reported on MAT structures in bold are far more significant. Interestingly, an experiment testing MAT structures in Ko Samui, Thailand, charged with various power levels, demonstrated that the reef structure with the lowest power experienced the most spontaneous settlement (Goreau, 2012a). While not proven, it is theorized that a MAT reef that grows at a slow rate due to a lower power level prevents newly settled coral larvae from being overgrown by the MAT material. If these results can continue to be replicated, the time and effort needed to restore reefs could become more efficient over time.

Table 2. Comparison of average settlement rate of corals using MAT (bolded) and without reported in the literature as per Goreau 2012a.

Study Location	**Average Settlement Rate (corals/m^2/month) as per Goreau, 2012a**	**Reference**
Seychelles	0.01–0.35	(Turner et al., 2000)
Maldives	0.21	(Loch et al., 2002)
Komodo, Indonesia	0.21–0.46	(Fox et al., 2002; Fox et al., 2003)
Komodo, Indonesia	0.11–2.2	(Fox & Pet, 2001)
Hawaii	0–6.8	(Fitzhardinge & Bailey-Brock, 1989)
Barbados	17.8	(Tomascik, 1991)
Great Barrier Reef	21.67	(Mundy, 2000)
Wakatobi, Sulawesi, Indonesia	15.36 (artificial substrate)	(Salinas-de-León et al., 2011)
Wakatobi, Sulawesi, Indonesia	30.33 (bare reef limestone)	(Salinas-de-León et al., 2011)
Pemuteran, Bali, Indonesia	**169.3**	**(Dwija, 2003)**
Negril, Jamaica	**194.4**	**(Goreau & Hilbertz, 2012)**

It is impossible to correlate the improved settlement of shellfish on a MAT reef in cold Atlantic waters based on the studies in Table 2, but the available results are difficult to ignore and fuel the motivation to test the efficacy of the technology the environment proposed in this project. There are, however, experiments that show significant settlement without directly testing it. Three MAT mesh substrates of different thicknesses were laid out side-by-side in waters in the Straits of Georgia, British Columbia, Canada (Goreau, 2012b). The structure which got the most power was completely colonized with mussels; the medium-powered structure had fewer mussels than the previous; the lowest powered structure had the least mussels (Figure 16). Even though the experiment was meant to test the effects of three different power levels of steel mesh structures, it is evident that the mussels favored settling on the structure with the highest power level. By proposing the replication of the experiment, adding a control, and measuring mussels' settlement over time, this project could confirm that mussels will quickly colonize a powered MAT structure. Replicating experiments by (Cheng et al., 1982) that determine where the point of diminishing returns lies, but within the context of MAT technology, would be an exciting project to undertake in the future. However, maximizing mussels' settlement and growth is not the only objective of installing a MAT reef in this project's context. As previously mentioned, slowly growing the structure promotes a MAT material with a higher composition of the stronger aragonite rather than the weaker brucite. If creating habitats for shoreline protection using MAT is to be done effectively, it should be done at a slow and sustainable pace.

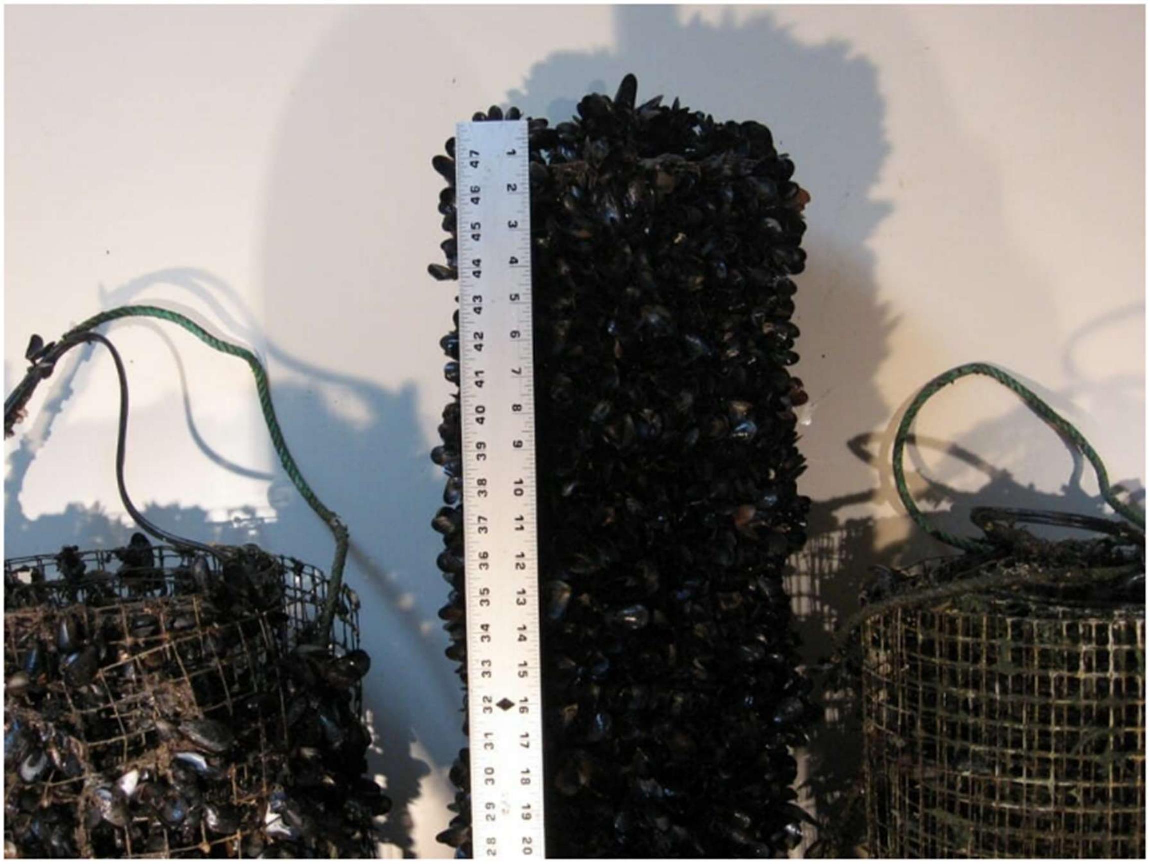


Figure 16. Spontaneous mussel settlement on steel mesh with very low (left), low (center), and zero trickle charge. Photo by Eric Vanderzee (Goreau, 2012b).

Chapter 9 Discussion

The body of research on MAT is small in comparison to other methods of marine restoration. Despite a positive trendline of publications between 2003 and 2020, the results are heavily influenced by the book Innovative Methods of Marine Ecosystem Restoration edited by Dr. Tom Goreau and Dr. Robert Trench. Studies investigating the potential of MAT reefs should continue and should be replicated to understand further the nuances of the technology's effectiveness, or lack thereof, to continue the positive trend of research in the future. MAT structures that have been maintained can assist communal marine life in being resilient in the face of an ocean that is rapidly changing. The literature review provides examples of how MAT has improved the growth and survival of a broad array of marine species, is a proven method to produce accreted mineral structures from seawater, and that can induce spontaneous settlement of a variety of larval forms. Despite the technology being studied in multiple environments, several other installations are discussed in the reviewed literature and additional records. Like any other construction project type, every single build cannot have an associated experiment and results to accompany it and publish. Securing the funds for marine habitat restoration is difficult enough as it is, securing access to the knowledge required to install and maintain a novel and technical technology. With more successful and well-maintained structures, knowledge exchange, and experiential learning, the ability to create more MAT structures can become more common over time.

In general, the studies investigating MAT's effects on enhancing marine habitat-forming organisms' resilience have had mixed results. Some projects produce significant growth, settlement, and survival; others are somewhat successful but do not show a significant difference from controls, and others perform worse than controls. One of the reasons for the results being mixed is the technical nature of the technology. If mistakes are made in the setup, maintenance, and monitoring of a MAT structure, results can be negligible, null, or even reverse. Goreau, 2014 reports an example of a project carried out by Texas A&M University Galveston Coastal Geology Laboratory that, in his words, failed significantly. The flow of power was set up in reverse, making the flow circulate from the power source to the cathode, through the seawater, and back through the anode. The mistake caused the cathode to rust faster than the controls, and the anode became encrusted with minerals. In addition to mistakenly setting up the flow of power in the wrong direction, failing to realize that no power is reaching the structure is another common mistake. Thesis projects carried by students out in the South Pacific, Australia, Indonesia, Thailand, the Philippines, Germany, Japan, and the United States have reported the technology failing to produce the positive effects reported by others (Goreau, 2014). The reasons for these poor results, as per Goreau, 2014, range from poor design as a result of not being advised by trained specialists, performing on experiments on existing MAT structures that were assumed to be powered but were not, sabotage by unsupportive stakeholders, accidentally damaged by other users of the coastal space, or damaged by powerful storm activity. While most of these reasons are at no fault of the researchers, publishing their research and concluding the technology is ineffective instead of discussing the events that cut off the structure's power leads to results that damage the overall research on the topic. Reporting findings of compromised experiments can also affect the perception of the positive results achieved by well-designed projects and diminish the success of other researchers and communities that invested the time and resources to build a well-designed structure.

There are several other cases where researchers maintain a current that is either too low or too high relative to the optimal range for the tested environment and species. A MAT project in Thailand monitored over three years from 2009-2012 reported nominal growth of corals in the first year because the power to the structure was cut off and the third year because the power connection was compromised and thus too low (Terlouw, 2012). Significant growth in the second showing corals growing at a rate five times faster than controls (Terlouw, 2012). Unlike others, the author of this study correctly reported the events that affected the power supply and was transparent about why the results had so much variation. The issues causing the varying results show how potentially significant the effects of MAT technology can be on corals' growth when properly functioning—in another project in Grande Isle, Louisiana, using MAT technology to grow ARs and enhance eastern oysters' growth and settlement over 22 weeks. The project resulted in significant mineral accretion with three different power levels than the control but did not report significant growth of transplanted oysters or spontaneous settlement of oyster spat (Piazza et al., 2009). According to (Goreau, 2014) the experimental design contained flaws, resulting in the current being applied directly to the cathodes, rather than creating an electrical field that would otherwise provide benefits to the cathodes and everything within the field, including the oysters and spat.

Like MAT systems that receive power levels that are too low to elicit an effect within a particular environment and upon a particular species, systems that receive too much power can produce negligible and even adverse effects upon species and structures. The data from an experiment by Cheng et al., 1982 is plotted on a semilogarithmic graph (Figure 17) to illustrate why too much power can affect the growth of organisms placed within the field of a MAT structure, as per Goreau, 2012a. ATP is the primary storing mechanism of the energy of all organisms on Earth. The data of Cheng et al., 1982 in Figure 17 shows that applying a current can increase the concentration of ATP in tissue. However, after point 5, there is a point of diminishing return. Therefore, if the current applied via the MAT structure's electrical field is too strong, the concentration of ATP can be suboptimal and potentially damaging to an organism within the field. According to Goreau, 2014, if the relationship between applied current and ATP concentration is not factored into a project's design, it can be one of the reasons some MAT projects fail to produce significant growth and survival of calcareous organisms that others do. Again, while failed experiments are an inherent part of the scientific method, it is damaging to the overall perception of the technology's advancement and success if results from failed experiments are not linked to the improper design of the experiment itself, and no that it simply does not work. Goreau, 2014 states this is the case with eight studies mentioned in his article. However, critiques can be made towards the articles that Goreau has repeatedly and selectively cited, some of which where he is an author or co-author, only appear in his book Innovative Methods of Marine Ecosystem Restoration. Despite the technology being used for over 40 years, only a small number of peer-reviewed cases and several un-reviewed articles and anecdotes document MAT's effectiveness with consistency.

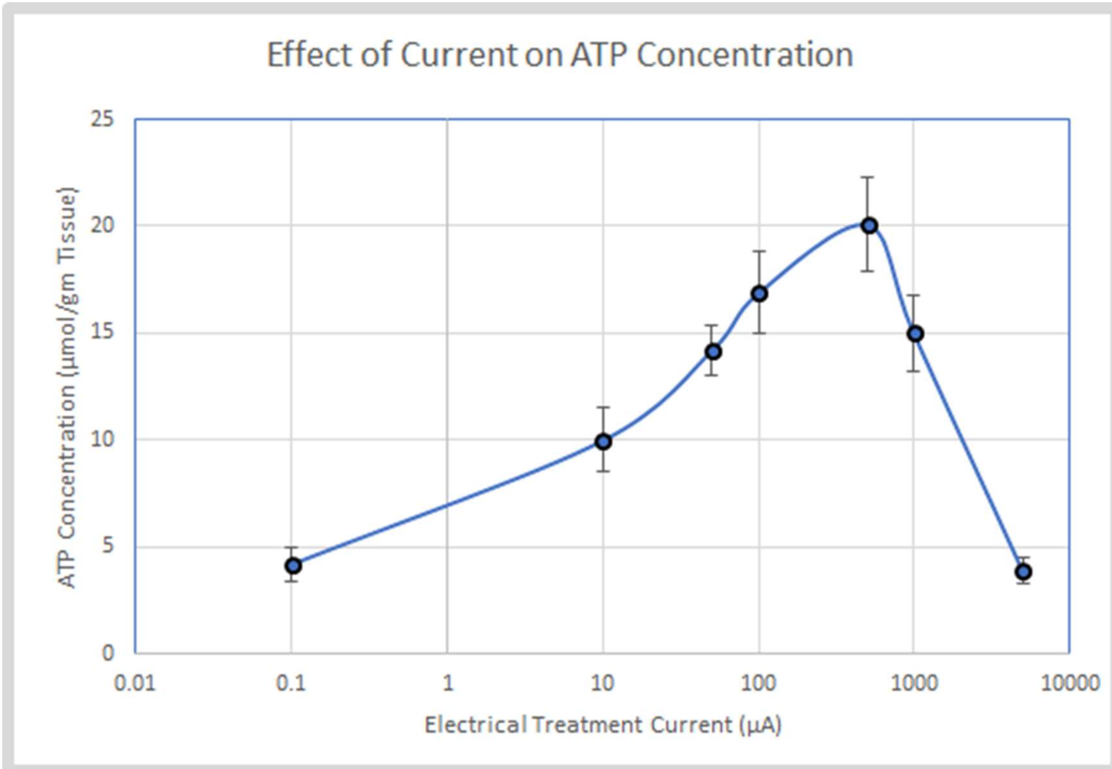


Figure 17. Effect of current's on ATP concentration and the point of diminishing return. Replicate of Goreau, 2014.

The earliest paper found that met the criteria for inclusion in this study was published in 2003. However, within these papers, there are several mentions of past projects built much earlier. The first-ever MAT structure was built by the technology's inventor, the late Wolf Hilbertz, in Grand Isle, Louisiana, in 1976. The pilot projects were intended to determine the viability of growing hard structures in the ocean to use as a construction material on land. The projects' results showed that Hilbertz had discovered a new method of growing sea-based concrete material that gets stronger the longer it remains in the ocean and is self-repairing in any shape or size (W. Hilbertz, 1979). An unintended side effect of his experiments was the sudden settlement of several layers of adult-sized oysters after leaving the pilot structures in the ocean for three months (Goreau, 2012a). Eastern oysters can grow at impressive rates given the right environmental conditions. The legal harvest size for oysters is 75mm, and eastern oysters in the Gulf of Mexico have been measured growing at rates ranging from, but not limited to, 0.38 - 0.98 mm/day (Hayes & Menzel, 1981). No similar studies tested the effectiveness of MAT in the Gulf of Mexico to compare growth rates through the literature review. However, Berger et al., 2012 reported growth rates of eastern oysters that were statistically significantly faster at 2.75

and 1.62 times faster than oysters in the control tank during two different flow-through lab studies in 2007 and 2008 using water from the Hudson River. An in situ study by Shorr et al., 2012 in a polluted section of the East River in New York state reported that control oysters showed minor growth of 4.86 mm, the medium-power oysters grew 5.82 times faster, and the higher-power oysters grew 9.30 times faster than the controls during the 2011 growing season. In the same experiment, Shorr et al., 2012 reported 100% survival at the end of their experiment for oysters in the experimental setup with the electrical field that had the highest power treatment, compared to the 8.54% survival rate of the controls. When executed with the proper guidance, MAT reefs for habitat restoration of oyster reefs and other shellfish certainly have potential. With further research to test the effects of settlement, growth, and survival of shellfish species in restoration projects, MAT could help rebuild critical habitats that offer crucial ecosystem services for many users of the coastal environment. These studies' results are motivating, given the similarities to this project's proposed MAT mussel reef installation.

The trend line for reviewed MAT studies with the goal field testing is positive. Figure 7 shows that 15 of the 18 years that were reviewed had between 0-4 publications. Outside that range, there were five publications in 2016, 8 publications in 2017, and 12 publications in 2012. The sum of studies in 2012 includes several from the 2012 release of the book Innovative Methods of Marine Ecosystem Restoration by Dr. Tom Goreau, and Robert Trench, marine biologist and one of the world's leading expert on corals and their symbiotic algae (Goreau & Trench, 2012). The book contains several studies investigating the effects of MAT and reviews describing the potential of the technology and its use for application such as habitat restoration, coastal protection, maritime infrastructure, and more. Reasons for zero published studies in 2006 remain unclear. Since the number of MAT projects that are constructed and currently operational supersede the number of published studies reviewed in this paper, a study that reviews all the operational projects would greatly benefit the advancement of the technology's general knowledge and awareness. Doing so would add to the work published in Innovative Methods of Marine Ecosystem Restoration.

Chapter 9.1 Barriers, Benefits, and Opportunities

The research on habitat reconstruction using MAT that has been done needs further replication, refinement, and questions answered related to the consistency of results. It is challenging to present such an innovative new solution to stakeholder groups if there are few proven examples of the technology making a positive and cost-effective difference compared to other proposed solutions that are more well known. The literature shows that one of the reasons for the lack of examples displaying the effectiveness of MAT is the scale and duration of most experiments that have been published to date have been insufficient to garner more support. There are several MAT reef construction projects that are currently operational that have not been studied that ought to. The protection of the technology under the Biorock™ Company has resulted in mixed perceptions and acceptance of its use. In the case of Biorock® Indonesia, support of the technology under the Biorock™ name has been long-lasting and positive.

Nevertheless, the literature does not present other examples at a similar scale of success. Implementing a technology of this nature at the scale of Biorock® Indonesia's projects could be interpreted as a form of integrated coastal zone management (ICZM). Implementing a coastal management strategy of any kind at the community level is challenging and may require relationship building, stakeholder participation, knowledge exchange, and long-term visions of common goals (Hoffmann, 2009; Maccarrone et al., 2014). Biorock® Indonesia was developed through a bottom-up approach and proved successful. However, using the same strategy may not be as effective in the context proposed in this study. The intrinsic value of the coastal environment shared at the community level in the Gili Islands is likely quite different from the private property owners of St. Margaret's Bay.

The speed at which the technology has progressed is not a concern per se, as most technologies or strategies take time to be proven or disproven as scalable within the complex, quickly evolving climate-related efforts. It may be a more personal reflection, but this could be a case where a negative view of technologies is seen as geoengineering, which has had a significant negative press as it is often perceived as 'messing with nature' (Corner et al., 2013). That being said, coastal defences and AR construction have been part of the more common and accepted activities in ocean science, and they may well not be seen as part of the broader geoengineering efforts that tend to focus on large ecosystems or global-scale solutions. This research and the possible direction of MAT use is more feasible at local scale efforts. A factor related to the awareness of MAT in coastal protection and marine habitat construction is the lack of funding for construction and monitoring. An AR monitoring review study by Becker et al., 2018 showed that most studies based their findings on data collected over three years or less with an average length of approximately 2.4 years. The researchers attribute the short studies to funding cycles lasting less than three years due to a general perception that three years is enough time for an AR to establish. However, there is a growing amount of evidence that the assemblage of species surrounding ARs can diversify over many years (Neves dos Santos & Zalmon, 2015; Perkol-Finkel & Benayahu, 2005; Polovina & Sakai, 1989; Relini et al., 2007; Scarcella et al., 2015). Becker et al., 2018 also found that only 62% of the 270 studies they reviewed identified whether ARs meet their pre-deployment goals. These findings are not surprising given that marine research has traditionally been costly due to the cost of crew and equipment necessary to survive at sea for extended periods. In 2017 the average daily cost of research vessels ranged from USD$ 10’000-40’000 (Valdés, 2017). These realities are exacerbated within the context of MAT reefs since there is less awareness of the technique compared to some of the other AR methods. However, with the advancements and growing availability of autonomous marine devices and vehicles such as gliders and submersibles, there are opportunities to increase the accessibility and lower the cost of AR monitoring. In addition, the growing adoption and application of citizen science that incorporates both top-down (volunteer marine scientists) and bottom-up (divers/community) can contribute to the understanding and identification of ecosystem trends or patterns surrounding ARs (Roelfsema et al., 2016), as well as exposing the general public to monitoring research and the idea of ARs. Apps such as eOceans, founded by marine scientist Christine A. Ward-Paige (Ph.D.), allow users to document encounters with marine organisms and record their numbers, locations, and habitats within an online community of ocean exploring citizens (People-Powered Science, n.d.). Integrating social and technological innovations can amplify the understanding and effectiveness of MAT for coastal protection and habitat construction.

While the innovation of technology can benefit the progress and implementation of MAT, the technological nature of MAT itself can act as a barrier. The construction of traditional ARs is similar because they are built using recycled materials, such as concrete pipes, tires, shipwrecks, and steel structures that provide structure in the marine space. There are also manufactured structures specifically designed to be used as ARs, such as Atlantic Pods or Reef Balls (Figure 18).

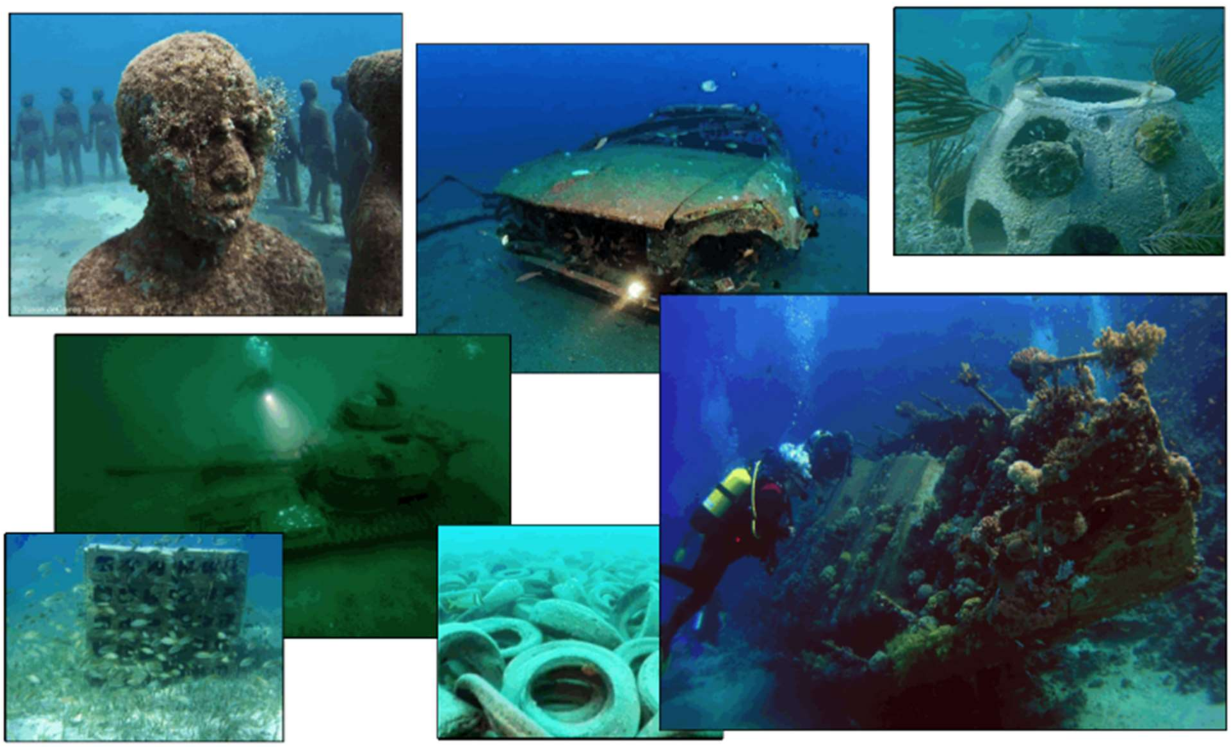


Figure 18. Examples of manufactured (statues and reef ball) and recycled (shipwreck, car, tank, tires, and cinderblocks) artificial reefs

These human-made, underwater structures are typically installed to promote marine life in zones of featureless benthos. In some cases, they are also installed to improve hydrodynamics for surfing, control beach erosion and wave attenuation to protect against damaging storm activity. What separates MAT reefs from the others is the requirement of a power source. The beneficial contributing factors of other AR construction methods are attributed to their shape, texture, weight, and material, and once they are installed, they require no input other than maintenance. MAT reefs can offer benefits similar to traditional AR techniques and offer the ability to grow and become stronger over time. To a certain extent, it is self-repairing, it can enhance the growth, survival, and settlement of calcareous marine organisms and marine vegetation, and it can be installed in an infinite number of shapes and sizes, such as the one in Figure 19 (Goreau, 2012a). Of course, these added benefits come with the added cost of having access to power and potentially the cost of the power itself, even though the energy requirements are relatively small. The dependency on power input presents a range of risks.

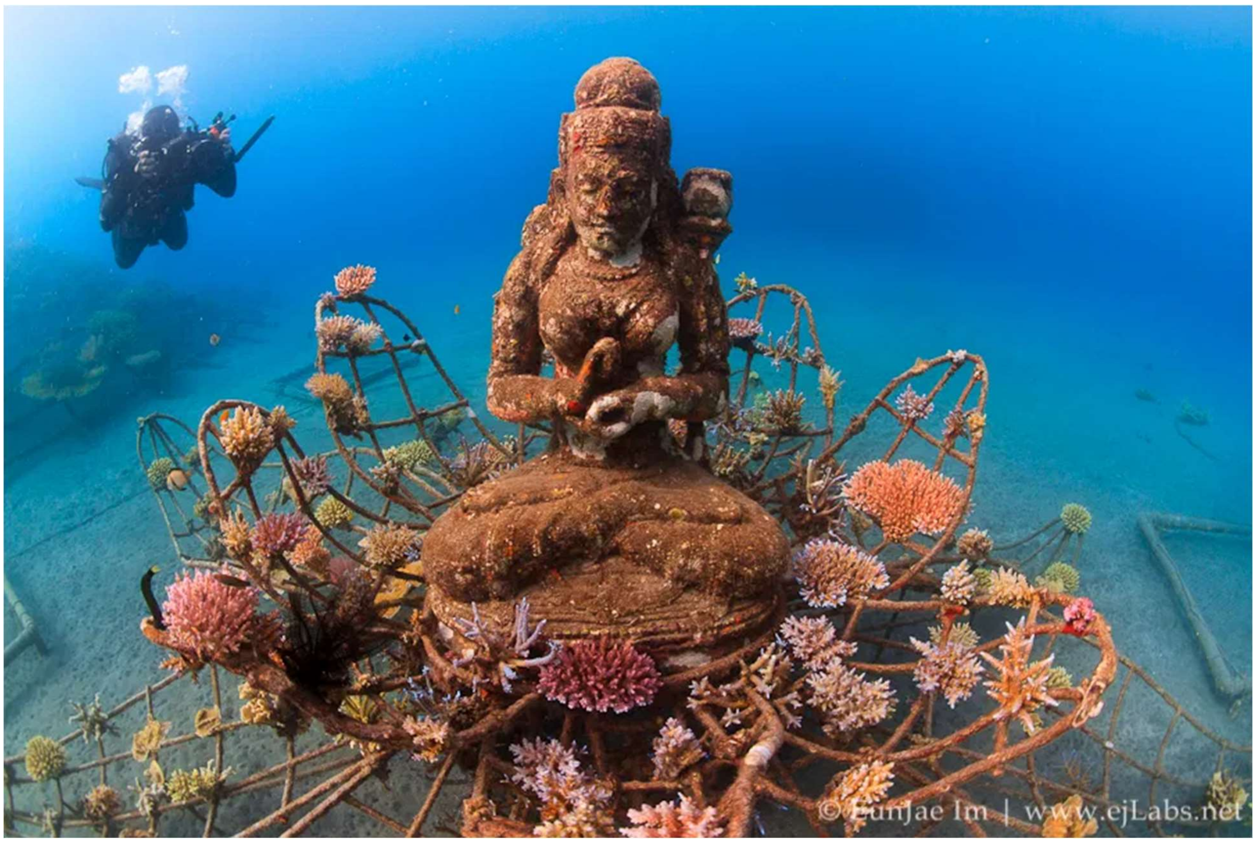


Figure 19. Aged MAT reef installed and maintained by Biorock® Indonesia in Bali (Bali Villa Arun, n.d.).

The literature review and additional research identified that accidental damage such as severe storms and scrapping boat hulls have caused cables to break and disconnect MAT reefs from their power source, rendering them inactive. Repairing severed insulated power cables or replacing them is a relatively normal task amongst many marine industries; however, knowing when the issue occurs is different. If an MAT reef is inconsistently monitored, the system can remain inactive for long periods. Especially if the damage is small or internal, making it challenging to identify. Despite these risks, there are methods of identifying when MAT is unpowered. The electrolytic reaction that is the basis of MAT catalyzes the creation of gas bubbles composed of oxygen on the anode and hydrogen on the cathode. Therefore, if the bubbles are not present, the system's power source's connection should be investigated.

Observing bubble formation is a viable measure if monitoring the structure consistently. Monitoring is not always possible for some projects due to funding, availability of volunteers, or a site's remoteness. It would be beneficial to use a coralAID device in these circumstances since it can notify when a system no longer receives power. The same circumstances dictate the methods available to power an MAT reef. It is generally recommended to use renewable energy forms such as solar, wind, or tidal to generate the necessary power for an MAT reef. However, these methods' initial costs may not be feasible within the project's budget, and grid energy or a generator may be the only available options. The main benefit of renewable energy sources, other than the lack of emissions, is it expands the range of locations where an MAT reef can be installed. The renewable energy sector continues to grow year after year, and costs continue to dwindle, making the technology increasingly accessible. The latest report by IEA, 2020 states that electricity generation from renewables will expand almost 50% in the next five years in 2025 to almost 9'745 TWh – equivalent to the combined demand of China and the European Union. Remoteness can be valuable when the goal of the MAT structure is to create new reef habitats since it can lower the potential of human contact or enhance an existing habitat in an area that is difficult to access consistently. But just like any other technology, issues with renewable energy sources can occur, and power can fail. For these reasons, further research and testing are required to improve the success and feasibility of MAT reef installations in remote locations. Herein lies another opportunity where the coralAID device or other available smart solutions can improve MAT reefs' success and improve coral growth (Figure 20).

Figure 20. Two years of coral growth on an MAT reef built and maintained by NHRC (NHRC n.d.).

Innovations in MAT will likely continue to improve as more projects from a variety of organizations are realized. Along with the programs in Thailand managed by the NHRCP and the massive community supported MAT reefs managed by Biorock® Indonesia, new organizations are emerging with plans to realize MAT installations since the expiry of the Biorock™ patent. In 2017, Reef Ecologic, a marine environmental consultancy based in Australia, in collaboration with AMPTO and Quicksilver Connections at Quicksilver Connection's Agincourt Reef pontoon site, implemented an MAT reef project at a high-value dive tourism site on the Great Barrier Reef (Figure 21) (Cook, n.d.). The project's four goals are:

1. Increase coral growth rates, and coral cover at target sites.
2. Assess the effectiveness of this innovative technique to stabilize loose coral rubble.
3. Investigate the potential for renewable energy to power reef restoration projects.
4. Encourage knowledge and skill sharing about monitoring and feedback between different stakeholders including visitors and the community.

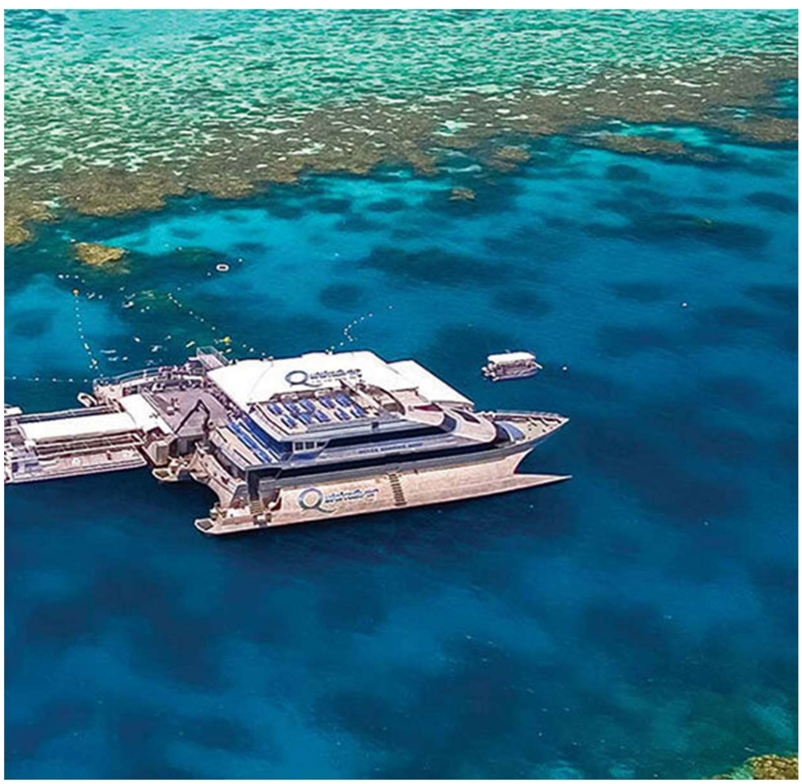


Figure 21. Quicksilver Connection's Agincourt MAT Reef pontoon site (Cook, n.d.).

The project, organized by applied marine scientist Nathan Cook of Reef Ecologic with over 20 years of reef restoration experience, is a joint effort between government, science, industry, and community. Depending on the results and community support, the adoption of MAT by companies working on the forefront of reef habitat restoration could contribute to the technology's reputation and acceptance.

A new non-profit organization called Ocean Life Foundation (OLF) is a foundation created in 2020 to create a multi-disciplinary team of globally recognized experts in marine engineering, coral sciences, project management, financing, and philanthropy. The new foundation's primary objective "is to provide funding for developing new methods and new technologies for protecting and restoring healthy oceans around the world, protecting marine ecosystems, improving water quality and reducing carbon emissions." (Ocean Life Foundation | Coral Reef Restoration & Protection, n.d.). The primary focus of OLF is to partner with entrepreneurs, start-up companies, researchers and academic institutions, and NGOs to fund the research and develop MAT. OLF intends to address the research gaps needed to further legitimize the use of MAT and to understand the long-term benefits of MAT in view of climate change stresses and diseases. Supported by visions of implementing MAT for applications such as marine aquaculture, coastal defences and beach erosion prevention, sustainably grown building materials, ocean-based renewable energy technology (i.e. wind, wave, solar, tidal), OLF's initiatives are the most comprehensive and ambitious projects concerning MAT in the marine space. The OLF website shows the effects of MAT in the field (Figure 22). The implementation of MAT by OLF is supported by Coralive, a Swiss-based environmental organization operating worldwide to help protect, manage, and restore coastal ecosystems, with several years of global MAT project experience.

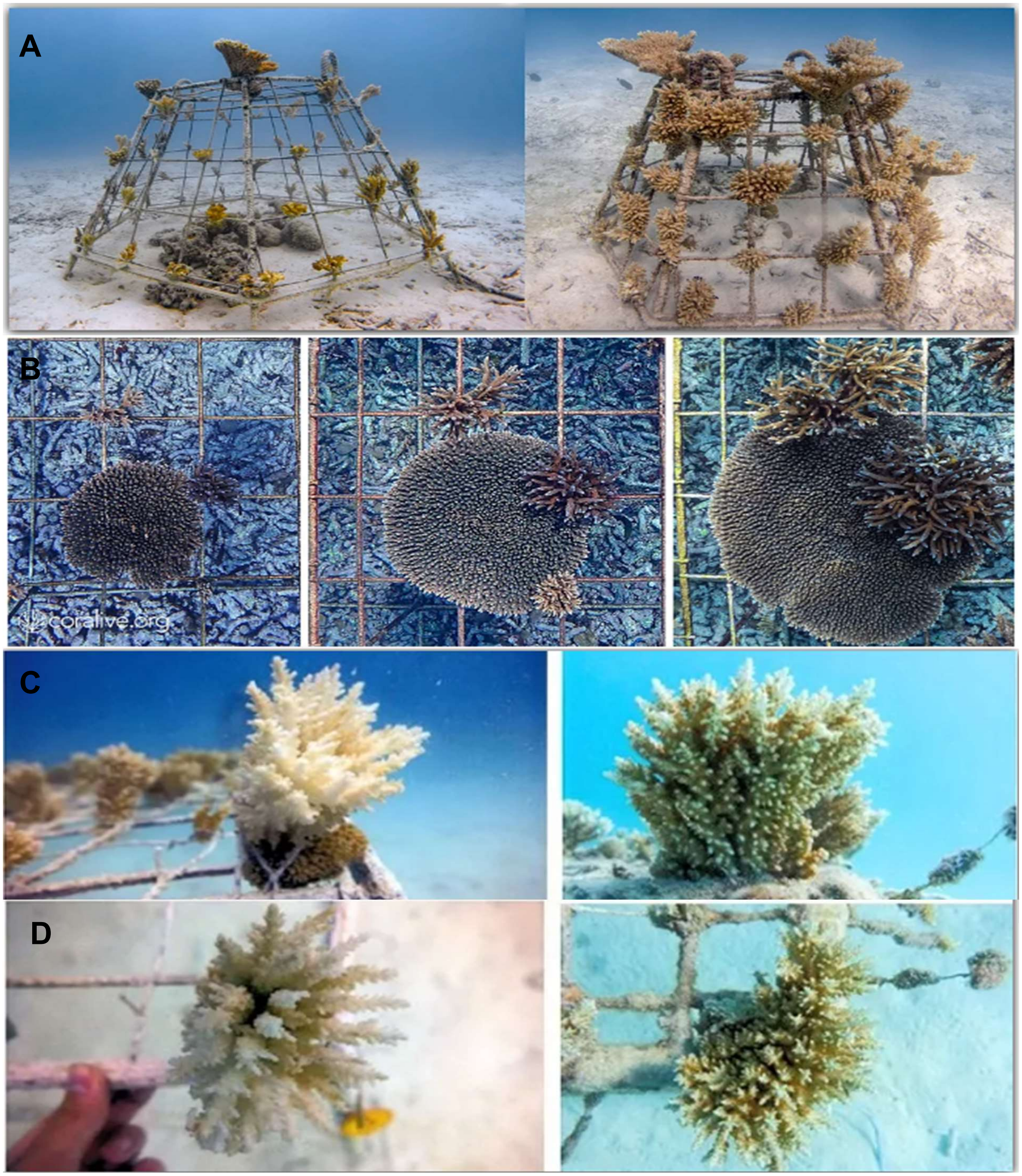


Figure 22. Coral growth comparison of OLF's MAT reef installations; A (left) day 1 to A (right) day 365 growth, B (left) 1 month growth, B (middle) 5 months growth, B (right) 15 months growth, C/D (left) bleaching coral during warming event, C/D (right) recovering after 4 months in MAT electrical field ("Downloads | The Ocean Life Foundation", n.d.).

With the increase of funding, projects, and research, MAT is beginning to have a more significant role in reef habitat conservation and restoration, amongst other applications. Despite these efforts, some studies are still investigating gaps in the technology's application in creating marine habitats other than tropical coral reefs. Studying the growth, survival, and settlement habitat-forming coralline algae, sponges, stromatolites, archaeocyathids, bryozoans, rudists, shellfish, seagrasses, salt marshes, and their associated communities on MAT structures could provide useful insights within marine habitat restoration. There are already massive habitat restoration projects concerning non-coral habitats such as shellfish reefs, seagrass meadows, and saltmarshes (Figure 23).

The Billion Oyster Project in New York Harbour has restored over 45 million oysters at 15 reef sites across the five boroughs, recycled 1.6 million pounds of oyster shells from restaurants, and plans to restore the Harbour's oyster population to over 1 billion oysters (Billion Oyster Project, n.d.).

Nature Conservancy manages several oyster restoration projects across the United States (*Oyster Restoration | Our Stories*, n.d.)

Namely the Chesapeake Bay oyster restoration project that will be the world's largest shellfish restoration project in the world when complete.

The Australasian Shellfish Reef Restoration Network is a Community of Practice that connects several shellfish reef restoration programs in Australasia (*Shellfish Reef Restoration Network*, n.d.).

Project Seagrass is a seagrass restoration project in Wales with the goal of planting over 750'000 seeds to create a 5-acre meadow (*Project Seagrass*, n.d.).

The South Australia Government's New life for our coastal environment project to re-establish around 10 hectares of seagrass off the Adelaide metropolitan coast (*Protecting Our Coastal Environment*, n.d.).

The joint efforts of the Virginia Institute of Marine Science and The Nature Conservancy to seed

With so many marine habitat restoration projects underway and new organizations emerging in the field of MAT, there are countless opportunities for the implementation of MAT. A factor that may improve upon the recent increase in MAT research and funding is multi-sectoral collaboration. OLF is the primary driver of cross-sectoral collaboration for MAT and ought to continue to expand its partnerships with other users of MAT for marine habitat construction and uses in other marine sectors such as aquaculture and coastal defence. The study of grey literature concerning MAT users other than the Biorock™ Company points to a disconnect and unawareness among similar projects. The general lack of awareness of MAT for marine habitat and its relatively recent resurgence due to the Biorock™ patent expiry has likely played a role.

Furthermore, despite the newfound adoption of MAT, it is still only being applied sporadically compared to other habitat restoration efforts. With most MAT installations, there are no associated research programs to track and document the effects. Many field research studies investigate the effects of existing structures rather than the long-term monitoring of a new structure's growth, colonization, and hydrodynamic effects. Creating an online repository for results, successes, failures, technical resources, conversation, and progress images could be of excellent service towards understanding MAT in the marine environment. Such a resource could help disseminate the academic studies on MAT by creating a dedicated open-source database of peer-reviewed and grey literature, technical reports, and pictures and video. Many resources exist on the topic that would be better served if they were organized and easily accessible. The need for social advancement in MAT's realm will be just as critical as the technical advancement.

Chapter 9.2 Potential in St. Margaret's Bay

One of the research gaps of MAT in coastal protection and marine habitat construction is the lack of studies carried out in cold water environments. The proposed MAT mussel reef installation is intended to contribute to addressing the research gap. The St. Margaret's Bay site was chosen based on availability, ease of access, and enthusiasm of the property owners. Given the success of MAT projects catalyzed by community efforts, such as with Biorock® Indonesia in the Gili Islands and NHRCP in Koh Tao Thailand, a bottom-up approach seems to be the favorable management style to gain community. Even if St. Margaret’s Bay is very different from these tourism and coral reef-dependent communities, collaborating with a small group of community members to realize a small pilot project is a more accessible approach than working with government agencies such as DFO or local ENGOs such as Coastal Action. If the proposed installation outcomes are positive and gain public support, approaching larger entities for support would be more feasible.

Based on the reviewed literature and current innovations surrounding MAT in the marine space, potential opportunities, and barriers for implementing the technology in St. Margaret's Bay and the rest of the province have been identified. Like with many coastal regions worldwide, the province of Nova Scotia is experiencing rising relative sea levels and significant damage from storm activity. The damage costs of Hurricane Dorian were in the range of CAD$ 39M, the highest incurred damage costs recorded by Nova Scotia Power and leaving nearly 80% of the province's households without power (BNN, 2019). On October 30, 2018, the following motion of the Halifax Regional Council was put and passed: "That Halifax Regional Council request a staff report to investigate a Municipal Climate Change Directorate (MCCD) working under the direction of the Chief Administrative Officer (CAO), to outline what HRM must do to meet the outcomes of the Intergovernmental Panel on Climate Change (IPCC) Special Report 1.5C of 2018.” (Dubé, 2020, p.8). On June 23, 2020, the HalifACT 2050: Acting on Climate Together plan was released to inform the public on the measures that the Halifax Regional Municipality (HRM) will take to meet the outcomes of the Intergovernmental Panel on Climate Change (IPCC) Special Report 1.5C of 2018. Figure 24 details the recommendations made in the report. Recommendation b), which indicates the need to retrofit new and existing municipal buildings to make them net-zero and climate-resilient, is expanded upon on pages 13 and 14 of the report.

In summary, the recommendation focuses on upgrading buildings to be more efficient, which is a great strategy, but there is no mention of implementing physical measures to protect these buildings from potential storm surges and the encroaching ocean. Page 17 discusses the upcoming flood and digital elevation models, land use bylaw regulations, and the implications of the Coastal Protection Act and any associated regulations and policies passed (Dubé, 2020, p.17). Despite being necessary, the issue with these recommendations is that they will cost money and take time, all while the climate continues to change, as the sea-level continues to rise, and HRM continues to subside. Some of that time and money ought to be used to implement actions today, such as physical defences that will help protect the investments that will fund municipal buildings' retrofitting. The global aspect of global warming should not be ignored. Even if HRM does its part in meeting the Intergovernmental Panel's outcomes on Climate Change (IPCC) Special Report 1.5C of 2018, other regions may not, and the impacts of climate change could still be felt. It is not enough to hope everyone contributes.

Direct the Chief Administrative Officer to prioritize efforts in the following critical core areas:

a) Create new energy retrofit and renewable energy programming.

b) Develop a detailed and costed plan for retrofitting existing municipal buildings to be net-zero ready and climate resilient.

c) Develop an electric vehicle strategy, increase charging infrastructure, and replace fleet
vehicles with electric vehicles.

d) Explore opportunities to require net-zero standards for new buildings in the municipality.

e) Develop a framework for assessing and protecting critical infrastructure.

Figure 24. Measures to improve the climate resiliency of municipal buildings in HRM (Dubé, 2020, p.13-14).

If the proposed MAT mussel reef experiment in St. Margaret's Bay can be fast-tracked and rigorously tested, HRM could have a cost-effective and long-term coastal defence measure that grows stronger over time and creates valuable habitat for the harbour's ecosystem. Using recycled steel products such as steel rebar, which will likely be a by-product of proposed municipal building retrofits, and renewable energy, which HRM plans to expand upon, the municipality could synergistically contribute to achieving several climate goals in a less emissive and efficient manner. MAT reefs are a nature-inspired solution that can offer benefits concerning wave attenuation, habitat construction, and resiliency for commercially and ecologically important species, ecotourism, and ocean technology. By accelerating the implementation of shellfish reefs with MAT, benefits including threatened ecosystem recovery, biofiltration, coastal protection, fish production, nutrient cycling, mitigation of erosion by changing water flow patterns and attenuating waves, and accumulating and stabilizing sediment could be achieved within the timeframe of the HalifACT 2050: Acting on Climate Together plan (Fitzsimons et al., 2020; Peyre et al., 2015). There are already detailed restoration guidelines produced by and for practitioners, managers, and community members involved in shellfish restoration (Fitzsimons et al., 2019). The research, ocean technology development, jobs, coastal development offset, and ecotourism that could be generated by using MAT at scale in HRM and other coastal municipalities are an opportunity for Nova Scotia to stand out as a global leader in coastal climate responsiveness. Also, the returned value in ecosystem services could be significant and could play a role in achieving the targets outlined in the HalifACT 2050: Acting on Climate Together plan.

With the development of innovation-centric organizations such as the Center for Ocean Ventures (COVE) and Volta, Atlantic Canada's premier innovation hub, in Halifax, considering projects of this nature fit within the efforts to make Halifax a global leader in ocean technologies such as robotics and autonomous vehicles, and underwater acoustics, sensing, and imaging.

There are many opportunities through COVE to acquire funding to assist in the research, development, and implementation of MAT at the proposed scale (Figure 25).

Figure 25. COVE infographic detailing the funding and growth of HRM's ocean tech industry (Oceans, n.d.).

In addition to the existing domestic funding, there are non-profits such as OLF whose primary goal is to support and guide the development of MAT projects at scale by providing grants, debt

& equity financing. The non-profit encourages large MAT solutions such as engineered living breakwaters, a combination of MAT and prefabricated rebar cages seeded with native reef-forming organisms such as blue mussels or eastern oysters (Ocean Life Foundation, 2020). With similar properties as standard steel-reinforced concrete used in construction, engineered living breakwaters can dissipate wave energy and retain sediment while improving over time, rather than displacing wave energy and sediment and breaking down over time like seawalls (Figure 26). Engineered living breakwaters can be a sustainable and cost-effective solution that contributes to creating valuable marine habitat instead of destroying it and reducing emissions instead of generating more. Ocean Life Foundation, 2020 estimated an approximate cost of USD$ 1M per kilometer of engineered living breakwater during the Asia Clean Energy Forum 2020. For example, the Halifax waterfront, a working port & one of the world's longest downtown boardwalks, is approximately three kilometers and would require an investment of USD$ 3M to build an engineered living breakwater based on the estimates provided by the OLF. Halifax is a port city surrounding one of the largest and deepest harbors globally, with a large ship-building industry comprising a large fleet of welding, electrical, and marine infrastructure specialists, in a province whose geological makeup is dominated by rocks. The skilled workers and many of the resources are readily available, making Halifax Harbour an ideal site for engineered living breakwaters using MAT for urban coastal protection.

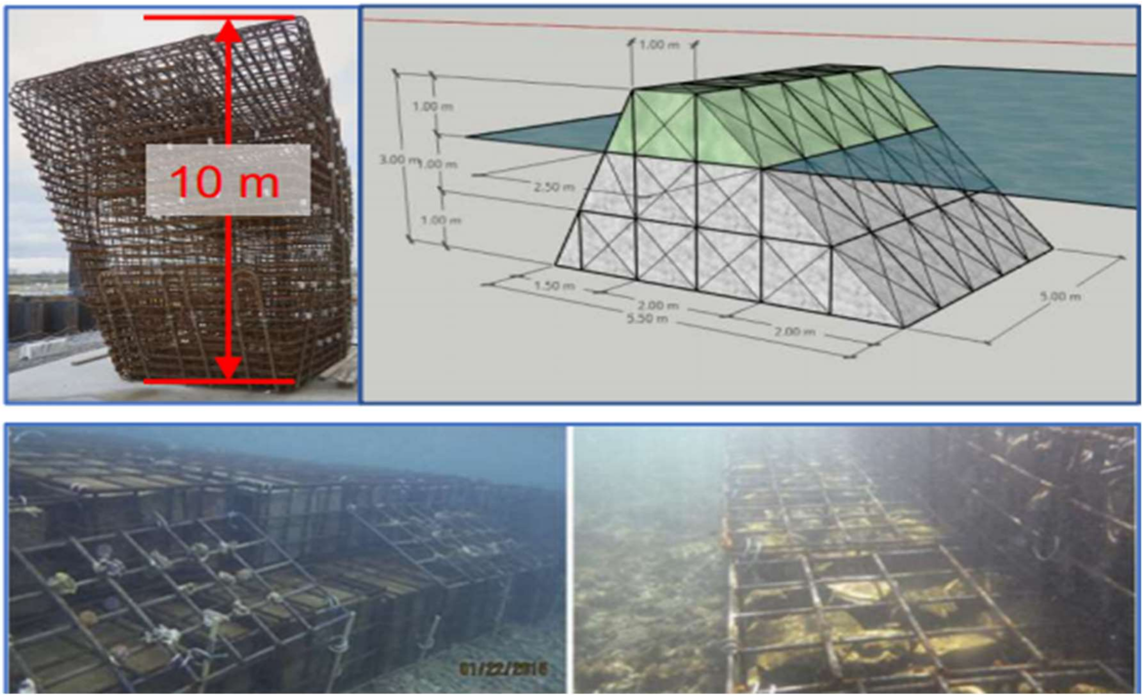


Figure 26. Engineered living breakwater installations (bottom), frame (top left), CAD design (top right) (Ocean Life Foundation, 2020).

An opportunity for testing the implementation of engineered living breakwaters using MAT is the 1.6-hectare winning design by KPMB Architects for the Art Gallery of Nova Scotia. The building's design has factored in storm surge and sea-level rise due to climate change by remaining above ground level and constructing a wetland and publicly accessed living shoreline within the property's landscape (Figure 27).

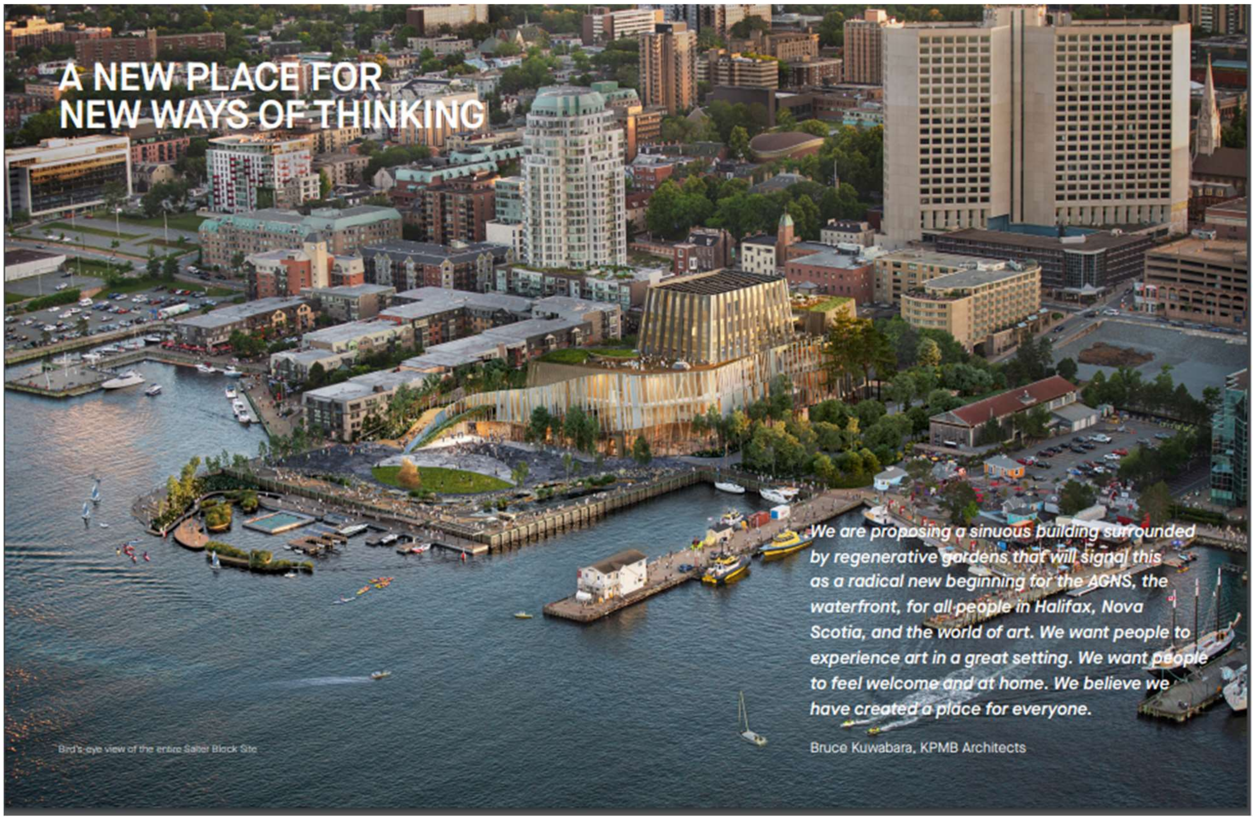


Figure 27. Conceptual design by KPMB Architects for the Art Gallery of Nova Scotia displaying the built-in wetland area, an opportunity to implement MAT (The Conceptual Designs n.d.).

The innovative building design is inspired by sustainability, climate resilience, nature, and K'jipuktuk's (Halifax) first peoples' (the Mi'kmaw) traditions. Incorporating an engineered living breakwater using MAT into the proposed gallery plan could extend beyond conventional design by continuing underwater. By using MAT, steel rebar can be welded and bent into any shape; the only barrier is the creator's imagination (Figure 28). Extending the gallery's design into the Harbour embodies the designers' goals by creating habitat and shore protection and connecting land and sea.

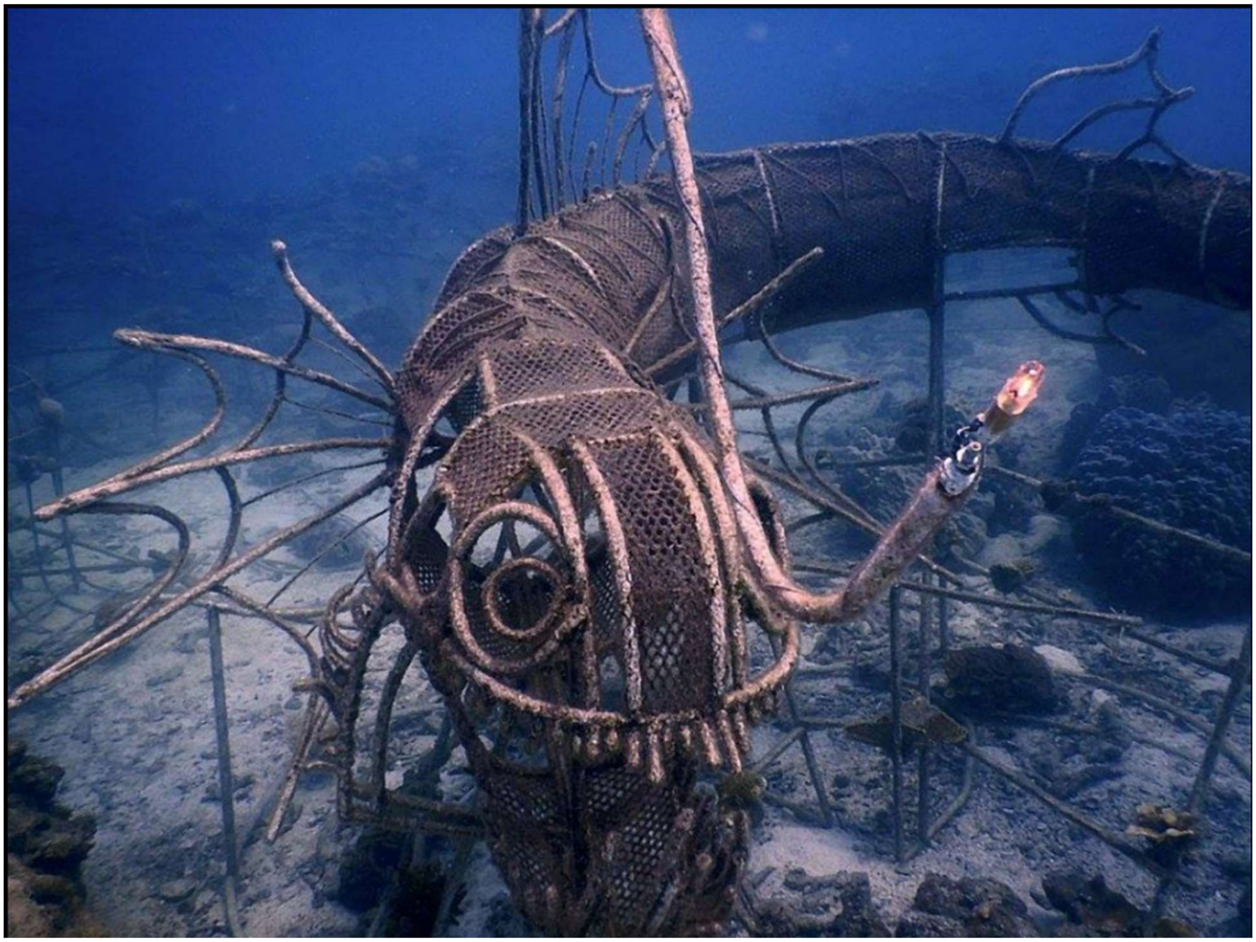


Figure 28. The “Electrified Viperfish” MAT installation built and maintained by NHRC (“Our Story” n.d.).

Chapter 10 Overall Conclusion

The original goal of this project was to determine if MAT would be an effective method for enhancing the growth, survival, and settlement of blue mussels and the accretion of carbonate minerals on an AR constructed of recycled steel rebar in St. Margaret's Bay, Nova Scotia. Due to restrictions and limitations surrounding the COVID-19 pandemic, the project direction pivoted, and the research changed into a literature review and a proposal for a MAT mussel reef installation. Through the review process and additional desktop research of peer-reviewed and grey literature, a better understanding of the history, the future potential, and the current status of MAT applied in the marine space was gained. There have been barriers such as a technology patent, preferential application to tropical environments, and insufficient research that have hindered a better understanding of MAT, and therefore a wider adoption. With such a long history and mixed acceptance under the name Biorock, it can initially be challenging to gain awareness of more recent initiatives concerning MAT. Despite the relatively slow progress of the technology, MAT's uses to rebuild marine habitats that exist today are a significant leap forward. More people than ever before understand the benefits and potential of MAT, and the awareness will likely continue to expand. If MAT continues to be tested in new environments, new species, new applications, and smarter technology, the feasibility and cost of building marine habitats can improve, and marine infrastructure could be built in a more sustainable and resilient way. With the information gathered from reviewing research such as the reports associated with the invention of MAT by the late Wolf Hilzbertz, the decades of work by the Biorock™ Company, the innovations catalyzed by NHRCP and coralAID, and the ambitions of OLF, the necessary steps to install an MAT mussel reef in St. Margaret's Bay and beyond are much clearer. With further research and development, MAT can create seemingly endless opportunities and cross intersectoral boundaries by connecting industry, the sciences, and the arts to protect the ocean and humans living on the coast.

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Appendix

Table A. List of studies included in literature review

Record Information			**Field Installation**		**Research Topic Distribution 1 = yes 0 = no**		
Title	Reference	Purpose	Location	Coastal Protection	Habitat Construction	Mineral Accretion	Social Impact
Alternative Substrates for Restoration Of The Chesapeake Bay's Eastern Oyster, Crassostrea Virginica: An Evaluation Using Additive Manufacturing And Electrolysis Mineral Accretion	(Arrington et al. 2019)	Lab testing	Chesapeak Bay, Virginia, USA	1	1	1	0
Biorock electric reefs grow back severely eroded beaches in months	(Goreau and Prong 2017)	Field testing	Pulau Gangga, Indonesia	1	1	1	1
Biorock reef restoration in Gili Trawangan, North Lombok, Indonesia	(Bakti et al. 2012)	Field testing	Gili Trawangan, North Lombok, Indonesia	1	1	1	0
Bottom-up community-based coral reef and fisheries restoration in Indonesia, Panama, and Palau	(France 2007)	Review		0	1	0	1
Coral reef rehabilitation on Koh Tao, Thailand Assessing the success of a Biorock Artificial Reef	(Terlouw 2012)	Field testing	Koh Tao, Thailand	0	1	0	0

Coral Reef Restoration–A guide to effective rehabilitation techniques	(Allahgholi 2014)	Review		1	1	0	0
Development of an eco-sustainable solution for the second life of decommissioned oil and gas platforms: The mineral accretion technology	(Margheritini et al. 2020)	Field testing	Hanstholm, Denmark	0	1	1	1
Effect of severe hurricanes on Biorock coral reef restoration projects in Grand Turk, Turks and Caicos Islands	(Wells et al. 2010)	Field testing	Grand Turk, Turks and Caicos	1	1	1	1
Branching and Growth in Jakarta Bay	(Zamani, Abdallah, and Subhan 2012)	Field testing	Jakarta Bay, Indonesia	0	1	0	0
Electrical Fields Increase Salt Marsh Survival and Growth and Speed Restoration in Adverse Conditions	(Cervino et al. 2012)	Field testing	Long Island Sound, New York, USA	0	1	0	0
Electrical stimulation greatly increases settlement, growth, survival, and stress resistance of marine organisms	(Goreau 2014)	Review		0	1	0	0
Electrical Stimulation Increases Oyster Growth and Survival in Restoration Projects	(Shorr et al. 2012)	Field testing	East River, New York, USA	1	1	1	0

Electrically stimulated corals in Indonesia reef restoration projects show greatly accelerated growth rates.	(Jompa et al. 2012)	Field testing	Barrang Lompo, Samalona, Pemuteran, Gili Trawangan	1	1	1	0
Electricity protects coral from overgrowth by an encrusting sponge in Indonesia	(Nitzsche 2012)	Field testing	Pemuteran, Bali, Indonesia	0	1	0	0
Electrolysis, halogen oxidizing agents and reef restoration	(Koster 2017)	Lab testing		0	1	0	0
Electrorock	(Lawrence 2016)	Lab testing		0	0	1	0
Enhancing settlement and growth of corals using feeble electrochemical method	(Kihara et al. 2013)	Field testing	Okinawa, Japan	0	1	1	0
Farming the High Seas: An adaptive approach for the inhabitation of oceanic recirculation gyres	(Jarvis 2020)	Theoretical		0	1	1	1
Geotourism combining Geo-Biodiversity and Sustainable Development of Tropical Holocene Coral Reef Ecosystems: Comparison of Two Indonesia Eco-regions using Biorock Technology	(Ontosari et al. 2014)	Social Impact		1	1	0	1

Geotourism resources as part of sustainable development in geopark indonesia	(Yuliawati, Pribadi, and Hadian 2016)	Social Impact		0	1	0	1
Gorgonian Soft Coral Have Higher Growth and Survival in Electrical Fields	(Fitri and Rachman 2012)	Lab testing		0	1	0	0
Green Tourism Development as a Community Empowerment Efforts In Pemuteran Village, Buleleng, Bali	(Suwena et al. 2017)	Social Impact		0	1	0	1
Growing the architecture of Barbados: from vulnerable to resilient shelters	(Coombes 2013)	Theoretical		0	0	1	1
Growth Rate of Acropora formosa and Montipora digitata Transplanted on Biorock in Gili Trawangan	(Damayanti et al. 2011)	Field testing	Trawangan, North Lombok, Indonesia	0	1	1	0
High-Resolution Underwater 3-D Monitoring Methods to Reconstruct Artificial Coral Reefs in the Bali Sea: A Case Study of an Artificial Reef Prototype in Gili Trawangan	(Vogler, Schneider, and Willmann 2019)	Field testing	Gili Trawangan, Indonesia	1	1	0	0
Increased oyster growth and survival using biorock technology	(Berger et al. 2012)	Lab testing		1	1	1	0

Increased zooxanthellae numbers and mitotic index in electrically stimulated corals	(Goreau, Cervino, And Pollina 2004)	Lab testing		0	1	1	0
Influence of mineral accretion induced by electric current on the settlement and growth of the scleractinian coral Pocillopora damicornis (Cnidaria, Anthozoa, Hexacorallia)	(Chavanich et al. 2013)	Field testing	Gulf of Thailand, Thailand	0	1	1	0
Laboratory tests on mineral deposition under sea water electrolysis	(Margheritini, Simonsen, and Bjørgård 2019)	Lab testing		0	0	1	0
Marine ecosystem electrotherapy: Practice and theory	(Goreau 2012a)	Review		1	1	1	1
Marine ecosystem restoration: costs and benefits for coral reefs	(Goreau and Hilbertz 2005)	Review		1	1	1	1
Marine electrolysis for building materials and environmental restoration	(Goreau 2012b)	Review		1	1	1	1
Mineral Accretion: An Environmentally Alternative to Plastic for Oyster Restoration.	(Hunsucker et al. 2019)	Field testing	Indian River Lagoon, Florida	0	1	1	0
Oyster recruitment and growth on an electrified	(Piazza et al. 2009)	Field testing	Grand Isle, Louisiana	1	1	1	0

artificial reef structure in Grand Isle, Louisiana							
Participatory planning workshop for the restoration of Ashton lagoon	(Sorenson 2008)	Theoretical		1	1	1	1
Reef Restoration as a Fisheries Management Tool	(Goreau and Hilbertz 2009)	Review		1	1	1	1
Reef restoration for coastal defence: A review	(Fabian, Beck, and Potts n.d.)	Review		0	1	1	0
Reef Restoration Using Seawater Electrolysis in Jamaica	(Goreau and Hilbertz 2012)	Field testing	Negril, Jamaica	1	1	1	0
Restoration of Seagrass Mats (Posidonia oceanica) with Electrical Stimulation	(Vaccarella and Goreau 2012)	Field testing	Torre Guaceto, Italy	0	1	1	0
Restoring coral reefs, oyster banks, and fisheries by seawater electrolysis: Coastal zone management and tourism applications	(Goreau, Hilbertz, Azeez, Hakeem, Dodge, et al. 2003)	Theoretical		0	1	0	1
Restoring reefs to grow back beaches and protect coasts from erosion and global sea-level rise	(Goreau et al. 2013)	Review		1	1	1	1
Science and Culture: Artistic endeavors strive	(Beans 2018)	Field testing	Cozumel, Mexico	0	1	0	1

to save coral reefs							
Shore protection, beach formation, and production of building materials and energy using seawater electrolysis technology	(Goreau, Hilbertz, Azeez, Hakeem, and Allen 2003)	Social Impact		1	1	1	1
Smart Port Breakwater Design and Construction	(Shaw and Goreau 2016)	Theoretical		1	1	1	1
Study on Biorock® Technique Using Three Different Anode Materials (Magnesium, Aluminum, and Titanium)	(Zamani et al. 2010)	Lab Testing		0	0	1	0
Suitability of Mineral Accretion as a Rehabilitation Method for Cold-Water Coral Reefs	(Strömberg, Lundälv, and Goreau 2010)	Field testing	Tjärnö, Sweden	0	1	1	0
Sunken Cities: Climate Change, Urban Futures and the Imagination of Submergence	(Dobraszczyk 2017)	Theoretical		0	0	1	1
Sustainability entrepreneurship in marine protected areas	(Bush, Bottema, and Midavaine 2016)	Social Impact		0	1	0	1
Sustainable pre-stressed concrete from seawater	(Millison and Countryman 2017)	Theoretical		0	0	1	1
The durability of private sector-led marine conservation: A	(Bottema and Bush 2012)	Social Impact		0	1	0	1

case study of two entrepreneurial marine protected areas in Indonesia							
THE EFFECT OF BIOROCK CORAL REEF RESTORATION ON TOURIST TRAVEL DECISIONS AT PEMUTERAN BAY, BALI	(Budisetyorini and Endah Cahyani 2016)	Social Impact		0	1	0	1
The effects of Biorock-associated electric fields on the Caribbean reef shark (Carcharhinus perezi) and the bull shark (Carcharhinus leucas)	(Uchoa, O'Connell, and Goreau 2017)	Field testing	Bimini, Bahamas	0	1	0	0
The escalation of coral growth by biorock technology applied in Sabang marine ecotourism	(Munandar et al. 2018)	Field testing	Rubiah Island, Sabang	0	1	1	0
The role of the community in supporting coral reef restoration in Pemuteran, Bali, Indonesia	(Trialfhianty and Suadi 2017)	Social Impact		0	1	0	1
Utilization of low-voltage electricity to stimulate cultivation of pearl oysters Pinctada maxima (Jameson)	(Karissa et al. 2012)	Field testing	Buleleng, Bali, Indonesia	0	1	1	1
Voluntarily Local Environmental Governance of	(Yakin 2011)	Social Impact		0	1	0	1

Marine Waters Tourism Area of Gili Matra (MWTA-GM) of North Lombok Regency						
Vulnerability assessment of small islands to tourism: The case of the Marine Tourism Park of the Gili Matra Islands, Indonesia	(Kurniawan et al. 2016)	Social Impact	1	1	0	1

Temperature	**Months**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Average °C	2.8	0.8	0.9	2.7	5.2	9.4	14.1	17.1	16.6	13.8	9.1	5.5
Min °C	-0.1	-0.9	-0.3	0.1	2.4	6.1	12	15.2	14.2	11.2	6.5	2.5
Max °C	5.7	2.5	2.1	5.3	8.1	12.7	16.2	19.1	19	16.4	11.7	8.6

Table B. Halifax average seawater temperature data for Figure 15 from http://www.seatemperature.org/north-america/canada/halifax.htm (Connect, n.d.).

Electrical Treatment Current µA	**ATP Concentration (µmol/gm Tissue)**	**Error**

0.1	4.2	± 0.8
10	10	± 1.5
50	14.2	± 1.2
100	16.9	± 1.9
500	20.1	± 2.2
1000	15	± 1.8
5000	3.9	± 0.6

Table C. Data from Cheng et al., 1982 for the effect of current's on ATP concentration and the point of diminishing return in Figure 17.