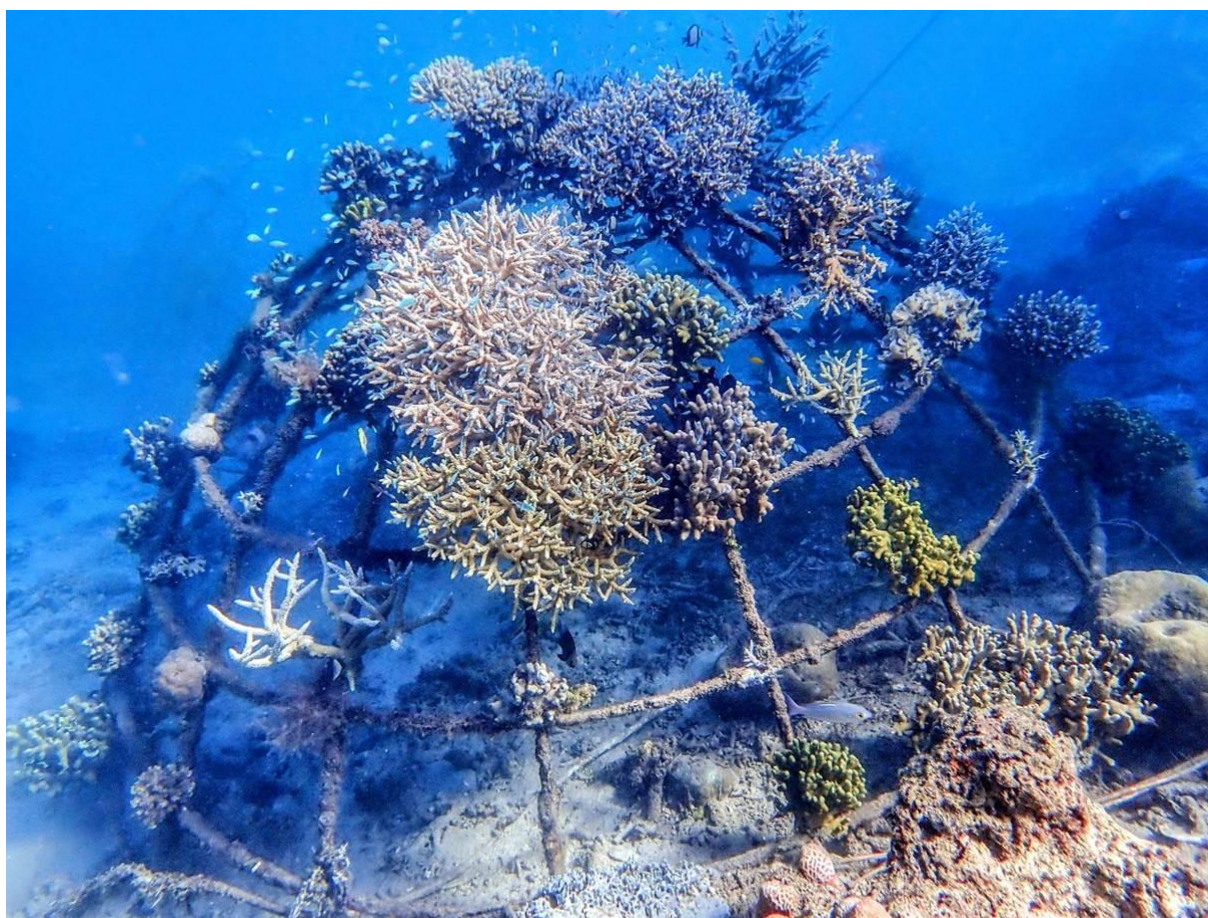


Growing Solid Rock

- Biorock as a Nature-Inspired Combination of Eco-Friendly
Materials and Resilient Marine Ecosystems



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Master thesis

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Environmental and Energy Systems Studies

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Cover photo: Biorock structure in Indonesia, used with permission from the Unsplash License

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Abstract

Acidification-threatened marine ecosystems and competition for land use along the coasts are merely some of the consequences of the climate crisis. A technology with growing interest that can contribute to solutions for these consequences is Biorock. As a nature-inspired approach based on electrolysis of seawater, Biorock offers two solutions in one technology; eco-friendly materials grown directly in the seawater and resilient marine ecosystems. So far, Biorock has mainly been used in tropical waters, making its function in colder waters an under-researched area. Therefore, the objective of this thesis is to explore the potential of the Biorock-technology to contribute to favorable habitats for marine ecosystems and to eco-friendly materials in a Swedish context.

To achieve this objective, a literature study and personal communications with authors and experts were carried out. The results show that the growing material can store carbon and protect against corrosion but at a relatively slow and non-linear growth rate. It also appeared to have physical properties similar to concrete. Moreover, the material structure and growth process depend on several factors. Regarding marine ecosystems, Biorock can contribute to some of the Swedish climate and biodiversity goals by providing a refuge with favoring water chemistry and natural materials, increasing their resilience against climate change. One identified challenge is, however, choosing an electrical stimulation level suitable for both marine ecosystems and useful materials.

Overall, it is evident that the strengths of Biorock lie not in large-scale acidification mitigation or energy- and cost-effective material production or carbon storage. Instead, its values are multifunctionality and sustainability. There are reasons for considering the growing material a solid rock, not just because of its physical strength but also because its benefits make Biorock a “solid rock”, a potential solution, in the unstable climate crisis. Therefore, apart from the seawater structures, with more research attention, Biorock might as well be growing on us.

Keywords: Biorock, Seacrete, Seament, electrodeposition, electrolysis of seawater, marine ecosystems, eco-friendly materials, artificial reef, corrosion, breakwater, acidification, carbon dioxide emissions, carbon storage, pollution capture, environment, climate

Preface

It all started with the back of a milk carton many years ago...

Nature has always been a source of knowledge and wonder for me. It is one of the places where I see the fingerprints of God. When the time came to plan my thesis at Lund University, I remembered the back of that milk carton. A captivating text had opened my eyes to biomimicry - learning from nature. Therefore, the thesis idea that first came to my mind was not surprising.

This thesis was performed at the Department for Technology and Society at the Faculty of Engineering (LTH) at Lund University.

Artificial intelligence has been used to a small extent in this thesis. More specifically, this means brainstorming ideas and finding suitable translations but not producing text.

I would like to thank Lund University, specifically LTH, for 5 years of challenging and inspiring education leading up to this thesis.

An extra thank you goes to Karin Ericsson, my supervisor, for the support along the way with ideas, knowledge, Word skills, and encouraging and enjoyable meetings that left me motivated to read and write more.

My gratitude also applies to Lars J. Nilsson, my examiner, for believing in my (strange!) biomimicry idea and starting the thesis process.

Additionally, the support from the Engineers of Sweden's Environmental Fund (Sveriges Ingenjörers Miljöfond) made it possible for me to think outside my box and provided useful advice.

Also, I would like to extend my thanks to the authors and experts who contributed valuable knowledge through different means of personal communication (see section 2.2).

I am also so grateful to my church family in Lekeryd, Lund, including Credo, and Iceland, among other dear friends, for being my home away from home and giving me pauses in the reading and writing with fika, walks and talks.

Finally, how can I thank God and the rest of my family for being with me all the way through never-ending encouragement, energy, shown interest, uplifting phone calls, technical support, funny messages and so much more love?

You have been, and are, my growing solid rock!

Thank you so much!

Lekeryd, June 2026

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1. Introduction

“... the Great Story which no one on earth has read: which goes on for ever:
in which every chapter is better than the one before.”

(Lewis, 1956, p. 160)

It is a truth, universally acknowledged, that a planet in climate crisis must be in want of solutions. The climate crisis significantly affects the oceans, as well as the ecosystems and services that depend on their well-being, with increased temperatures, changed water currents and eutrophication. Another important consequence is ocean acidification, caused by increased levels of carbon dioxide in the atmosphere. Acidification hinders calcification of calcareous organisms, including corals, mussels and calcareous algae. The oceans have, however, a limited capacity for absorbing carbon dioxide and are already major carbon sinks. During the year 2025, the planetary boundary for ocean acidification was exceeded (Planetary Boundaries Science, 2025). Additionally, the climate crisis is caused by our unsustainable lifestyles, resulting in greenhouse gas emissions, as well as competition for land use, for example along the coasts where infrastructure and marine ecosystems are supposed to coexist.

Solutions are, in many cases, found when new perspectives are taken or when looking for inspiration from other sources. The climate crisis is probably no exception. Since the climate crisis takes many forms, so must the solutions. For example, if additional applications for existing solutions are investigated, the possibilities increase to find solutions that meet pressing demands caused by the climate crisis, and hopefully live up to how the Great Story is described by C. S. Lewis (1956). One such available source of inspiration is nature. The more nature is explored, the more evident the number of solutions that are already embedded in nature, created for us as a gift to use and learn from. This way of drawing inspiration from nature is called biomimicry (Nordic Biomimicry, n.d.).

One example of a biomimicry-technology is Biorock, which offers a combination of new perspectives and inspiration from nature. Based on electrolysis of seawater, Biorock encourages a change regarding what is considered undesirable by-products or valuable multifunctional materials. The reason is that, compared to the traditional purpose of electrolysis to produce hydrogen and avoid mineral deposition on the structures, the material is important for the Biorock-technology, growing directly in the oceans (Hilbertz, 1979). There is evidence that this growing material is an attractive habitat for marine ecosystems, increasing their resilience to climate change, but also a useful and eco-friendly material for different construction applications as well as for carbon storage, but the extent and characteristics of these abilities are partly being questioned, requesting more studies.

This Biorock-technology has been used for decades, however mostly in tropical waters (Goreau, 2022) and with less focus on the construction applications. This indicates that the performance of Biorock in cold waters, such as in Sweden, is an under-researched area in comparison. One could ask what prevents this technology, that sounds so promising, from being used more (F. Moberg, personal communication, July 9, 2025). If Biorock can produce multifunctional materials from an unlimited resource like seawater, would it not be of interest to places beyond the tropical areas as well? Therefore, this thesis will explore the Biorock-technology by diving deeper into the subject, towards growing solid rock.

1.1 Objective and Research Questions

The objective of this thesis is to explore the potential of the Biorock-technology to contribute to favorable habitats for marine ecosystems and to eco-friendly materials in a Swedish context. This is done with the following questions:

- What effects does the Biorock-technology have on marine ecosystems?
- What are the characteristics and controlling factors of the material grown with the Biorock-technology?
- How can the Biorock-technology be implemented in Sweden?

1.2 Delimitations

For the purpose of fulfilling the objective, the focus is primarily on information that can be applied to the Swedish colder environments. However, studies in warmer environments are also included, since the results could be used as overall guidelines, for comparison and as valuable knowledge to consider for a potential implementation of Biorock in Sweden.

1.3 Outline

The following chapter 2 describes the method. After that, the results are presented in chapters 3, 4 and 5. Chapter 3 provides information about the set-up, chemical processes and history of the Biorock-technology. Besides information retrieved from the literature study, the section about history consists of information from relevant websites. In chapters 4 and 5, the two main applications for the Biorock-technology are described, which aim at answering the first two research questions. The first section in each of these two chapters contains information that is not a result of the literature study or personal communication but a combination of information from for example news, agencies and organizations. Chapter 6 consists of the discussion regarding both the results and the method. The discussion of the results is supposed to answer the third research question. Lastly, chapter 7 presents the conclusions.

2. Method

The method for gathering information primarily included a literature study, but personal communication like interviews and other means of communication were used as well. These are described in the two sections below.

2.1 Literature Study

The main source of the results in chapters 3, 4 and 5 is articles from a literature study, primarily through the search tool Finn with the peer-reviewed filter. Finn searches the databases of Lund University. A selection of search terms is presented in Table 1. Truncation was useful to increase the search results. Additionally, OpenAI was used, to some extent, to find similar items or suitable search terms.

Table 1. A selection of search terms, consisting of keywords and their synonyms

Keyword	Synonyms
Biorock	mineral accretion, electrodeposition, calcareous deposition, seament, seacrete
Marine ecosystems	ocean, maritime, sea + habitat, environment
Construction materials	Building materials, building blocks, infrastructure, cement, concrete
Sustainable	eco-friendly, environmentally friendly, climate-friendly

The searches were conducted differently during the process. In the first search, only the search terms for Biorock were used, in order to gain an overview of the amount of material items, including articles, reports and books. As the following searches resulted in further synonyms for Biorock, the search with only terms for Biorock was repeated to make the overview more accurate. For example, the search “Biorock OR "mineral* accret*" OR electrodeposit* OR "calcare* deposit*" OR seament* OR seacrete*” in Finn resulted in 217 768 items, which further emphasized the need to find more suitable keywords to limit the results to the specific subject. In contrast, the search “Biorock” only gave 59 items in Finn. However, some of these items were not relevant since it became clear that the term Biorock is used in other contexts as well, like space, water filtering and medicine. For that reason, one search was conducted using the filter “All text” instead of “All fields” meaning that the term Biorock was searched for in the whole item instead of only the title, abstract and keywords, which resulted in some more relevant articles. Because of the origin of Biorock, items by Hilbertz and Goreau (see section 3.2) were included from the beginning.

The literature items had more purposes than their own information. Through some of them, more items were identified via the so-called snowball effect. Moreover, common authors in this subject area were found through the items. Some examples are Strömberg et al. (2010) and Devi et al. (2025) based on which other interesting authors and items were identified, such as Rotta Loria, Colaleo, Margheritini, Carré, Sabater and Yap. The items also served to indicate potential research gaps and inspiration to direct the search differently, for example the lack of studies in colder waters. Since the objective of this work is to explore the potential of Biorock, the search functioned as some kind of guidance, meaning that the literature search was more than an initial step but a reappearing part through the whole work process in order to reshape the search as more information was found. In the end, 33 studies were included in the results in chapters 3, 4 and 5.

2.2 Personal Communication

The personal communication was primarily conducted through email communications, but phone calls, physical meetings and video interviews were also included. Some of the results from these conversations are used in chapters 3, 4 and 5 and referred to as Personal Communication but all of them were very helpful for the understanding of the topic.

Email communications have been made with almost every author with available contact information, including Tom Goreau, Susanna Strömberg, Alessandro Rotta Loria, Alessandro Benedetti, and Cameron Penney. These conversations were mainly used to ask questions about their respective studies and to learn more about the authors' knowledge in the subject area. In many cases, this information provided clarifications about some parts of the articles or background information to the content, which means that an extra reference as Personal Communication was not needed but these contacts were nevertheless useful.

A video interview was conducted with Pere Ferriol Buñola about a planned Biorock project in the Balearic Islands. I also had a meeting with Lars Wadsö, professor at the department of Building Materials at LTH, discussing different Biorock applications compared to common concrete, mostly marine constructions. Additionally, a video interview was conducted with Tom Goreau about his experience and thoughts on Biorock.

In the planning phase of the thesis, contact was made with Fredrik Moberg, environmental researcher, communications advisor and author of the book *Den uppfinningsrika planeten - Biomimikry och naturens lösningar på vår tids utmaningar* (*The Ingenious Planet - Biomimicry and Nature's Solutions to the Challenges of Our Time*). Email conversations have also been made with Kristian Tammo from Swerock about marine concrete infrastructure, as well as a phone call. Moreover, email conversations were made with Stina Bertilsson Vuksan, environmental strategist and marine biologist at Helsingborg Municipality, about their ecological design project in the harbor, which were followed by a phone call and a video meeting about how Biorock could be used in their project. Additional email correspondence was conducted with Sara Schlyter and Martin Forsberg, who are managing an ecological design project in Helsingborg, as well as Alex Goad from Reef Design Lab in Australia.

3. Biorock

In this section, the structure as well as the flows and chemical conversions of substances of the Biorock process are described followed by some of the history of Biorock.

3.1 Description

Biorock, also called Mineral Accretion Technology, Seament and Seacrete, is based on electrolysis of seawater (Global Coral Reef Alliance [GCRA], n.d.) meaning that its components are a cathode, an anode, an energy source to produce electricity, and seawater. In this technology, Safe Extremely Low Voltage (SELV) electrical fields are generated (Goreau, 2022). A structure, acting as the cathode and made of electrically conductive materials like steel, is submerged in the seawater (GCRA, n.d.), as illustrated in Figure 1. The cathode's metal potential, meaning the metal's ability to release electrons and thereby corrode, is reduced from its corrosion domain to its immunity domain, which protects the cathode from corrosion (Carré et al., 2020). The anode is made of a metal that has a more negative electrochemical potential than the material of the cathode, for example titanium (Margheritini et al., 2020). A variety of energy sources can be used, including solar, wind, wave, ocean current and traditional energy sources like fossil fuels (Goreau, 2022; Hilbertz, 1991).

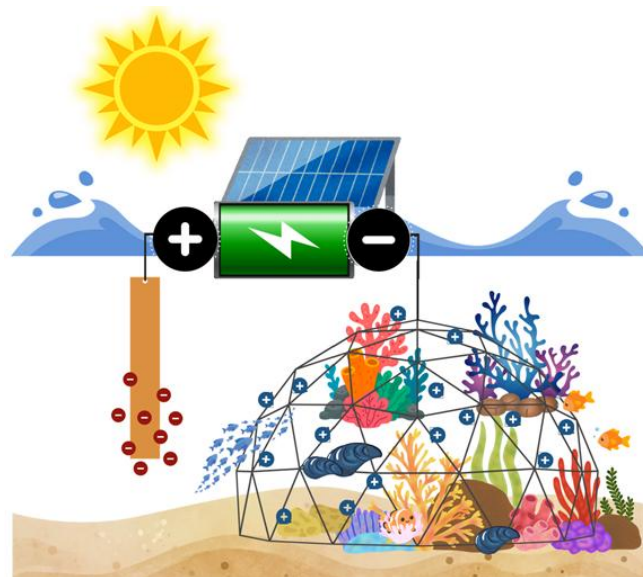


Figure 1. An example of a Biorock set-up with the brown positive anode, the metal structure as the negative cathode where the material grows and the marine organisms settle, powered by a floating solar panel as the energy source, created with Canva

Several physical quantities are used when describing and evaluating this technology. Electric current is the number of charges flowing through a material per unit of time (Gregersen, 2026a) and is measured in Ampere (A, amp) (Gregersen, n.d.). The current density is the current flow per unit area (A/m^2) (Britannica editors, n.d.-a). Electric potential is the work required to move a charge between two points in an electric field, where this work is equal to the difference in potential energy between these points, in other words potential difference or voltage (Gregersen, 2026b), which is measured in Volt (V) (Britannica editors, n.d.-b). The voltage drives the electric current (Gregersen, 2026b). A collective term for voltage, current and current density, used in the literature is electrical stimulation, which will be used in most cases in this thesis.

When an electrical stimulation is added to a natural system, such as seawater, through the electrolysis, the water composition is divided into negative and positive ions, with the negative ions accumulating at the positive anode and the positive ions at the negative cathode (Hilbertz & Goreau, 1996; Margheritini et al., 2020). This process is illustrated in Figure 2, where the negative ions include chloride ions (Cl^-) and the positive ions include calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions (Hilbertz, 1991). Because of these negative and positive ions, seawater can be electrolyzed and is called an electrolyte (Margheritini et al., 2020). This results in production of hydrogen gas (H_2) at the cathode while oxygen gas (O_2) and chlorine (Cl_2) are produced at the anode (Hilbertz, 1991; Margheritini et al., 2020). Besides these movements of ions due to the electrolysis, the accumulations at the anode or cathode depend on concentration gradients at these locations (Hilbertz & Goreau, 1996).

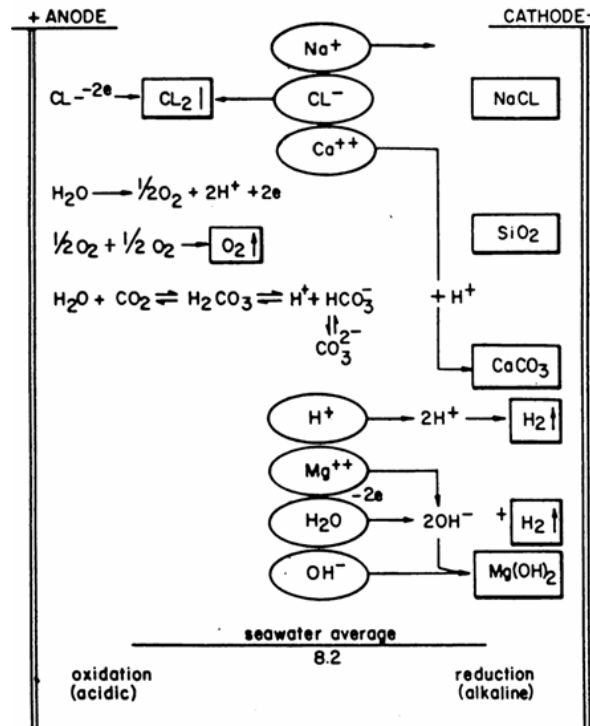
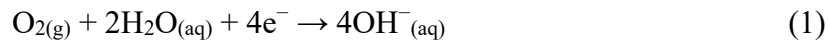
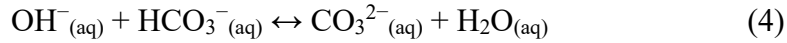
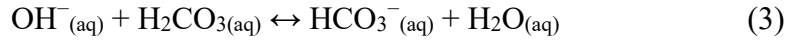


Figure 2. Chemical reactions at the anode and cathode in the Biorock process, reproduced from Hilbert (1991), Copyright 1979, IEEE

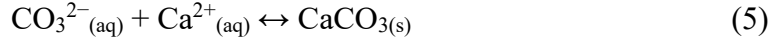
Another result of this technology due to the electrolysis is that hydrogen ions (H^+) are released at the anode and hydroxide ions (OH^-) at the cathode, which means decreased pH at the anode and increased pH at the cathode (Margheritini et al., 2020). The hydroxide ions from the cathode are due to reduction reactions, more specifically oxygen reduction (Eq. 1) or water reduction (Eq. 2) (Carré et al., 2020). Oxygen could preexist in the electrolyte or diffuse from the anode.



The concentration of hydroxide ions affects the carbonate system, where hydroxide ions turn carbonic acid (H_2CO_3) into bicarbonate ions (HCO_3^-) (Eq. 3) (Carré et al., 2020). Higher concentrations of hydroxide ions, and higher pH, favor the carbonate form (CO_3^{2-}) (Eq. 4) while lower concentrations of hydroxide ions, and lower pH, favor the bicarbonate form (Margheritini et al., 2020). In the opposite way, the hydrogen ions from the anode can shift the carbonate system towards carbonic acid and then carbon dioxide, as seen in Figure 2 (Hilbertz, 1991).



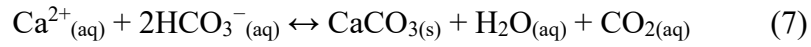
Combined with calcium ions, calcium carbonate (CaCO_3) is produced from the carbonate ions (Margheritini et al., 2020) according to Equation 5 (Carré et al., 2020).



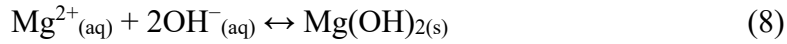
When combining Equations 4 and 5, the reaction equation for precipitation of calcium carbonate is as follows in Equation 6 (Margheritini et al., 2020).



Precipitation of calcium carbonate without electrolysis instead follows Equation 7, which is what normally occurs during the calcification of corals, mussels, calcareous algae and other calcareous marine organisms (Goreau, 2012).



Another consequence of these hydroxide ions is that they react with the earlier-mentioned positive magnesium ions to form magnesium hydroxide (Hilbertz, 1991), according to the reaction equation (Eq. 8) below (Carré et al., 2020). This co-precipitation of calcium carbonate and magnesium hydroxide occurs at certain environmental conditions, like increased pH (Colaleo et al., 2022).



Consequently, the electrical stimulation results in a limestone-based material growing on its surface (GCRA, n.d.), which usually consists of magnesium hydroxide ($\text{Mg}(\text{OH})_2$) and calcium carbonate (CaCO_3) (Hilbertz, 1979). The production of this material mimics nature through the way coral reefs and similar calcareous organisms create their skeleton structures (Hilbertz, 1979), which is why Biorock is described as a so-called biomimicry-technology (Nordic Biomimicry, n.d.).

3.2 History

Biorock was invented in 1976 by the architect Wolf Hilbertz with the main purpose of growing natural building materials in seawater with a low electric current (GCRA, n.d.). The relationship between electric current and precipitation of materials was discovered by Michael Faraday (Science History Institute, n.d.), but at that time these materials were not considered useful (Hilbertz, 1979).

In the beginning, Hilbert primarily used the other earlier-mentioned names for Biorock, but when a collaboration started between him and biogeochemist Tom Goreau in 1987 with the aim of using the technology for the restoration of marine ecosystems, they renamed it Biorock (GCRA, n.d.). Another term used by Goreau is electrotherapy (Goreau, 2022). Since its invention, 500-1000 Biorock structures have been built in 40-45 countries, mainly in Indonesia (GCRA, n.d.; Goreau, 2022). One of the Biorock structures in Bali is shown in Figure 3 (Goreau, 2022). This technology has been under patent protection four times between 1981 and 1996 (Justia Patents, 1995) and registered trademark between 2000 and 2010 (Justia Trademarks, n.d.).



Figure 3. Biorock structure from Bali, reproduced from Goreau (2022), CC BY 4.0

From the literature study, two main applications for Biorock were identified; creation of favorable habitats for marine ecosystems and production of material for different kinds of applications. These two will be presented in chapters 4 and 5, based on the literature study as well as personal communications.

4. Marine Ecosystems

One of the two main applications for Biorock that were identified from the literature study was the creation of favorable habitats for marine ecosystems. In the following chapter, the current status of the Swedish marine ecosystems is briefly presented as a background, together with Swedish and international cooperations aiming to protect and support these marine ecosystems. Subsequently, the role of Biorock for marine ecosystems is analyzed in order to understand its effects on these ecosystems.

4.1 Background

When it comes to marine ecosystems in Sweden, there are numerous goals, directives, reports and projects focusing on their well-being, both Swedish and international. Since oceans are transboundary, cooperations with other countries are important tools. Among them are the Helsinki Convention (Convention on the Protection of the Marine Environment of the Baltic Sea Area, HELCOM) and the Oslo-Paris Convention (Convention for the Protection of the Marine Environment of the North-East Atlantic, OSPAR) (Sveriges Miljömål, n.d.). There are also EU directives for example the Marine Strategy Framework Directive (MSFD) and the Water Framework Directive (WFD) (Sveriges Miljömål, n.d.).

Moreover, marine environments are included in the 14th UN Sustainable Development Goal called “Conserve and sustainably use the oceans, seas and marine resources for sustainable development” (United Nations, n.d.). Research and long-term tracking are among the actions used to handle ocean acidification and to increase marine ecosystem resilience (United Nations, n.d.). Ocean acidification is especially relevant since 2025 marked the first year that this planetary boundary was exceeded (Planetary Boundaries Science, 2025).

Regarding Sweden, one of the 16 environmental goals is “A Balanced Marine Environment and Thriving Coasts and Archipelagos”, consisting of several specifications to clarify the goal (Sveriges Miljömål, n.d.). Among the threats against this goal are eutrophication, maritime traffic, infrastructure and littering, which call for further action since, to date, this goal has not been achieved (Naturvårdsverket, 2026c; Sveriges Miljömål, n.d.). Eutrophication is more urgent in the Baltic Sea than in the North Sea, while the opposite is true regarding littering (Havs- och Vattenmyndigheten [HaV], 2024a). Especially shallow areas are threatened by maritime construction (Naturvårdsverket, 2026c). Moreover, OSPAR reported that emissions of the most environmentally harmful substances have decreased but that the current urgent environmental threats are climate change and increasing acidification (HaV, 2024b).

Furthermore, according to the Swedish Environmental Protection Agency’s yearly evaluation of the Swedish environmental goal described above (Naturvårdsverket, 2026c), Good Environmental Status (GES) is in most of the cases not achieved in Sweden. GES is included in the goals of the EU MSFD (HELCOM, 2023). The results about GES are consistent with the latest report from HELCOM, which states that most of the Baltic Sea does not reach GES (HELCOM, 2023). GES applies both to human pressures on the oceans and to the species and ecosystems (HaV, 2025a). One of the actions for GES is the ongoing project for ecosystem-based marine management, focusing on interactions between humans and the ecosystem as well as within the ecosystems, enabling connections among several sectors in society (HaV, 2022).

The responsible government agency for this Swedish environmental goal about coasts and other marine environments is the Swedish Agency for Marine and Water Management (Havs- och vattenmyndigheten, HaV) (Sveriges Miljömål, n.d.). Together with four other agencies,

HaV made a proposal for the Swedish Government in the beginning of 2026 concerning restoration of marine environments, among others, according to the EU Nature Restoration Regulation and the Swedish Programme of Measures for the Marine Environment based on MSFD (HaV, 2026a). The EU Nature Restoration Regulation is part of the European Commission's EU Biodiversity Strategy for 2030 and is therefore binding on the Member States (Naturvårdsverket, 2026b). The requirements for mapping and monitoring the ecosystems have been further specified in this regulation (Naturvårdsverket, 2026a).

The proposal from HaV and the four other agencies addresses seven types of habitats in Sweden, including calcareous algae, seagrass, sponges, corals and soft sediments (Naturvårdsverket, 2026a). Swedish goals and actions concerning these organisms' habitats that do not achieve GES have been developed and must be executed by 2030 for at least 30 percent of these habitats. There are also goals for 2040 and 2050. Some of the distribution estimates of these habitats are, however, described as uncertain, and especially the distributions of calcareous algae, corals and sponges are relatively limited. The proposal also focuses on enhancement of efforts to restore several threatened marine habitats, like eelgrass, blue mussels and oysters, for example by biotope protection intended specifically for smaller or extra significant species or habitats.

Concerning the status of the species in these marine ecosystems, the trend is concerning according to the Sweden's Red List of Threatened Species which was published in March 2026, where for example the blue mussel is now included (Sveriges Lantbruksuniversitet, 2026). The number of Red-listed marine species is increasing and several species that used to live on the coasts can now only be found further out in the sea (Naturvårdsverket, 2026c). Sweden is also part of the Convention on Biological Diversity (CBD) which aims at preserving biodiversity and addresses different sectors of society (Naturvårdsverket, 2025).

Consequently, the attention on the well-being of marine ecosystems is extensive and emphasizes numerous reasons to examine all possible solutions, so the question is what role Biorock could have in this matter.

4.2 The Role of Biorock

The general response in literature where Biorock is examined is positive, but there are some concerns regarding its effects on the marine ecosystems as well as indications that Biorock itself might not be the determining factor for the positive results. However, both the growing material and the electrical stimulation seem to contribute to its favorable environment.

4.2.1 Effects of the Growing Material

4.2.1.1 *The Material as a Habitat*

The mineral structure growing from the electrolysis appears promising regarding habitat for marine organisms, like its suitability as settlement (Bellezze et al., 2025; Hilbertz, 1979; Knoester et al., 2024; Moffitt & Penney, 2024), and therefore has the potential to contribute to increased biodiversity (Bellezze et al., 2025). Biorock is an example of design methodology, connecting a variety of species in a living system (Weber, 2024). A high biodiversity of marine organisms has shown increased growth rates on Biorock structures, including oysters, mussels, calcareous algae and hard and soft corals (Goreau, 2022). Moreover, these structures attract algae, fish and sponges (Weber, 2024). Depending on the shape and porosity of the growing material, it is more or less suitable to different marine organisms, meaning that the Biorock structure, to some extent, could be designed to monitor the biodiversity, for example to avoid algae bloom (Goreau, 2022).

There are some given reasons for the benefits of the Biorock material. One is that the precipitation of material provides the calcareous marine organisms with building blocks (Hilbertz & Goreau, 1996). Another is that the material was found to resemble natural calcareous structures (Bellezze et al., 2025; Margheritini et al., 2021), like corals and shells, regarding chemical and mineralogical composition, density, porosity and strength but also that its porosity benefits the settlement of some larvae (Margheritini et al., 2021). Because of the natural characteristics of Biorock, Margheritini et al. (2021) mean that this kind of structure is in alignment with the 2009 London Convention and Protocol/UNEP (United Nations Environment Programme). Some of its required aspects are environmentally friendly, natural and durable materials as well as shapes that attract marine organisms (UNEP, 2009), which also apply to Biorock (Margheritini et al., 2021).

4.2.1.2 Implementation and Experiments

The ecological suitability of this material can be observed for decommissioned off-shore oil and gas platforms. Several alternatives for these platforms are presented in Figure 4 (Bellezze et al., 2025). These platforms have, in most cases, been protected from corrosion with sacrificial anodes or applied electric currents, which eventually results in a deposition of material remaining on the structures for some time beyond their active time (Colaleo et al., 2022). Therefore, Colaleo et al. (2022) present that decommissioned platforms have proven to provide a material that is an important habitat for marine ecosystems, especially some endangered species. This study was part of the EU-funded project PLaCE (Platform Conversion for Eco-sustainable uses) in which the extension of the life of these platforms was investigated through material precipitation from electrolysis for the purpose of for example supporting marine ecosystems (Aalborg universitet, n.d.). It was shown that if actions to preserve the material, like this electrodeposition, are not taken, the material will eventually degrade and this sustainable reuse of the platforms will be almost impossible (Colaleo et al., 2022). If this support for marine ecosystems is combined with using these decommissioned platforms for renewable off-shore generation and ecotourism, the platforms can have multiple sustainable purposes, illustrated in Figure 4G (Bellezze et al., 2025).

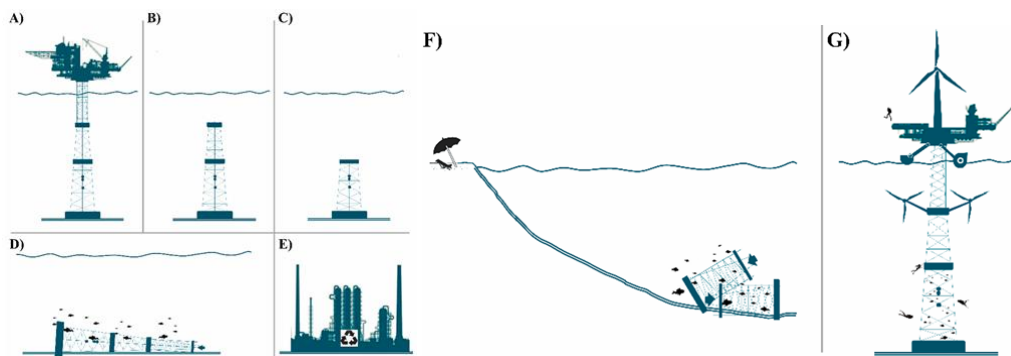


Figure 4. Alternatives for decommissioned platforms, where D, F and G include different types of reefs, reproduced from Bellezze et al. (2025), CC BY 4.0

In most cases, Biorock is implemented in marine environments, but it has been proposed for applications in terrestrial environments as well. Penney (2023) describes how Biorock could act as an ecological scaffold for alvar landscapes and thereby decrease some of its natural and anthropogenic abrasion, like limestone quarrying, since both alvars and Biorock are made up of a limestone-based material. When the Biorock material grows, some of it flakes off during rain and is carried with the wind to alvar landscapes nearby and thereby supports the existing alvar landscapes (Moffitt & Penney, 2024).

Moreover, a Biorock project, named Kiki and seen in Figure 5, was conducted in Corsica in 2023 using a solar panel on land as energy source (Weber, 2024). Kiki was destroyed in a storm after 6 months (Weber, 2024). According to Weber (2024) corals or other marine organisms were not transplanted onto the Biorock structure, called fragmentation, but, instead, nature was left to inhabit the structure in its own way, starting with pioneer organisms. In the studied literature, fragmentation is often used in laboratories but if the study is conducted in the sea, both fragmentation and the natural way are used.



Figure 5. The Biorock project Kiki in Corsica, reproduced from Weber (2024), CC BY 4.0

One reoccurring aspect in the literature is the use of controls to evaluate the effects of Biorock. The controls are untreated organisms of the same kind as the treated ones, with the purpose of comparing the untreated organisms with the treated, which in this case are the organisms treated with the Biorock-technology. Since the controls are not transplanted in some of the cases, it might seem from the comparison with the treated organisms that the controls managed better because fragmentation could cause stress, despite being a useful method (Sabater & Yap, 2002). On the other hand, sedimentation, predation (Knoester et al., 2024; Strömberg et al., 2010), less hydrodynamical circulation (Strömberg et al., 2010) and less access to light can cause negative results for the controls if they are not transplanted, meaning that they are left without an elevated structure to settle on (Knoester et al., 2024). If, however, the control organisms are transplanted, but on structures without electrical stimulation compared to the treated organisms, and the results are better for the treated ones, the explanation could be that the controls might have been disadvantaged by corrosion, because of the absence of electrical stimulation (Knoester et al., 2024). Apart from stress, insufficient nutrition in the studies performed in a laboratory could be a reason for limited growth rates (Strömberg et al., 2010). However, uncertainties about the effects of Biorock could also be due to a variety of species, locations, structures, or conditions, making the method strongly dependent on several factors (Knoester et al., 2024).

4.2.1.3 Bioremediation and Increased Resilience

Moreover, Biorock seems to be able to absorb some substances. As the material is growing, there are traces in the material indicating that some substances are being sequestered into the material (Colaleo et al., 2022; Devi et al., 2025; Goreau, 2012; Moffitt & Penney, 2024; Penney, 2023). These include pollutants, like heavy metals (Carré et al., 2020; Colaleo et al., 2022; Moffitt & Penney, 2024; Penney, 2023) and suspended sediment material, which could change the color of the material (Goreau, 2012). Some examples are phosphorus (Colaleo et al., 2022), copper and aluminum (Colaleo et al., 2022; Penney, 2023). Consequently, Moffitt

and Penney (2024) suggest that Biorock has the potential to reduce some environmental toxins. An additional proposed application for Biorock, concerning absorbed substances, is to add nutrients when growing the Biorock material. The purpose would be to feed mosses and other organisms that could be desired in some places, which simultaneously could act as a way of encapsulating nutrients from agricultural run-off water and thereby reducing eutrophication (Penney, 2023).

The ability of Biorock to absorb substances is used in a project being developed by the organization REefVOLUTION for bioremediation of the coasts of the Balearic Islands, for example Mallorca (Blanes Centre for Advanced Studies [CEAB], n.d). Biorock is considered to indirectly contribute to removing some remaining pollutants from wastewater, including pharmaceutical compounds (P. Ferriol Buñola, personal communication, March 31, 2026). The project aims at creating a suitable habitat for filter-feeding or suspension-feeding benthic organisms, like sponges, with the growing Biorock material, along with protecting and restoring marine ecosystems affected negatively by this wastewater (CEAB, n.d).

According to studies, Biorock can also enable growth in some extreme environments, like seagrass at a toxic waste site in New York or in muddy and nutrient-poor environments (Goreau, 2022). Furthermore, Goreau (2022) describes that oysters on a Biorock structure proved to be able to grow even during dormant periods without any mortality. Goreau (2022) also writes that Biorock made it possible for seagrass to grow on bare limestone rock in Italy despite the otherwise required layer of sand or mud (Goreau, 2022). Another reported advantage of Biorock is supporting seagrass, salt marsh grass and mangroves to establish roots instead of being washed away by waves as is otherwise often the case (Goreau, 2022).

4.2.2 Effects of the Electrical Stimulation

4.2.2.1 *The Presence of Electrical Stimulation*

In addition to the growing material, the electrical stimulation is thought to affect colonization of marine organisms. One reason is the ability that some organisms possess to detect electromagnetic fields, so-called magnetoreception, which guides them to the Biorock structure (Cárdenas-Rojas et al., 2025). On the other hand, studies made on sharks describe high avoidance of low current electric fields and a decrease in feeding at these places for bull sharks and Caribbean reef sharks (Uchoa et al., 2017). However, according to Goreau (2022), this characteristic of Biorock structures might not be negative since it could make these structures safe places for tourism. Nevertheless, Weber (2024) gives a reminder that these living systems, which Biorock is an example of, are primarily meant for the marine ecosystems, not for humans, emphasizing that our intentions with and choices about a Biorock structure must be based on what is natural.

Moreover, Schuhmacher and Schillak (1994) reported that no marine organisms were observed on the structure when the electrical stimulation was connected, from which they concluded that hard material from both electric and biogenic origins could not grow at the same time. In another of their experiments, a structure was submerged in the sea for 6 months without electrical stimulation, which resulted in a diversity of marine organisms settling on the structure, but when the electrical stimulation was added, most of the algae and the organisms without calcareous structures disappeared. In studies by Chavanich et al. (2013), Bellezze et al. (2025) and Benedetti et al. (2011), it was found as well that substrates disconnected from the electrical stimulation attracted more marine organisms than substrates connected. Even current densities below 0.01 A/m² reduced the settlement significantly (Benedetti et al., 2011).

Despite some uncertainties regarding the effects of the electrical stimulation, a study by Sabater and Yap (2004) showed that the overall survival was higher for corals exposed to an electric current than without. Moreover, SELV has proven to increase biodiversity, healing and growth, to name but a few (Goreau, 2022). Sabater and Yap (2004) also reported results about the importance of keeping the electrical stimulation on, since the absence of it increased the algae growth which competed with the existing marine organisms on the structure. Furthermore, Hilbertz's (1979) observation was that the fish populations showed no negative effects from the electrical stimulation. Goreau (2012) reports that the positive effects on the marine organisms disappeared when the electrical stimulation was disconnected but returned when it was turned back on but emphasizes that the full explanation of the effects of electrical stimulation requires more research. Despite the initial absence of marine organisms due to the first phase with electrical stimulation, Schuhmacher and Schillak (1994) found that the organisms that settled on the structure during the following phase without the electrical stimulation continued to grow when the electrical stimulation was turned on again. The given explanation was that, during the phase without electrical stimulation, these organisms had grown further than the material layer, which gave them a lead in the growing process (Schuhmacher & Schillak, 1994).

In other words, Schuhmacher and Schillak (1994) recommend alternating between the on- and off-times with electrical stimulation for the most suitable conditions for marine organisms. One proposal from Knoester et al. (2024) is to use electrical stimulation only in the first stage to grow a settlement layer, which would decrease costs and resources in the long-term. Regardless of the importance of this stimulation, combining it with an elevated position seems to be successful for the marine ecosystems (Hilbertz & Goreau, 1996; Strömberg et al., 2010).

4.2.2.2 The Level of the Current Density

Besides the presence of electrical stimulation, the level of the current density has proven to be a sensitive factor for Biorock, as seen in Table 2 where results from different studies are summarized. The study that is thought to be the first to apply Biorock in temperate deep-water habitats, at 8 degrees in Sweden, showed that the optimal current density, in this case for the cold-water coral *Lophelia pertusa*, was lower than in previous studies in tropical environments since the positive effects mostly applied to the lowest current density in the study (0.06 A/m^2) (Strömberg et al., 2010). Compared to higher current densities, the lowest current density also resulted in surprisingly high budding frequency in the corals and did not cause any mortality (Strömberg et al., 2010). This increased budding and branching indicate that Biorock promotes the growth of tissue more than calcification (Goreau, 2022). These improved effects from low current densities compared to higher ones are found in more studies. A stony colonial coral in the seawater temperature of 26-32 degrees showed higher survival at lower current density (0.01 A/m^2) for 40 days than at higher current density (0.1 A/m^2) and the control corals (Huang et al., 2020). In addition, juvenile corals in the seawater temperature of 28 degrees exhibited higher survival at the lowest current density (0.4 A/m^2) for 4 months than at higher current density (0.9 A/m^2) (Chavanich et al., 2013).

The results from Strömberg et al. (2010) indicate that the current densities in previous studies might have been too high, resulting in mortality or decreased growth instead of benefits and that the response of the marine ecosystems is dependent on the current density. One study showing that corals on a Biorock structure were more affected by coral bleaching during a heatwave than control corals on the same structure but without electrical stimulation, resulted in that the authors refrained from recommending this method for corals but also acknowledged that these results could be due to too high current density, in this case 0.8 A/m^2 .

(Knoester et al., 2024). A decrease in the current has, however, been observed to occur naturally as the material is growing (Huang et al., 2020, Goreau, 2012) because of the increased resistance of the system from the increased thickness of the growing material, resulting in colonization of algae, sponges and fish (Schuhmacher & Schillak, 1994). Overall, the impact of the current level on marine ecosystems needs to be more carefully examined before determining the effects of Biorock (Knoester et al., 2024).

The explanation for the negative effects at higher current density could be higher amounts of other minerals in the growing material as the current is increased, like magnesium hydroxide, together with the rising production of hydrogen and chlorine gas (Goreau, 2012). The reason is that these substances may be a disadvantage to some marine organisms (Goreau, 2012). Therefore, according to Goreau (2012), the severity of the effects from electric currents might depend on the species of the marine organisms or on products from the electrolysis. For example, the chlorine gas produced at the anode through the electrolysis can cause threats to marine organisms if Biorock is performed in closed systems like aquaria but is often not a problem in the sea since the gas is neutralized by reactions with other compounds in the seawater (Goreau, 2012). Nevertheless, to be sure, the anode should be placed above, beside or downstream of the cathode (Hilbertz & Goreau, 1996).

Concerning the calcification of stony corals, the rate increased for 30 days at low current density (0.01 A/m^2), but a longer exposure to this current density did not increase this rate any further (Huang et al., 2020). Moreover, higher current densities and the control corals experienced their highest calcification rates after 45 days but with very small differences compared to 30 and 60 days (Huang et al., 2020). The fact that the growth was mostly increased during the first time period is consistent with a study by Sabater and Yap (2004) where the most significant differences were seen between the first and second months of the treatment. This study also showed that the treated corals continued to have higher growth rates after the treatment but with relatively small margins compared to the untreated corals (Sabater & Yap, 2004). Another study showed, however, no significant effect of different current densities on the growth rates of juvenile corals (Chavanich et al., 2013).

Table 2. Overview of the current densities and temperatures used in the literature

Authors	Current density (A/m^2)	Temperature ($^{\circ}\text{C}$)	Comment on the current density
Benedetti et al. (2011)	0.01	15-20	Still too high, keep reducing settlement
Chavanich et al. (2013)	0.4-0.9	28	Higher survival at lower values
Huang et al. (2020)	0.01-0.1	26-32	Higher survival and calcification rate at lower values
Knoester et al. (2024)	0.8	25-29	Appeared to be too high
Strömberg et al. (2010)	0.06	8	Few positive effects above that value

4.2.2.3 Changes in Energy and Water Chemistry

A possible benefit from Biorock is also the described increase in ATP (adenosine triphosphate) production that occurs in marine organisms when exposed to microcurrents (Cheng et al., 1982). ATP is an energy carrier needed for active transport of ions. Therefore, electrolysis creates conditions that could increase the metabolic efficiency of the marine organisms (Hilbertz & Goreau, 1996). For environments with unsaturated calcification, ATP

becomes the limiting factor, suggesting that increased ATP levels through electrolysis could deceive calcareous organisms to branch and is suggested to be the main reason for the positive results on marine ecosystems (Strömberg et al., 2010). It has also been observed that Biorock, with its SELV, can increase the fluorescence of marine organisms and heal physical damage, which explains the term electrotherapy (Goreau, 2022). On the other hand, the effects on ATP production can become negative if the current density exceeds the optimal level (Cheng et al., 1982).

Regarding local changes in the water, the locally increased pH is thought to prevent filamentous and fleshy algae from settling on the structure which prevents competition for the corals (Sabater & Yap, 2004). On the other hand, studies indicate that the positive effects on marine ecosystems from the electrical stimulation used in Biorock might not be due to this locally increased pH, which was earlier thought to be the case, because the generated hydroxide ions from the electrolysis are consumed by the deposition of material at the cathode (Goreau, 2012). Another reason for this suggestion is that even organisms without calcareous skeletons showed increased growth rates on the Biorock structures and that organisms around these structures were positively affected, not merely the ones on the structure (Goreau, 2012).

Moreover, studies emphasize that reasons for the positive effects of Biorock include increased concentrations of mineral ions close to the cathode (Sabater & Yap, 2004), primarily calcium and carbonate ions, along with the facilitated cation uptake (Hilbertz & Goreau, 1996; Sabater & Yap, 2004) and transport due to the electron availability from the electrolysis (Hilbertz & Goreau, 1996). It is proposed that this enrichment in ions increases the asexual reproduction of corals since the energy usually needed for active ion uptake can instead be directed to reproduction when ions become more available through electrolysis (Sabater & Yap, 2004).

The altered water chemistry because of the electrolysis could also stimulate specific microbes, like nitrogen-fixing bacteria, which indicates that Biorock indirectly becomes an important nitrogen source for the marine ecosystems (Goreau, 2022). Moreover, it can support organismic carbon-fixing activities (Hilbertz, 1991). Additionally, the oxygen produced at the anode favors marine ecosystems and could locally prevent anoxia (Goreau, 2012).

These water chemistry changes at the cathode from the electrolysis, including carbonate and calcium concentrations and pH, were also predicted in a study using the two independent continuum simulation approaches COMSOL and CrunchFlow (Lees et al., 2024). The two approaches differ slightly in their method but resulted in very similar outcomes. In these approaches, diffusion, acid-base reactions and convection were accounted for together with several coefficients. Lees et al. (2024) therefore mean that electrolysis results in favorable water conditions for corals but that these results are most useful when combined with controlled experiments with living corals.

Despite earlier-mentioned positive effects from Biorock on marine ecosystems, some of these effects are regarded as in need of confirmation from more evidence, funding and research to be confirmed (Cárdenas-Rojas et al., 2025; Goreau, 2022; Knoester et al., 2024). Different sensors and devices are, however, available for studying and monitoring parameters in the water close to the Biorock structure, such as pH and oxygen levels, which can indicate the suitability for marine ecosystems (Cárdenas-Rojas et al., 2025).

5. Construction Materials

The other of the two identified main applications for Biorock connects to the material produced as a result of the technology. In the first section below, a background of materials similar to the Biorock material is briefly described, with regard to its application and composition. Mostly, this refers to cement, environmental impacts and marine infrastructure. This is followed by a section about this growing Biorock material.

5.1 Background

On a global scale, cement production is responsible for around 8 percent of anthropogenic carbon dioxide emissions (Kullman, 2023). Concerning Sweden, limestone quarrying by Heidelberg Materials in Slite in Gotland accounts for approximately 75 percent of the Swedish cement demand while being one of the largest sources of carbon dioxide in Sweden (Widegren, 2025). Besides the carbon dioxide emissions from cement production, mining involves a large impact on ecosystems. This environmental aspect resulted in a revoked permit for the Heidelberg Materials production, causing a cement crisis in Sweden around the year 2021, but since then they have received a 30-year permit (Widegren, 2025). However, at the end of spring 2026, the company received extra attention when high levels of lead from their facility in Slite were released into the environment (Edling, 2026).

There are, on the other hand, initiatives to reduce the carbon dioxide footprints from concrete, with varying success so far regarding costs, scaling and knowledge. Some examples are adding fly ash, ground granulated blast furnace slag (GGBFS), clay, less cement (Research Institutes of Sweden [RISE], n.d.-a), recycled concrete (RISE, n.d.-c) or other Supplementary Cementitious Materials (SCM) (RISE, n.d.-b) in the concrete mix or using Carbon Capture and Storage (CCS). The CCS project in Slite is one of them (Widegren, 2025) as well as the cooperation between Vattenfall and Cemvision with the purpose of producing close to zero-emission cement (Melander, 2025). Regarding means of reducing carbon dioxide emissions in general, CCS projects are increasing, such as Carbfix in Iceland and Northern Lights in Norway. In these types of projects, the energy requirement and costs for all steps need to be considered, including capture, transport and storage.

Regarding marine infrastructure, OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations prohibits leaving whole decommissioned oil or gas platforms, or parts of them, in the OSPAR maritime area (OSPAR, n.d.). This is relevant since many such platforms are assumed to be decommissioned in the near future (OSPAR, n.d.). Since Sweden is part of OSPAR, this is also the Swedish approach to decommissioned platforms. Even if Sweden in principle lacks such platforms, there are similar Swedish marine infrastructures related to for example energy, transport and fishery. Overall, the coexistence of these marine infrastructures with other interests, such as nature areas, is controlled in the Swedish maritime spatial plans (HaV, 2023). Furthermore, coastal infrastructure is especially exposed to environmental influences, including winds, waves and salt, which is cost- and maintenance-demanding (S. Schlyter, personal communication, May 12, 2026). More specifically, the so-called splash zone, closest to the water surface, is most exposed because of the combination of saltwater and oxygen, meaning high demands on material quality (M. Forsberg, personal communication, May 21, 2026). Adding structures on existing infrastructure could cause corrosion (S. Schlyter, personal communication, May 12, 2026), which means that it is more cost- and time-effective to include such structures from the beginning (M. Forsberg, personal communication, May 21, 2026; S. Schlyter, personal communication, May 12, 2026).

It is, in other words, many aspects to consider regarding cement-like materials and their applications. Therefore, what follows now is to examine the role of Biorock in this context.

5.2 The Role of Biorock

The use of electrolysis to grow materials in the seawater offers the opportunity of tailored minerals and aggregates for different kinds of construction purposes, both regarding shape and chemical composition as well as physical characteristics. Nevertheless, the growth and composition of the material, and consequently also its thickness, strength and other properties, depend on several factors.

5.2.1 Chemical and Mineralogical Composition

The ratio between calcium carbonate (CaCO_3) and magnesium hydroxide ($\text{Mg}(\text{OH})_2$) is controlled by many factors (Carré et al., 2020; Devi et al., 2025), presented in the section 5.2.2. Mostly, these materials grow in the mineralogical forms of the polymorphs calcite and aragonite when it comes to calcium carbonate (Carré et al., 2020; Devi et al., 2025; Johra et al., 2021), and brucite for magnesium hydroxide. However, vaterite, which is a more unstable polymorph of calcium carbonate, can also occur (Carré et al., 2020; Devi et al., 2025).

When chemically analyzing material growing from electrolysis of seawater, the transition of its composition regarding calcium carbonate and magnesium hydroxide appears to vary to some extent between different studies. Samples from material growing for approximately 1.5 years in brackish water, in other words relatively low salinity, in the Gulf of Mexico, showed that magnesium hydroxide decreased over time while calcium carbonate increased, which is presented in Table 3 (Hilbertz, 1991). The given explanation for this transition of the material is that the magnesium hydroxide gradually dissolves in the water, releasing hydroxide ions and thereby increasing the pH to a level where the balance of the carbonate system shifts into more carbonate ions (Eq. 4), facilitating the precipitation of calcium carbonate (Eq. 5) (Colaleo et al., 2022; Dang et al., 2017; Goreau, 2012; Hilbertz, 1991; Margheritini et al., 2020). However, in a similar study in the Mediterranean Sea for around 4 months, there was more magnesium than calcium after Time 1, which is shown in Figure 6 (Colaleo et al., 2022). Colaleo et al. (2022) suggest that this could be due to a possible overpotential since the ratio between calcium and magnesium decreases with increased current density (more about that in section 5.2.2.1).

Table 3. Transition in the growing material for almost 1.5 years, where magnesium hydroxide decreases and calcium carbonate increases, created based on Hilbertz (1991)

Date	$\text{Mg}(\text{OH})_2$ (%)	CaCO_3 (%)
April 23	70.9	17.5
June 7	61.7	31.8
July 18	69.5	24.2
October 3	57.2	32.7
November 5	53.0	38.9
November 27	61.5	21.7
January 1	61.3	24.8
February 27	60.5	34.6
March 3	49.3	42.8
May 1	53.4	37.8
June 1	29.5	63.6
July 1	25.5	68.9
August 1	42.1	50.3
September 1	29.9	62.0
September 20	29,5	67.0

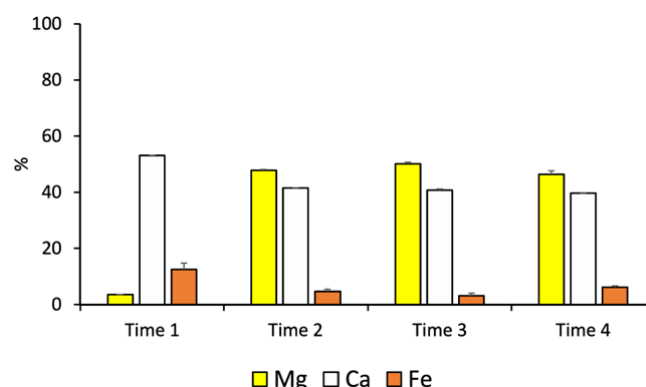


Figure 6. Transition in the growing material for around 4 months, where magnesium increases rapidly initially, while calcium and iron decrease slowly, reproduced from Colaleo et al. (2022), CC BY-NC-ND 4.0

When instead analyzing the mineralogical composition of the growing material, regarding brucite, aragonite and in some cases calcite, there are some differences as well. Table 4 shows the transition, for almost 1.5 years, from brucite to aragonite via some amount of calcite, regarding the predominant constituent, indicating that the material becomes more crystalline (Hilbertz, 1991). Similarly, a study in Denmark resulted in an increase in aragonite and decrease in brucite, in this case from 14 days to 3 months, according to Table 5 (Margheritini et al., 2020). Moreover, in a study in the Mediterranean Sea for 5 months, aragonite increased compared to brucite, except for at Time 2, according to Figure 7 (left) (Bellezze et al., 2025). However, the results from another Mediterranean study, for around 4 months, presented in Figure 7 (right), showed more brucite than aragonite after Time 1 (Colaleo et al., 2022).

Table 4. Transition of the growing material for almost 1.5 years, where brucite is gradually replaced by aragonite as the predominant constituent, created based on Hilbertz (1991)

Date	Predominant constituent	Secondary constituent
April 23	Brucite	Aragonite/calcite
June 7	Brucite	Aragonite
July 18	Brucite	Aragonite
October 3	Brucite	Aragonite
November 5	Brucite	Aragonite
November 27	Brucite	Aragonite
January 1	Brucite	Aragonite
February 27	Brucite	Calcite/Aragonite
March 3	Brucite	Aragonite/Calcite
May 1	Brucite	Aragonite
June 1	Aragonite/Brucite	-
July 1	Aragonite/Brucite	-
August 1	Brucite	Aragonite
September 1	Brucite/Calcite	Aragonite
September 20	Aragonite	Calcite

Table 5. Transition of the growing material for 3 months, where aragonite increases and brucite decreases, reproduced from Margheritini et al. (2020), CC BY 4.0

Composition after 2 Weeks	Composition after 3 Months
Aragonite: 65.9 Brucite: 33.2%	Aragonite: 75.8% Brucite: 23.3%
Calcite: 0.8%	Calcite: 0.8%

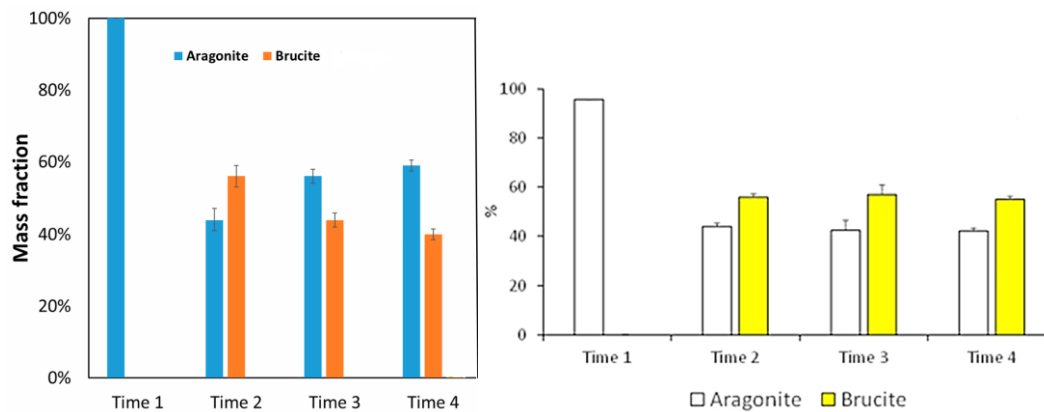


Figure 7. Transition of the growing material (Left) for around 5 months, where aragonite decreases between Time 1 and 2 but then increases, reproduced from Bellezze et al. (2025), CC BY 4.0. and (Right) for around 4 months, where aragonite decreases compared to brucite, reproduced from Colaleo et al. (2022), CC BY-NC-ND 4.0

Furthermore about the transition of the aragonite composition, the study in Denmark also tested several combinations of different temperatures, seawaters and currents for 14 days which showed that the ratio of aragonite is lower when the total weight of the growing material is higher, as seen in Figure 8 where every green dot is one of these combinations (Margheritini et al., 2020). This relationship between the percentage of aragonite and the total weight is proposed to be inverse (Margheritini et al., 2020; Sharker et al., 2023).

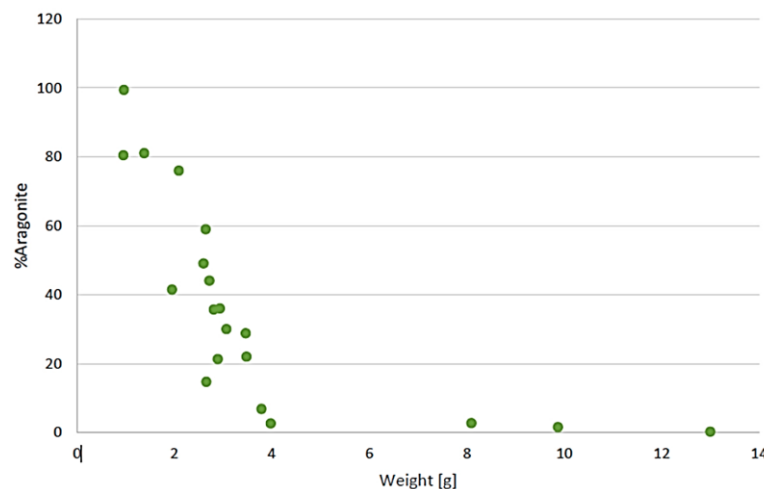


Figure 8. Relationship between the ratio of aragonite and the total weight of the material for 14 days, reproduced from Margheritini et al. (2020), CC BY 4.0

5.2.2 Influencing Factors

The composition, as well as the growth, of the material are controlled by temperature, concentrations of magnesium and calcium ions, pH, salinity, applied voltage, current density and injected carbon dioxide, to name but a few factors. Moreover, the composition and growth rate are connected since the composition depends on the growth rate and vice versa. In the following section, the controlling factors are presented, divided into applied electrical stimulation, electrolyte, structure and growth rate.

5.2.2.1 Applied Electrical Stimulation

The applied voltage is one of the factors affecting the growth and composition of the material (Devi et al., 2025; Penney, 2023). With low applied voltage, oxygen reduction (Eq. 1) will be the dominant reaction, termed oxygen reduction reaction (ORR) regime (Devi et al., 2025). This lower voltage results in a stronger and less porous material (Devi et al., 2025; Hilbertz, 1979; Johra et al., 2021; Schuhmacher & Schillak, 1994), meaning higher content of calcium carbonate like in the form of aragonite (Carré et al., 2020; Colaleo et al., 2022; Macias et al., 2024; Margheritini et al., 2020; Sharker et al., 2023). This is because of a controlled reaction process, even material growth (Devi et al., 2025; Hilbertz, 1979) and increased pH from the hydroxide ions due to the reduction reaction (Johra et al., 2021). In addition, at this low voltage, the chlorine gas production at the anode can be reduced (Goreau, 2012).

If, however, the voltage increases so that the pH reaches values above the suitable level for calcium carbonate, the magnesium hydroxide precipitation increases in the form of brucite (Carré et al., 2020; Colaleo et al., 2022; Johra et al., 2021; Macias et al., 2024). pH above 9 is often more suitable for precipitation of brucite (Hilbertz, 1979), more specifically around 9.5 (Benedetti et al., 2011). This higher voltage therefore results in a more porous (Devi et al., 2025; Hilbertz, 1979; Johra et al., 2021) and gelatinous material (Carré et al., 2020), due to a more aggressive reaction process and uneven material growth (Devi et al., 2025; Hilbertz, 1979). In this case, the dominant reaction will be water reduction (Eq. 2), termed water reduction reaction (WRR) regime (Devi et al., 2025), meaning that hydrogen gas is produced (Carré et al., 2020; Devi et al., 2025).

In other words, ORR is limited by oxygen mass transfer, without which the occurring reactions shift more from ORR to WRR (Carré et al., 2020; Macias et al., 2024). For low voltages, oxygen reduction is the reaction producing the hydroxide ions, meaning higher pH, needed for the precipitation of material, but when the oxygen mass transfer is prevented by the grown material, water reduction occurs to produce hydroxide ions instead, since this reaction is not limited by oxygen mass transfer (Devi et al., 2024; Carré et al., 2020). This results in a higher ratio of magnesium hydroxide in the material (Carré et al., 2020). Therefore, the formation of hydroxide ions is limited by mass transport in the ORR while the reaction rate is the limitation in the WRR (Devi et al., 2024; Macias et al., 2024). However, at high voltage, the produced hydrogen gas can cause the grown material to detach from the structure (Devi et al., 2024). The mineral compositions of materials grown with low respective high voltage are presented in Table 6 (Johra et al., 2021).

Table 6. Mineral composition for low- respective high-voltage material, reproduced from Johra et al. (2021), used with permission from Elsevier

Mineral	Low-voltage Seacrete mass content [mass%]	High-voltage Seacrete mass content [mass%]
Aragonite	80.8	46.6
Brucite	18.9	52.3
Calcite	0.3	1.1

This voltage pattern was also observed on a wire mesh where the material closest to the connection points to the energy source was weaker and less crystalline, but faster growing, than the material farthest from these points (Hilbertz, 1979). Therefore, Hilbertz (1979) concludes that the amount of material, as one of the consequences of the voltage, affects the material composition. This corresponds to the observation that the distance between the cathode, where the material grows, and the anode affects the growth rate (Penney, 2023).

Another aspect of the voltage is what Hilbertz (1979) calls phasing, which, in this case, means that the electrical stimulation is removed when a layer of material has deposited on the structures. His preliminary conclusion was that phasing results in a more crystalline structure of the material, in other words not regarding the composition but only the structure (Hilbertz, 1979). In one of Hilbertz's (1979) phasing experiments, the grown material, consisting mainly of brucite, was disconnected from the electrical stimulation and placed in the sea. The material became harder during the times without the electrical stimulation (Hilbertz, 1979; Schuhmacher & Schillak, 1994) and the non-crystalline material, like organic matter, increased during this phase (See Table 7) (Hilbertz, 1979). This is because of the uncontrolled growth process as well as the compaction and structural reorganization of the material due to the absence of the electrical stimulation (Hilbertz, 1979). According to Hilbertz (1979), the brucite developed a foliate structure from the phasing which has crystalline characteristics. In a study by Bellezze et al. (2025), aragonite decreased compared to brucite when the electrical stimulation was removed, resulting in a more equal composition of aragonite and brucite, according to Figure 9. Regardless of the material composition, Bellezze et al. (2025) also found that the material thickness almost remained when the electrical stimulation was removed, as seen in Figure 10.

Table 7. Material samples from four times during the phasing experiment. In the three last samples the electrical stimulation was disconnected, created based on Hilbertz (1979)

Description	Brucite (%)	Aragonite (%)	Non-crystalline (%)	Other (%)
Before phasing	79	15	0	6
After 7 days of phasing	64	25	0	11
After 10 days of phasing	50	25	24	1
After 19 days of phasing	40	17	38	5

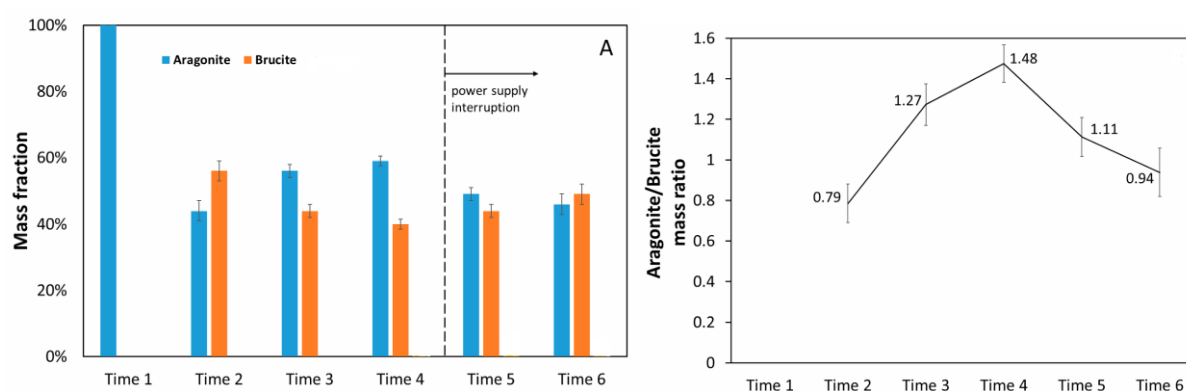


Figure 9. Transition of the composition of the material before and after the electrical stimulation was removed (after Time 4) regarding (Left) the fraction between aragonite and brucite and (Right) the aragonite/brucite mass ratio, reproduced by Bellezze et al. (2025), CC BY 4.0

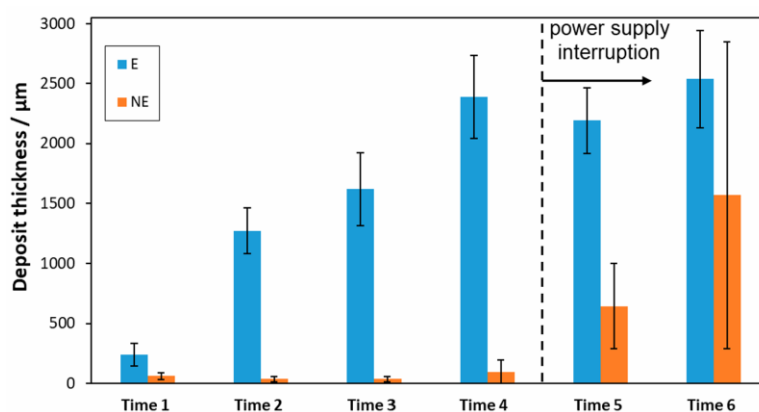


Figure 10. Thickness of the material before and after the electrical stimulation was removed for structures with electrical stimulation (blue) and without (orange), reproduced from Bellezze et al. (2025), CC BY 4.0

While the voltage level decides if the dominant reaction is ORR or WRR, and therefore also if precipitation of magnesium hydroxide or calcium carbonate is favored, the rate of these reactions, and thereby also the precipitations, is controlled by the current density (Devi et al., 2025). However, an analysis by Colaleo et al. (2022) showed that current density to some extent affects the chemical composition of the material, as well. Moreover, at least 0.55 A/m^2 was required to initiate precipitation of material and to protect the structure against corrosion in a study by Sharker et al. (2023).

Pulsed currents or voltages are discussed in the literature and also proposed as an alternative by Hilbertz and Goreau (1996). To pulse the current is reported to prevent water reduction and therefore benefit aragonite precipitation (Carré et al., 2020). The reason is that during the off-phase of the on-off pulse pattern, the produced hydroxide ions have time to move away from the structure, preventing the pH from reaching the required level for brucite precipitation (Robinson et al., 2024). Moreover, Robinson et al. (2024) write that the off-phase enables ions to accumulate at the structure, which facilitates the reaction rates during the on-phase. This means that pulsed voltages, in the case of Robinson et al. (2024), can contribute to controlling the local pH and availability of ions for precipitations of a calcium carbonate-rich material. High frequencies result in a more protective material (Carré et al., 2020) as well as a larger mass, while low frequencies give a higher calcium content (Robinson et al., 2024). However, besides frequency, Robinson et al. (2024) include duty cycle as a factor, which is the fraction of time for the on-phase, resulting in more calcium in the material at low duty cycles.

The influence of the current densities and applied voltage on the material characteristics and growth is also reflected in growth-promoting features of the resulting porosity of the material. When the material becomes porous, hydrogen gas production is able to continue since the porosity provides access to active sites on the structure where the water reduction can occur and thereby more material can grow (Devi et al., 2025). More specifically, the pores become channels for the electron flow, enabling the growth to continue even when the growing material covers the cathode surface (Goreau, 2012). Moreover, the porosity supports movements of calcium and magnesium ions into the material which facilitate the growth (Devi et al., 2025). The continued bubbles from the hydrogen gas (See Figure 11) also act as confirmation that the reactions in the growth process work (Goreau, 2012).



Figure 11. Bubbles from the hydrogen gas emerging from the growing material (the white layer), reproduced from Marionpinta (2011), CC BY-SA 3.0

Even though higher current densities result in a higher growth rate, the mass of this material is less than if a lower current density is used, since the porosity of brucite is lower than that of aragonite (Goreau, 2012). Moreover, only one of the produced hydroxide ions from the electrolysis is used to precipitate calcium carbonate while two are needed for magnesium hydroxide (Goreau, 2012), as presented in Equations 6 and 8.

5.2.2.2 *Electrolyte*

Together with current density, an analysis by Colaleo et al. (2022) showed that environmental variables account for 70 percent of the chemical composition of the growing material. One of these environmental variables is the electrolyte, which includes for instance its temperature (Colaleo et al., 2022; Margheritini et al., 2020; Sharker et al., 2023). This is for example reflected in the relationship between temperature and solubility of the different versions of the material. Regarding brucite, the solubility increases with temperature, but for calcium carbonate minerals, like aragonite, a faster growth rate and a harder material is often produced in warmer waters than colder (Colaleo et al., 2022; Goreau, 2012). The sample in Figure 12, grown in the Maldives for around one year, is one example of the relationship between temperature and growth (Goreau, 2012). In the Mediterranean Sea, a study gave an almost linear relationship between the growth rate and the water temperature, as seen in Figure 13, where the growth rate increases with temperature (Colaleo et al., 2022). Sharker et al. (2023) also showed that higher temperatures increased the total material but decreased the ratio of aragonite, although low current densities could increase the aragonite to some extent despite the higher temperature.



Figure 12. Biorock grown in the Maldives on a steel bar with 6 mm in diameter for around one year, reproduced from Goreau (2012), CC BY 3.0

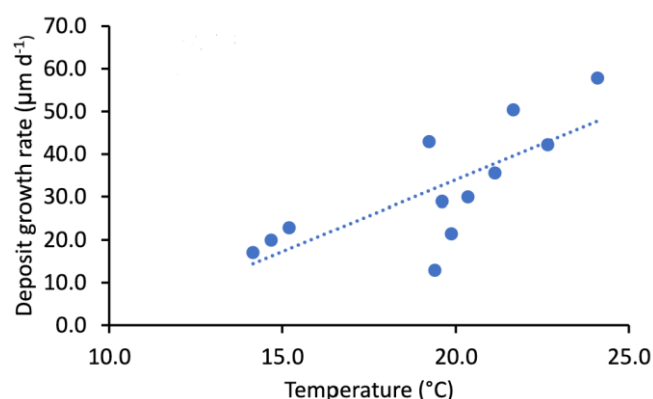


Figure 13. An almost linear relationship between the growth rate of the material and temperature, reproduced from Colaleo et al. (2022), CC BY-NC-ND 4.0

Nevertheless, even if Biorock has mainly been tested in warm waters, it works in colder waters as well, although more slowly. This was the case in an experiment in waters at around 2 degrees in the north (Hilbertz, 1991). A study made in Sweden at 8 degrees in the water showed that the growth rate was, as expected, slower than in warmer waters, which the authors suggested was due to the earlier-mentioned solubility characteristics of the different versions of the material (Strömberg et al., 2010). Margheritini et al. (2020) compared the results in Table 5 from their study in Denmark to a sample grown in Thailand consisting of 78 percent aragonite and 22 percent brucite and therefore concluded that material with similar composition can be grown both in warmer and colder waters. Margheritini et al. (2020) also observed more aragonite at this lower water temperature than at higher temperatures, around 22 degrees. This promotion of aragonite is due to the fact that the reactions are less effective at lower temperatures, resulting in a lower concentration of hydroxide ions which means a more suitable pH for aragonite than brucite (Margheritini et al., 2020).

However, studies by Sharker et al. (2023) report that, although temperature is an important factor for the growth and composition of the material, conclusions must be made based also on the current density, which is illustrated with four combinations of different temperatures and current densities for 2 weeks in Figure 14. For example, Figure 14C shows no rust compared to Figure 14A, even if the temperature in Figure 14A is slightly higher, so the determining factor appears to be the current density in these two cases. Experiments with the same time duration also showed that material grown at 22 degrees at a current density of 2.65 A/m² resulted in 9.03 grams of material but when decreasing the current density to 0.55 A/m², the weight was reduced to 1.57 grams (Sharker et al., 2023), as included in Table 8. Furthermore, in an experiment at 7 degrees, a current of 0.25 A appeared to be too high for aragonite to precipitate and was therefore reduced to 0.22 A, under which no material could precipitate (Margheritini et al., 2020).

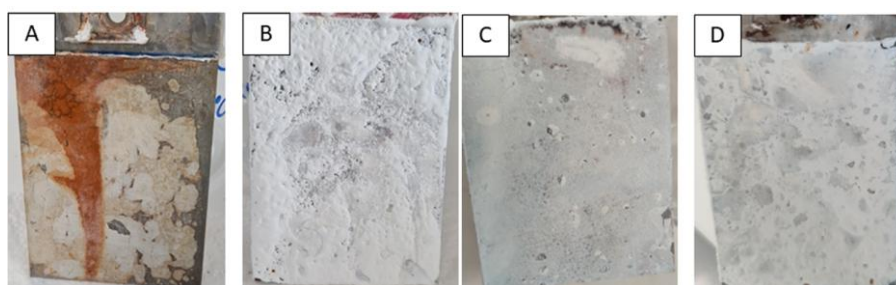


Figure 14. Cathodes after 14 days at (A) 7 degrees, 0.55 A/m², (B) 22 degrees, 3.1 A/m², (C) 4 degrees, 1.5 A/m² and (D) 25 degrees, 1.5 A/m², reproduced from Sharker et al. (2023), CC BY 4.0

The composition of the seawater is another affecting factor, including the suspended particles in the water (Margheritini et al., 2021). One example is that organic matter can interfere in the growth process but also strengthen the material by making it more compact (Carré et al., 2020). Also, the availability of ions has impacts, since high concentrations of calcium and magnesium ions showed increased growth rates of the material (Carré et al., 2020; Devi et al., 2025; Hilbertz, 1979). For example, the concentration of calcium ions is proportional to the growth rate of calcium carbonate but does not influence the ratio of calcium in the growing material, meaning that the transport of calcium ions is not a limiting factor for this composition (Carré et al., 2020). Magnesium ions, on the other hand, prevent calcite from precipitating (Carré et al., 2020) and instead promote precipitation of aragonite, indicating that magnesium ions are controlling the polymorph of calcium carbonate (Dang et al., 2017). In a study by Margheritini et al. (2020) in Denmark, material growth was tested in a standard solution of marine water by the American Society of Testing and Materials (ASTM) as well as in waters with local concentrations of magnesium and calcium ions, but the result showed insignificant differences in growth between these seawater compositions.

Other aspects of the composition of the seawater that control growth and composition of the material are salinity (Colaleo et al., 2022; Goreau, 2012; Margheritini et al., 2021; Penney, 2023), oxygen (Carré et al., 2020; Colaleo et al., 2022) and pH (Colaleo et al., 2022; Goreau, 2012). One example is that the material grew fast but became weaker, consisting of more brucite than aragonite, when hyper-saturated run-off saltwater was used as electrolyte (Penney, 2023). Concerning oxygen, its concentration near the structure controls whether the reduction reaction is water or oxygen (Carré et al., 2020; Colaleo et al., 2022)(see section 5.2.2.1 about oxygen mass transfer). This diffusion of oxygen increases with temperature, since the movement of molecules increases with temperature, while its dissolution decreases with temperature (Carré et al., 2020). When it comes to pH closest to the cathode, or the concentration of hydroxide ions (Carré et al., 2020), it affects the growth and composition of the material since increased pH influences the carbonate system, in favor of the precipitation of calcium carbonate up to a limited pH level (Colaleo et al., 2022). Furthermore, a small increase in pH above the suitable level for calcium carbonate results in a rapid precipitation of magnesium hydroxide in the form of brucite (Goreau, 2012).

Injected carbon dioxide close to the cathode is also an influencing factor in the electrolyte, since injection rate and volume have been shown to affect the characteristics of the growing material (Devi et al., 2025). Adding carbon dioxide together with increased applied voltage promotes the fraction of calcium carbonate in the material, according to Devi et al. (2025), even if solely increased voltage could result in a pH too high for precipitation of calcium carbonate. The reason given by Devi et al. (2025) is that injected carbon dioxide decreases the pH, which means that an optimal injection rate and volume, together with higher voltage, would result in a suitable pH for calcium carbonate precipitation even at higher voltages. Too much carbon dioxide could, however, influence the water chemistry in a way that, for example, decreases the pH below what is suitable for calcium carbonate (Devi et al., 2025).

Consequently, this composition of the seawater, regarding salinity, magnesium, calcium and hydroxide ions (pH), oxygen, carbon dioxide and organic matter, is highly controlled by marine current regimes by their mass transfer to and from the structure. Through these marine currents, both desired and undesired substances can be removed from or brought closer to the cathode (Carré et al., 2020). In other words, marine currents can act as both an advantage and a disadvantage for the material growth and its composition, and are therefore an important factor (Carré et al., 2020; Colaleo et al., 2022). However, as the material grows, its thickness could prevent the water flow to the structure and thereby eventually decrease the importance of the marine currents (Colaleo et al., 2022).

5.2.2.3 Structure

The structure is also impacting the material growth and composition. One aspect is the material of the cathode, which could affect within what range of the applied voltage that water or oxygen reduction dominates (Carré et al., 2020). In most of the studies (Bellezze et al., 2025; Colaleo et al., 2022; Goreau, 2012; Hilbertz, 1979; Robinson et al., 2024; Sharker et al., 2023; Strömberg et al., 2010), the material of the cathode was steel, more specifically mild steel or carbon steel. However, galvanized steel (steel with a zinc layer) (Hilbertz, 1979; Penney, 2023), stainless steel 316 (Benedetti et al., 2011; Devi et al., 2025; Macias et al., 2024) and iron (Knoester et al., 2024) were used as well to some extent. Concerning the applied voltage, a higher voltage is needed for brucite precipitation on stainless steel than on mild steel, which means that the voltage range for aragonite precipitation is larger for mild steel than stainless steel (Carré et al., 2020).

The material of the cathode also controls the reactions at its surface (Carré et al., 2020). One given example is oxides present on the surface, which can change the electrochemical conditions and prevent reactions from occurring. Moreover, the presence of biofilm on the cathode can inhibit mass transfer of ions and oxygen, thereby influencing the reactions and the growing material. However, this negative effect decreases with increased voltage (Carré et al., 2020).

Additionally, the material of the anode was shown in a study by Margheritini et al. (2020) to influence the material growth and composition. In this study, two materials were compared, which were a titanium plate covered with metal oxides, called dimensionally stable anode (DSA), and a titanium anode coated with platinum (Pt-Ti). The DSA resulted in both more brucite and more total material than Pt-Ti, which could be due to the fact that the activation voltage of DSA is higher than for Pt-Ti. Consequently, Pt-Ti resulted in a material with slightly more aragonite than the material on the DSA (Margheritini et al., 2020).

In addition to the substrate, the shape of the structure results in differences in the material. One study resulted in more gained weight from the growing material on fine grids than on wide grids, seen in Figure 15, more specifically 12.91-14.72 grams for the fine grids and 8.3-11.93 grams for the wide grids (Margheritini et al., 2020). In this way, a fine grid could make the material more continuous and therefore more suitable for some applications (K. Tammo, personal communication, April 13, 2026).



Figure 15. Grown material on fine (left) and wide (right) grids, reproduced from Margheritini et al. (2020), CC BY 4.0

5.2.2.4 Growth Rate

There are several studies examining a value for the growth rate. Overall, the growth rate is found to be around a few centimeters per year, depending on the voltage (Johra et al., 2021).

In one study, the material reached 2.39 ± 0.35 mm after 6 months with 2.5 V (Colaleo et al., 2022). Another study showed that material growing in a water temperature of 25-30 degrees with around 2.5 V had a growth rate of a maximum 2 cm/year while in a water temperature of 3-24 degrees with 400 000 V, the growth rate was around 3 cm/year (Margheritini et al., 2021). In a similar study, the growth rates were instead reported to be around 0.8 cm/year for the low-voltage (2.5 V) material and 5.5 cm/year for the high-voltage (400 000 V) material (Johra et al., 2021). Additionally, in a study in water temperatures of 15-21 degrees for 6 months at 2.5 V, the material grew 2.5 mm (Bellezze et al., 2025). These results are summarized together with other studies in Table 8.

Table 8. An overview of the relationship between temperature, electrical stimulation, duration and grown material in different experiments in the literature

Authors	Temperature (°C)	Electrical Stimulation	Duration	Grown Material
Bellezze et al. (2025)	Mediterranean sea, 15-21	2.5 V, 0.175-0.902 A/m ²	6 months	2.5 mm
Benedetti et al. (2011)	24	1.5 A/m ²	2 weeks	0,022 mm (see Figure 16)
Colaleo et al. (2022)	Mediterranean sea	2.5 V	6 months	2.39 ± 0.35 mm
Johra et al. (2021)	LV: 25-31 HV: 3-24	LV: 2.5 V HV: 400 000 V	1 year	LV: 8 mm HV: 55 mm
Margheritini et al. (2021)	LV: 25-31 HV: 3-24	Low voltage (LV): 2.5 V High voltage (HV): 400 000 V	1 year	LV: 20 mm HV: 30 mm
Margheritini et al. (2020)	Denmark, 2.4-20.0	2.5 V, 0.2-0.3 A	9 months	2-7 mm (0.121 kg)
Schuhmacher & Schillak (1994)	Mediterranean sea, 13-20	8-12 V, 3-5 A	7 weeks	12 mm
Sharker et al. (2023)	4-25 Ex. 1: 7 Ex. 2: 7 Ex. 3: 22 Ex. 4: 22	0.55 – 3.5 A/m ² Ex. 1: 0.55 A/m ² Ex. 2: 2.65 A/m ² Ex. 3: 0.55 A/m ² Ex. 4: 2.56 A/m ²	2 weeks	1.14-9.03 g Ex. 1: 1.14 g (0.011 g/cm ²) Ex. 2: 6.53 g (0.065 g/cm ²) Ex. 3: 1.57 g (0.016 g/cm ²) Ex. 4: 9.03 g (0.090 g/cm ²)
Strömberg et al. (2010)	8	LI: 2.0 V, 0.01 A, 0.06 A/m ² LII: 2.5 V, 0.12 A, 0.75-0.31 A/m ² LIII: 3.0 V, 0.35 A, 2.19-1.31 A/m ²	6 months	(closest to-furthest from the anode) LI: 1.53 ± 0.74 - 0.99 ± 0.60 mm LII: 5.07 ± 0.85 - 2.48 ± 0.62 mm LIII: Ca 10 mm (but too porous)

Moreover, the material growth rate appears not to be constant over time but instead increases in the beginning and then decreases, as presented in Figure 16, and is described as being inversely proportional to the thickness of the material (Benedetti et al., 2011). This non-linear growth rate was further confirmed in a later study but during a longer time, as seen in Figure 17, with a growth rate between 0.02 and 0.0503 mm/day (Colaleo et al., 2022). One example is that the growth rate of brucite is described as proportional to the square of the local pH (Goreau, 2012). The explanation for the non-linear growth rate is that, as long as the material is thin, oxygen can easily diffuse to the surface of the cathode and hydroxide ions are produced in the reduction reactions, but this diffusion is prevented when the material grows too thick (Benedetti et al., 2011). Based on Figure 17 (Colaleo et al., 2022), the current density is affected by the increased thickness as well, since the current density has a peak at Time 2 and then at Time 4 decreases to around the initial level due to the increased thickness of the material and influence from marine currents. Despite a lower growth rate, the growth will continue as long as the electrical stimulation is connected (T. Goreau, personal communication, April 17, 2026). Figure 17 also shows that the relationship between the growth rate and the current density is almost linear (Colaleo et al., 2022).

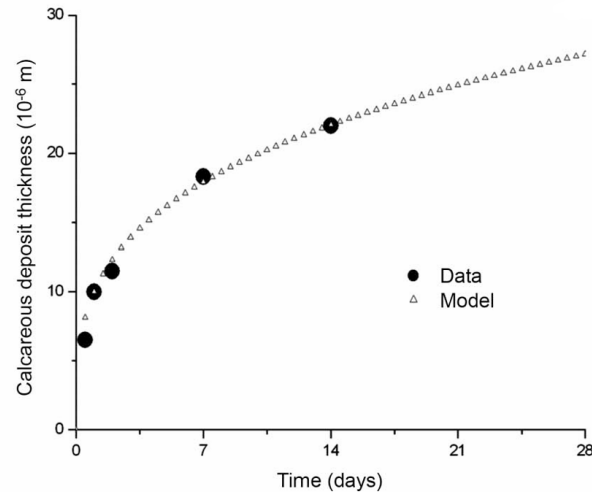


Figure 16. The growth rate of the material presented as the thickness in 10^{-6} m as a model function of the time in days, based on four data points, reproduced from Benedetti et al. (2011), Copyright 2011, reprinted by permission of Informa UK Limited, trading as Taylor & Francis Group

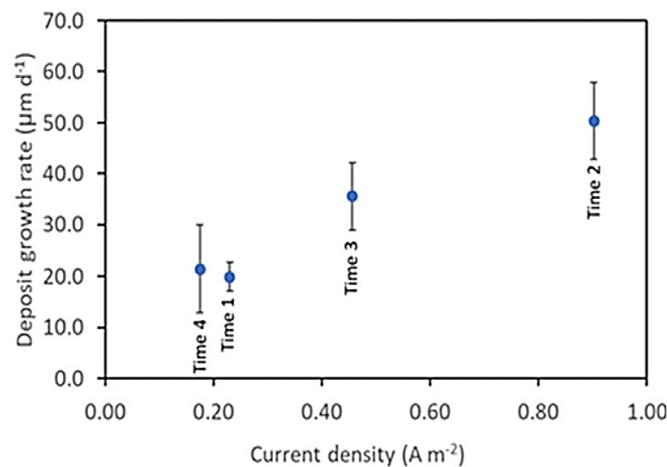


Figure 17. Growth rate as a function of the current density illustrating the decreasing rate after the peak at Time 2, reproduced from Colaleo et al. (2022), CC BY-NC-ND 4.0

5.2.3 Physical Properties

Among the physical properties evaluated for the grown material is strength. Regarding compressive strength, twenty samples grown from electrolysis showed an average value of 4267.5 psi, which is slightly higher than for concrete used for stairs, steps and sidewalks, (Hilbertz, 1979) and equal to 29.4 MPa. A similar test resulted in an average value of 311.5 kg/cm² (Hilbertz, 1991), which equals 30.4 MPa. In comparison, the compressive strength for material grown with high voltage (400 000 V) was 16.8 MPa compared to 24.2 MPa for concrete (Johra et al., 2021).

If approximately 80 percent of the magnesium hydroxide in the material is converted into hydrated forms of magnesium carbonate and undergoes further carbonation, the compressive strength is around 1.4-6 MPa (Devi et al., 2025). However, it has been found that the compressive strength for material grown with electrolysis can reach 80 MPa, which would be around three times the strength of concrete from Portland cement (Goreau, 2012).

In a penetration test, which evaluates another type of strength, the puncture resistances were 3.9 kN for material grown with low voltage (2.5 V), 1.4 kN for material grown with high voltage (4000 000 V) and 3.4 kN for standard concrete (Johra et al., 2021). Moreover, based on the Mohs scale, brucite has a hardness of 2.5-3, while the value for aragonite is 3.5-4, but crystals are found in both of them, although larger in materials grown with low voltage (Margheritini et al., 2021).

Regarding existing materials, like concrete, exposed to electrolysis, Rotta Loria et al. (2023) analyzed studies of compressive, tensile and flexural strength. With a current density of 0.5 A/m², the compressive strength increased from around 20 to 28 MPa after 30 days (Rotta Loria et al., 2023). Concerning tensile strength, at the same current density, the value increased from around 2.25 to 2.9 MPa after almost 60 days (Rotta Loria et al., 2023). Margheritini et al. (2021) further explain that the metal structure, together with the growing material, results in a combination of high compressive strength from the material and extra tensile strength from the metal, which gives higher stiffness and stability than merely the metal structure. The increase in flexural strength, at the same current density and after almost 60 days, depends on the width and depth of the cracks, with around 20.75-21.5 MPa for the smallest cracks to around 18.6-20.5 MPa for the largest (Rotta Loria et al., 2023).

When instead comparing the density of low (2.5 V) and high (400 000 V) voltage material together with concrete, the measurements resulted in 2499.2, 1771.1 and 1800–2400 kg/m³ respectively, which are compared to other common building materials in Figure 18 (Johra et al., 2021). In a similar study, a material grown with low voltage (2.5 V) measured the density of 2.7 g/cm³ and the value for a material grown with high voltage (400 000 V) was 2.24-2.54 g/cm³ (Margheritini et al., 2021), which equals 2700 and 2240-2540 kg/m³. This variation in density is due to the different growth rates from different voltages (Margheritini et al., 2021).

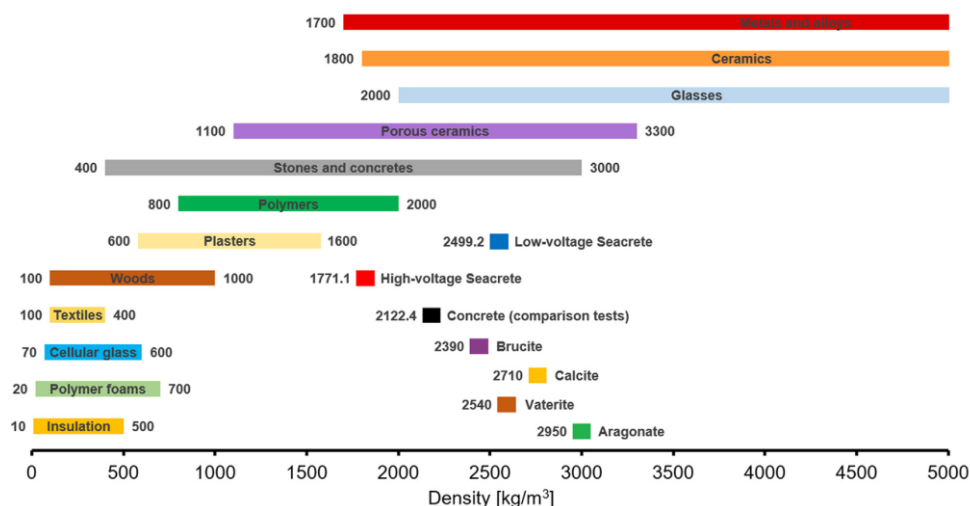


Figure 18. The densities of low- and high-voltage materials together with brucite (magnesium hydroxide) and three calcium carbonate minerals (calcite, vaterite and aragonite), reproduced from Johra et al. (2021), used with permission from Elsevier

When measuring the pore size, the low-voltage material showed an even distribution, compared to the high-voltage material, which is usually related to high strength (Margheritini et al., 2021). In this study, natural coral structures were compared to low- and high-voltage material. Natural coral structures were found to be the weakest despite consisting of more aragonite than the other two materials, which, according to Margheritini et al. (2021), indicates that pore-size distribution might be a more important factor determining material strength than mineral and chemical composition.

Concerning the surface impedance, Bellezze et al. (2025) found a decreasing effect from around 3 to 1.5 $\text{k}\Omega \text{ cm}^2$ when the electrical stimulation was turned off, presented in Figure 19, indicating a layer that is less protective, despite being almost constant in thickness, but more accessible for precipitation reactions. One given reason for this decrease is tunnels in the material caused by marine organisms, exposing the substrate to corrosion and resulting in localized degradation of the material (Bellezze et al., 2025). Therefore, increased material thickness could be connected to increased surface impedance (Bellezze et al., 2025; Colaleo et al., 2022). In a study by Colaleo et al. (2022), the surface impedance of the grown material was 2 orders of magnitude higher than that of a material without the applied electrolysis, which indicates that the precipitated layer from the electrolysis provides significant protection against corrosion. Decreased surface impedance appears, on the other hand, to be possible without decreased material thickness but instead due to biological interference (Bellezze et al., 2025).

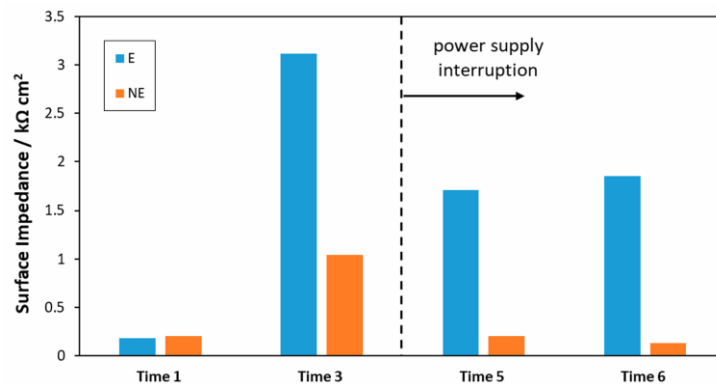


Figure 19. Surface impedance of the growing material with (blue) and without (orange) electrical stimulation before and after this stimulation is turned off, reproduced from Bellezze et al. (2025), CC BY 4.0

Materials grown with electrolysis are regarded as suitable enough to be used in the construction industry (Devi et al., 2025; Johra et al., 2021), primarily low-voltage material (Johra et al., 2021). With a higher content of calcium carbonate, the material has physical properties that would make it suitable for some coastal structures (Robinson et al., 2024). Based on studies of its material properties density, compressive strength, puncture resistance, thermal diffusivity, thermal conductivity, and water vapor sorption isotherms, this material resembles concrete (Johra et al., 2021). The positive thermal properties also indicate a thermal inertia, concerning stabilized indoor temperatures, like that of cement (Johra et al., 2021). With concurrent carbon dioxide injection, the material is considered to be in accordance with the Standard Specification for Concrete Aggregates (ASTM C33/C33M-23) (Devi et al., 2025).

The high-voltage material, on the other hand, exhibits significantly lower values for these material properties, but still comparable to stones and some concrete materials used for some types of constructions (Johra et al., 2021). Moreover, because of its high porosity, this material is described by Johra et al. (2021) to have other desirable properties, like a higher moisture buffering capacity and larger ability to breathe, which benefit the indoor relative humidity and air quality. High porosity and low strength are observed to be interdependent in the material, together with high moisture buffering capacity and low thermal diffusivity (Johra et al., 2021).

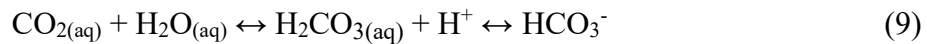
5.2.4 Carbon Dioxide Balance

Biorock is said to be a technology that removes carbon dioxide and stores it, when renewable energy sources are used, (Hilbertz, 1991) but there are contradictory statements about Biorock being neither carbon dioxide negative nor neutral (Johra et al., 2021).

Goreau (2012) explains that natural limestone precipitation, including calcium carbonate, is a source of carbon dioxide despite being a sink of bicarbonate, which can be seen in Equation 7. Part of the reason is also that there is more dissolved inorganic carbon in the sea, like bicarbonate, than there is carbon dioxide in the atmosphere, which means that the absorption of bicarbonate during precipitation of calcium carbonate does not result in more carbon dioxide being stored in the sea (Johra et al., 2021). On the other hand, if magnesium hydroxide instead of calcium carbonate is precipitated from some of the hydroxide ions, less carbon dioxide is released since precipitation of magnesium hydroxide is not a source of carbon dioxide (Goreau, 2012), according to Equation 8.

Electrolysis changes, however, this natural process since it enables calcium carbonate to precipitate without releasing carbon dioxide (Eq. 4, 5, 6) because of the increased pH from the production of hydroxide ions (Eq. 1, 2) from the electrolysis (Carré et al., 2020; Margheritini et al., 2020). Furthermore, when the currents from the electrolysis are high enough for brucite precipitation, hydroxide ions are consumed which prevents bicarbonate ions from being turned into carbonate ions (Eq. 4) (Goreau, 2012). This inhibits precipitation of calcium carbonate and therefore also the risk of carbon dioxide being released if calcium carbonate would precipitate outside the elevated pH zone close to the cathode (Goreau, 2012), according to Equation 7 like in the natural case described above. Besides this process at the cathode, the anode is part of the whole Biorock system, which means that the total carbon balance includes the potential carbon dioxide release from the hydrogen ions produced at the anode during the electrolysis, as described in Section 3.1 according to Figure 2 (Hilbertz, 1991).

Furthermore, Devi et al. (2025) emphasize the benefits of injecting carbon dioxide during the electrolysis. If carbon dioxide is added to seawater, it would dissolve into bicarbonate and hydrogen ions via carbonic acid, as in Equation 9, decreasing the pH (Devi et al., 2025).



Another consequence is that any available carbonate ions in the water react with some of these hydrogen ions to form bicarbonate, resulting in both a decrease in carbonate ions and an increase in bicarbonate ions, which affect the precipitation of calcium carbonate (Devi et al., 2025). However, if electrolysis is introduced to this process, the hydroxide ions from Equations 1 and 2 contribute, since they can control decreased pH and availability of carbonate ions (Carré et al., 2020; Margheritini et al., 2020).

The study by Devi et al. (2025), where carbon dioxide is injected into the electrolyte in controlled environments, is described as a balance between injected carbon dioxide and the intensity of the electrolysis, since this affects the growing material and the amount of captured carbon dioxide. More specifically, this process and the amount of material are influenced by the voltage or current and the injected carbon dioxide, as presented in Figure 20 (Devi et al., 2025). This is based on the pH since injected carbon dioxide decreases the pH while electrolysis increases it (Devi et al., 2025). The purpose of injected carbon dioxide is to interfere in the carbonate system by increasing the production of bicarbonate and carbonate ions, resulting in faster precipitation of material (Devi et al., 2025). Devi et al. (2025) describe that to capture 1 mole of injected carbon dioxide into 1 mole of calcium carbonate, 4 moles of

hydroxide ions need to be produced. As a result, the pH is controlled and 1 mole of magnesium hydroxide is precipitated (Devi et al., 2025).

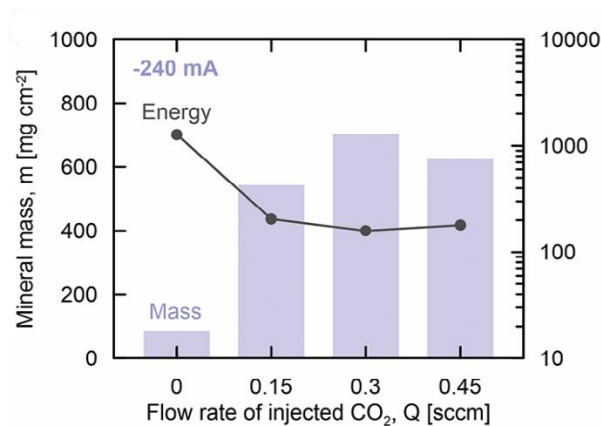


Figure 20. Mineral mass of the precipitated material as a function of the flow rate of carbon dioxide injection together with energy requirement in the unit MJ/kg at the current -240 mA, reproduced from Devi et al. (2025), CC BY-NC 4.0

If the composition of the material has a 70:30 ratio between calcium carbonate and magnesium hydroxide, one ton is estimated to be able to store 0.084 tons of carbon (Hilbertz, 1991), which corresponds to approximately 0.31 tons of carbon dioxide. The presence of magnesium hydroxide in the material further enables increased storage of carbon dioxide if the magnesium hydroxide is converted into hydrated forms of magnesium carbonate (MgCO_3) by absorbing carbon dioxide (Devi et al., 2025; Goreau, 2012), whether the carbon dioxide is injected or exists in the sea. Consequently, it is calculated that a 50:50 ratio of calcium carbonate and the hydrated forms of magnesium carbonate theoretically could store around 0.5 tons of carbon dioxide per ton of grown material (Devi et al., 2025).

5.2.5 Self-Healing Ability

Besides using electrolysis to grow material from the start, it can be applied to existing material, like concrete, to affect its properties and to heal possible cracks, which means that the material is not only growing on an existing structure but also within it (Rotta Loria et al., 2023). An example of this healing structure is illustrated in Figure 21 where the cathode is inside the damaged concrete (Feng et al., 2023). Goreau (2012, p. 275) describes Biorock as “the only GROWING marine construction material that gets larger and stronger with age, and is self-repairing, like biological materials”. If the material is damaged, the growth is increased at that point, even if the voltage is the same for the whole metal structure, because of increased electric current and mass transfer directed to that point (Goreau, 2012).

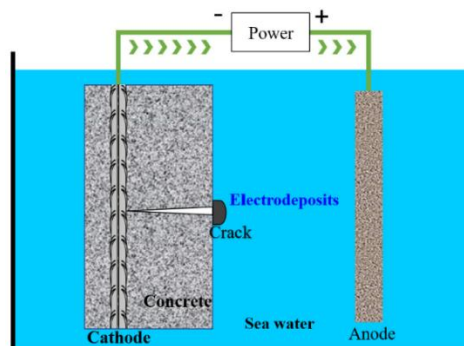


Figure 21. A Biorock structure where the cathode is in the damaged concrete, reproduced from Feng et al. (2022), Copyright by JCI - reprinted with permission

The hydroxide ions for this healing process come from both reactions on the cathode and from the concrete due to the electrical stimulation, as shown in Figure 22 (Feng et al., 2022). Besides mass transfer to the damage point, using electrolysis to heal cracks in concrete provides transfer from this point, which for example is the case for chloride ions, also seen in Figure 22, that otherwise increase the corrosion of the concrete (Feng et al., 2022; Rotta Loria et al., 2023).

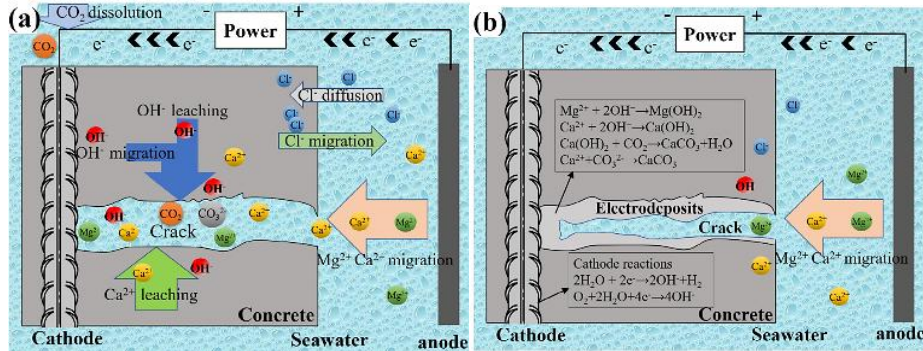


Figure 22. The healing process illustrating (a) the mass flow of ions and (b) the reaction equations, reproduced from Feng et al. (2022), Copyright by JCI - reprinted with permission

This gradual enhancement of the material, illustrated in Figure 23 (Rotta Loria et al., 2023), depends on some factors. Feng et al. (2022) examined this enhancement ability by comparing the current densities 0.25, 0.5, 1 and 2 A/m², the electrode distances 0, 20, 40 and 60 mm, as well as the material of the anode for 42 days. In addition to these varying factors, the characteristics of the damaged material and of the fluid in its pores affect the healing process (Rotta Loria et al., 2023). Feng et al. (2022) showed that cracks in concrete can be fully healed after these 42 days and that the efficiency of removing chloride ions can reach 16.25 percent. Both Rotta Loria et al. (2023) and Feng et al. (2022) analyzed the crack closure rate which was found to be highest at the beginning of the healing process and then, in most cases, slowly decreases.

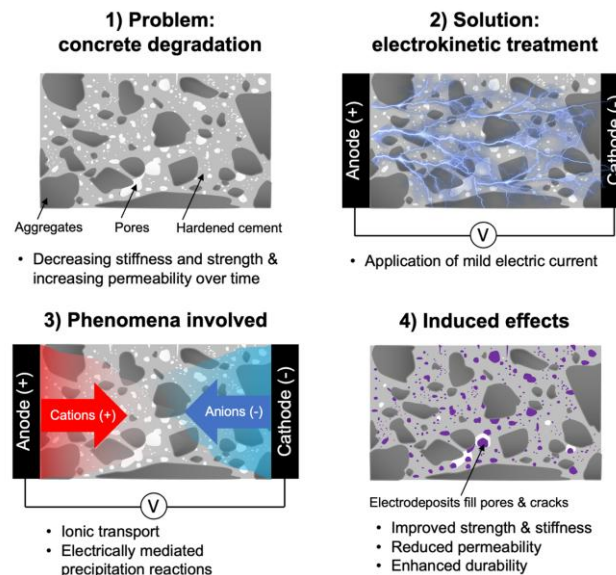


Figure 23. Step-by-step process from the electrolysis, reproduced from Rotta Loria et al. (2023), used with permission from Springer Nature

Concerning the current density, electrode distance and anode material, the healing abilities were highest when using 0.25 and 0.5 A/m², 0 mm distance and titanium anode (Feng et al., 2022). Rotta Loria et al. (2023) also found that lower electric current levels are preferable.

One of the explanations from Feng et al. (2022) is that higher current densities would mean a faster precipitation rate of the material, resulting in larger and irregularly structured crystals, less dense material and thereby a reduced ability to heal the material. Moreover, Rotta Loria et al. (2023) write that higher concentrations of ions in the fluid increase the growth rate but that lower concentrations result in a more effective healing. Despite promising studies, more information is needed about the process within the healed material during this healing process (Rotta Loria et al., 2023).

5.2.6 Energy Requirements

The tailoring of the growth also offers the possibility to find the optimal conditions for both the suitability of the material and the lowest energy requirement (Devi et al., 2025). The energy requirement can be reduced by placing the cathode and anode very close together, using materials that are highly conductive and locating the technology in warm waters at low voltage (Hilbertz, 1991). An estimation of the energy requirement for this technology is 0.4-2 kWh for 1 kg of grown material (Hilbertz, 1979) or around 1000 kWh per ton material (Hilbertz, 1991) which is 1 kg/kWh. An experiment by Goreau and Hilbertz with 1.5 V resulted in 1.07 kg/kWh (Goreau, 2012). However, based on an experiment in Denmark, 0.121 kg of material was obtained with 3.4 kWh, which was estimated to 0.04 kg/kWh (Margheritini et al., 2020). Margheritini et al. (2020) therefore request more studies to reduce the energy requirement per unit mass material.

If all hydroxide ions from the electrolysis are assumed to be neutralized by the growing material, 3.7 g of calcium carbonate is estimated to be produced per amp hour of electrical stimulation (Ah) but a voltage, which is connected to the energy efficiency, is needed to convert the unit into kWh (Goreau, 2012). The minimum voltage for electrolysis of seawater is 1.23 V (Goreau, 2012). Otherwise, the lower the voltage, the higher the efficiency, according to Goreau (2012), indicating a reverse relationship between voltage and efficiency above the minimum voltage. One example is that 6 V gave 0.62 kg calcium carbonate per kWh, which would be around 80 percent energy loss (Goreau, 2012).

Energy efficiency is, however, also dependent on the chemical composition of the growing material (Goreau, 2012). As previously mentioned, precipitation of brucite requires twice as many hydroxide ions from the electrolysis as aragonite does to produce the same number of molecules, and brucite is more porous than aragonite, resulting in a lower density for brucite than for aragonite. Therefore, the energy efficiency in weight is higher for aragonite (Goreau, 2012).

When it comes to pulsed voltage, Robinson et al. (2024) report that the energy requirement per mass is significantly higher, up to 14 times, than for a constant voltage. However, despite the energy requirement, controlling different parameters could result in a material with more favorable characteristics for marine applications and thereby might compensate for the energy requirement, even if more cost-benefit analyses are needed as well (Robinson et al., 2024).

5.2.7 Applications

Suggestions for applications for this technology include mainly marine constructions like floating habitats, breakwaters, storage tanks, pipelines, tunnels and mariculture facilities but also ideas about growing construction components in the sea for the purpose of being used on land (Hilbertz, 1979). An example is that the low-voltage material could be used for low-rise indoor construction elements based on its physical properties (Johra et al., 2021). Compared

to growing these constructions from scratch, metal grids, acting as a starting base for a Biorock structure, could be placed on existing marine infrastructures where the growing material could possibly become a protective layer (L. Wadsö, personal communication, March 20, 2026). This layer would also be able to act as a habitat for marine ecosystems. There seems to be an interest in this application, partly because of the attractive aspect of the material growing in-situ (S. Bertilsson Vuksan, personal communication, March 27, April 1, April 24, 2026). A material like Biorock that is deformable in the beginning because of the metal grid and then becomes stronger, could provide other possibilities compared to some common solutions and materials (K. Tammo, personal communication, April 13, 2026). Since a large amount of the world's population lives close to the coasts, it is convenient that Biorock is produced in seawater (Johra et al., 2021). Due to the fact that the material grows in situ, the need for transportation, as well as mining and extraction of material, decreases considerably compared to the usual concrete blocks (Hilbertz, 1979; Johra et al., 2021). Moreover, it is a significant benefit that one of its main components, seawater, is a virtually infinite resource (Johra et al., 2021).

Moreover, Hilbertz (1979) and Margheritini et al. (2021) emphasize the optimal advantage of the dual function of these marine constructions acting as artificial reefs. The difference in characteristics between the stronger and the more porous version of the Biorock material suggests that it can have different applications depending on how the affecting factors are controlled (Johra et al., 2021). For example, breakwaters can be constructed as a grid instead of solid material since this would decrease resistance to waves, and also provide space for marine organisms (Hilbertz, 1979). Reef structures, where the main purpose is not mechanical strength, can be grown faster with higher voltage, while stronger material can be produced when time allows it (Margheritini et al., 2021). Therefore, Margheritini et al. (2021) suggest that combining slow and fast growth could be the optimal way to obtain material that could act as both reef and coastal protection. This way of using marine infrastructure for ecological and environmentally friendly purposes makes Biorock an example of ecoengineering (Cárdenas-Rojas et al., 2025). Another proposal regarding a variation in growth rate is to change the level of the current density during the day, meaning some periods with higher current densities, resulting in higher growth rates but weaker material, and some periods with lower current densities, resulting in lower growth rates but stronger material, to handle the trade-off between material strength and growth rate (Strömberg et al., 2010).

Another application of this type of electrodeposition is a kind of soil cementation, where the metal grid is placed in the sediment of the seabed, instead of in an elevated position, which has been studied in the literature. One example is the study by Macias et al. (2024) which showed that electrical stimulation could sustainably reinforce marine soil to mitigate coastal erosion in a more nature-mimicking way than existing methods. As the material precipitates, the particles in the soil are bound together, resulting in changes in the structure of the soil due to decreased porosity and therefore decreased hydraulic conductivity and increased mechanical strength of the soil (Macias et al., 2024). According to Macias et al. (2024), these effects primarily occur during the WRR, achieved at a voltage between 2 and 3 V. Compared to other methods for soil cementation, injections of external fluids are not required here, and the electrical stimulation suits a variety of pore sizes (Macias et al., 2024).

Besides marine applications, Penney (2023) describes in a design proposal for Toronto how hyper-saturated run-off saltwater from winter roads can act as electrolyte in a Biorock

experiment to grow building components. The oxygen that is produced in the Biorock process is released to the urban areas to improve the quality of the air (Moffitt & Penney, 2024). This way of using Biorock on land with decommissioned urban structures instead of in the sea is called synthesizing a terrestrial reef and could have unexplored possibilities (Penney, 2023).

Since the Biorock-technology enables tailoring of the material and its thickness, it also becomes attractive regarding the production of hydrogen gas, which electrolysis is traditionally used for. The reason is that the control of the grown material means possibilities to monitor the growth, composition and thickness of the material in the most effective way for hydrogen production (Devi et al., 2025). There are also suggestions that the hydrogen gas produced from the Biorock process could be collected and used as fuel (Macias et al., 2024; Moffitt & Penney, 2024).

6. Discussion

With the results in chapters 3, 4 and 5 as a starting point, a Swedish implementation of the Biorock-technology is discussed in the following chapter. Different parts of the results are connected, compared and then related to a Swedish context. In section 6.4 the Method is discussed as well.

Based on the results, it is evident that the Biorock-technology comes with both challenges and possibilities, providing a dual function as ecological support and material for marine infrastructure. Because of all studies not using the same units regarding for example strength and electrical stimulation, comparison was sometimes difficult but in most cases, it was possible to convert units to make them comparable. There could be trade-offs regarding finding a suitable current density that does not harm the marine ecosystem but still results in a useful and cost-effective material within a reasonable time frame. The scale of these trade-offs does, however, depend on the purpose of applying Biorock, since a focus on a durable material allows for higher current densities to some extent, while restoration of marine ecosystems limits these levels, especially in the colder Swedish waters. Overall, low voltage and current densities seem to be preferred for both marine ecosystems and a durable material, but marine ecosystems apparently have a lower max level to prevent harmful effects. For example, since Table 2 shows that the current densities should be lower than 0.1 A/m^2 , preferably around $0.01\text{-}0.06 \text{ A/m}^2$, for marine ecosystems, there is a contradiction with the results from Sharker et al. (2023) that 0.55 A/m^2 is required to achieve cathodic protection. Nevertheless, it is clear that the effects from a certain electrical stimulation must be analyzed in the context of the application and the other influencing factors in section 5.2.2, making Biorock complex but, to a quite large extent, controllable.

6.1 The Growth Process

6.1.1 Suitable Material Properties

A perhaps more apparent trade-off, than the one between a suitable current density for both marine ecosystems and a durable material, is the one between the growth rate and the strength of the material. The reason is the clear patterns from the results that higher voltages and current densities result in a weaker and more porous material at a higher growth rate. This is compared to the stronger material from lower voltages and current densities at the cost of a longer growth time. As seen in the results, this trade-off is also reflected in the composition since the calcium carbonate/magnesium hydroxide ratio as well as the aragonite/brucite ratio decreased when the growth rates increased. One example is the fact that the portion of aragonite was higher when the material mass was larger in the study by Sharker et al. (2023). This could be due to that brucite increases more than aragonite because of changes in the surrounding environments. However, this transition of the composition is the result of increased rates, mainly from increased current densities, which is not the same as the transition resulting from material growing with a constant electrical stimulation, like in section 5.2.1, which will be discussed further below.

Regardless of the growth rate being a limiting factor, to some extent, the fact that the discussed strength of the grown material is proven to be suitable means that the applications of this material should not be seen as a problem. This considers both the low- and high-voltage material, but for different purposes, and the compliance with the standards. It should, for instance, not be underrated that the values of the low-voltage material in many measurements, including density, penetration and in some cases compressive strength, were at

the same level, or even higher than, standard concrete. Moreover, the application where Biorock is combined with existing materials to strengthen or heal these materials is a way of using Biorock as a complement, which could be one of the most important benefits of Biorock for a possible implementation. The observed variation in the values for the compressive strength in section 5.2.3 could appear confusing but based on the impact of the several factors described in section 5.2.2, this variation is reasonable. Besides, from the literature, it was sometimes unclear if the tests were performed on the surface of the material or further in, which could give different results about the material strength.

If further comparing Biorock to concrete, the hardness of concrete varies locally in the material since concrete consists of more than one component. For example, quartz, which is about the hardest component in the concrete mix, has a hardness of 7 (International Gem Society, 2025). This would make the overall hardness of concrete less than 7, compared to 3.5-4 for aragonite. Additionally, since this growing material layer is described in the literature as corrosion protective, it has multiple functions, including prolonging the lifetime of otherwise corroding materials. This means that stainless steel is not required as Biorock structure but that mild steel can be used instead. This is positive since mild steel benefits aragonite, which is often the preferred version of the material for a durable purpose. Consequently, for applications where time is not restricted, Biorock has proved to be reliable. This could be compared to concrete, which can protect reinforcing bars from corrosion to some extent but could eventually become exposed to carbon dioxide or chlorides, causing corrosion of the bars.

The most effective way to handle this trade-off between the growth rate and strength of the material seems to be pulsed current density or voltage, or in other ways alternating these levels, due to the evidence that this could increase the growth rate and still provide a relatively high ratio of aragonite or calcium carbonate. Since alternating electrical stimulation also suits the marine ecosystems, some kind of alternating current density or voltage could be the ultimate compromise to suit both marine ecosystems and durable materials. Since the literature gives examples of both short pulses or longer phases, such as during the night, with different levels of electrical stimulation or the absence of it, there seems to be many possible methods. This makes this alternating approach a suitable option for Sweden, due to the trade-off between sensitive cold-water marine ecosystems and durable material. On the other hand, since pulsed current densities or voltages increase the energy requirement, the economic aspect needs to be considered in relation to the time duration, depending on priorities. However, in most cases, the focus of implementation is either ecological or constructional, meaning that a suitable level can be chosen primarily based on purpose.

6.1.2 The Context of Influencing Factors

The results that the trade-off between growth rate and strength has proven to be complex, based on the several other factors mentioned affecting the outcome of the Biorock process, emphasize the need for a holistic view of the context. Therefore, it seems difficult to draw general conclusions from the results about relationships between material, voltage, current density, temperature and location, to name but a few, even if some patterns of these relationships have been identified. The fact that low temperatures seem to be able to interfere with the growth process despite high current densities, in the study of Sharker et al. (2023), especially reveals the importance of the temperature of the electrolyte. This emphasizes the significance of considering the water temperature of the location of a possible Biorock project when choosing a suitable current density and voltage, in particular in Nordic waters.

Moreover, the result that salinity is another factor corresponds to Ohm's law, where the resistance, which equals the voltage/current ratio, is influenced by salinity. This means that high salinity reduces the resistance, meaning that a lower voltage is required to give a certain current compared to if the salinity is lower. Regarding the Swedish seas, the salinity of the Skagerrak is close to that of the world seas, while the Baltic Sea has a much lower salinity (Sveriges Meteorologiska och Hydrologiska Institut [SMHI], n.d.). This means that, considering salinity, the results from the Biorock projects in for example Bali could be applied at least in the Skagerrak. On the other hand, the differences in water temperature between Sweden and the tropical places where Biorock has usually been implemented need to be considered. Furthermore, for places like Sweden, with seasons, some adaptations might be required because of the lower temperatures during winters. This is partly because of frost damage, reduction in chemical reaction rates due to lower temperatures and the decreased ability of colder water to conduct electricity.

6.1.3 Transition of the Material

Besides the quite clear relationship between the levels of the electrical stimulation and the composition of the material, the transition of the material composition during the growth showed some contradictory results. This is based on the results in Figures 7 (right) and 6, indicating that the proportions of aragonite respective calcium are lower at the end of the study than brucite respective magnesium, while the other figures and tables in that section instead show that the aragonite/brucite and calcium carbonate/magnesium hydroxide ratio increase. However, part of the explanation could be the duration of the studies, since, for example, the study presented in Tables 3 and 4 lasted for about 1.5 years while Figure 7 (right) and 6 show results from about 4 months. This means that the material composition might have been more similar if the time frames were the same. However, since the authors of the 4-month study suggested that their results could be due to too high electrical stimulation, the most probable conclusion would be that more aragonite respective calcium carbonate is precipitated as time goes by, at least if the electrical stimulation is not increased to the WRR regime, promoting brucite and magnesium hydroxide. Nevertheless, these transition patterns need to be considered with regard to the several factors, such as the solubility patterns for aragonite, not least for a Swedish implementation since this would mean that aragonite dissolves more easily in these colder waters.

Another interesting part of the material during the growth process is the identified connection between the structure and the growth rate, since the growth rate seems to increase if the material is more porous while the growth slows down if the majority of the material is compact. In addition, even if the voltage controls the reaction regimes (WRR or ORR), and thereby also the composition of the material, the growth rate affects the material as well, but regarding the structure. This is because of the results that a high growth rate gives a more porous and less organized material, while a slow growth rate gives a more crystalline structure. Since the current density controls this growth rate, even the current density could be considered a factor for the material structure. Moreover, because the growth rate slows down if the material becomes too thick as well, as seen in the results, there seems to be a trade-off between thickness and growth rate, in addition to the earlier-mentioned trade-off between strength and growth rate. This is unless the current densities are increased as the thickness increases as compensation, which would be a question about the costs for electricity.

Nevertheless, when discussing the precipitated material, there is a difference between thickness and mass, since aragonite has a higher molar mass and density than brucite, but only slightly when it comes to the density. Biorock can therefore result in a material layer that is

thick compared to its mass but not necessarily durable. Furthermore, since the availability of ions controls whether aragonite or brucite dominates, it also controls the growth rate of either of these minerals as well as the growth rate of the material as a whole, because aragonite and brucite have different growth rates. More specifically, since magnesium ions promote aragonite and are released together with hydroxide ions when brucite is dissolved, the dissolution of brucite benefits calcium carbonate with both magnesium ions and increased pH from the hydroxide ions. However, since this water composition is affected by marine currents, the composition of the material may differ due to the turnover time, depending on the location of a possible Biorock structure in Sweden. For example, high currents could transport hydroxide ions from the cathode and therefore prevent the pH from rising to a suitable level for brucite, favoring aragonite in some range, but too high currents would not favor any precipitation.

6.1.4 Growth Rate

An initial remark about the growth process is the fact that the growth rate is proven to be non-linear. For that reason, the approximate thickness is difficult to predict, because even if a study showed 2.5 mm after 6 months, the predicted thickness after 1 year should not be assumed to be doubled to 5 mm. This complicates the planning of Biorock projects regarding what thickness could be expected within a certain time frame. Additionally, in areas with seasonal changes, like Sweden, the growth rate and resulting thickness will be reflected in these changes, as well as the previously mentioned effects from trade-offs and ion availability. However, in some cases, what is most important is that some material is growing and not necessarily how fast, which means that this non-linearity is not necessarily a disadvantage.

6.1.5 Absence of Electrical Stimulation

Besides the growth process due to electrical stimulation, discussed so far in section 6.1, the results on the growth process from the tests when removing this stimulation revealed some interesting aspects. When comparing the change in the aragonite/brucite ratio in Figure 9 with the change in thickness in Figure 10, it seems that absence of electrical stimulation decreases aragonite, favoring brucite. This does not mean that more brucite is precipitated but that its portion compared to aragonite increases. This increase in the brucite portion could explain why the thickness from Time 4 in Figure 10 was resumed at Time 6. This brucite change could also be due to an increase in organic or other non-crystalline matter, like the explanation given by Hilbertz (1979) for the material change from the phasing in Table 7. Moreover, absence of electrical stimulation would decrease the pH, shifting the carbonate system to bicarbonate and thereby decreasing the driving force for fast precipitation of calcium carbonate, which would reduce the aragonite portion. Additionally, brucite could be more resistant to changes than aragonite, further explaining the decreased aragonite/brucite ratio. In other words, if the desired material property is strength, the electrical stimulation should not be turned off permanently, since this seems to result in a decrease in aragonite but also a reduced corrosion protection.

6.2 Effects on the Marine Ecosystems

6.2.1 Electrical Stimulation, Material or Elevated Position

Although electric stimulation is important for the material, one interesting point identified in the literature is the different views about whether the effects of the electrical stimulation are

beneficial, harmful or unnecessary regarding the marine ecosystems. Since the current densities in many studies were thought to have been too high, resulting in negative effects or absence of effects, it is possible that these and more studies made on the effects of Biorock on marine ecosystems have questionable validity. This is especially important to consider if these results are to be applied to a Swedish context, due to the sensitive cold-water marine ecosystems. On the contrary, in the studies that did show positive effects during the presence of electrical stimulation, like higher survival and absence of competitive species, the current densities might have been at a suitable level, or the benefits did not originate from the electrical stimulation. An aspect that might be useful is therefore the fact that the current density decreases with the distance from the energy source, since this could offer many different electrical stimulation levels along the Biorock structure so that most organisms would hopefully find a place with a suitable level for them.

Regardless of whether the effects of electric stimulation are positive, negative or irrelevant for the organisms, the reasons for these effects remain speculative, varying from ATP increase inside the organisms to changes in water chemistry with more available ions for calcification. If, as suggested in the results, ATP is the limiting factor in unsaturated waters, and if it is true that electrolysis can increase the ATP in organisms, electrolysis appears to be very important for the growth and survival of the marine organisms on the Biorock structures. Moreover, the fact that even non-calcareous organisms are attracted to the Biorock structures gives reasons to believe that electrical stimulation results in at least something that benefits even non-calcareous organisms, which could be ATP. The results on electrolysis facilitating carbon- and nitrogen-fixing are other connections to non-calcareous organisms, for example since carbon-fixing can support the photosynthesis in organisms like algae and seagrasses.

This reasoning about what aspects of the electrical stimulation are attracting marine organisms is, however, based on the assumption that this attraction is due to electrical stimulation and no other aspects of Biorock. This is because of the quite confusing results on whether marine organisms benefit from the electrical stimulation itself or merely the material that it results in. This is for example based on the results that indicated that organisms were more attracted to structures without electrical stimulation. On the other hand, it also seems possible that the growing material is not a benefit for the marine organisms but a disturbance, especially for their initial settlement. This refers to the study that showed that corals only continued to grow if they had grown more than the material, and that they did not seem to be prevented by the electrical stimulation when it was reconnected. Therefore, the reason for the initial absence of organisms when the electrical stimulation was connected might have been that the growing material prevented their settlement or that the organisms were overgrown by the material. This would mean that the growing material is no longer a problem once the organisms have settled and had time to grow. However, it is possible that even these experiments used too high current densities, making the effects of the electrical stimulation difficult to distinguish.

In addition to electrical stimulation and the material, the mention of the elevated position of Biorock should probably not be overlooked, because of the many benefits following it. This is partly because of the discussion in the literature that some of the control organisms used in the studies seemed to achieve better outcomes when they were placed on the elevated Biorock structures instead of being left on the seabed. If the promoters are the material and the elevated position, and not the electrical stimulation, Biorock might not be that different from common artificial reefs that try to mimic natural structures. Since these differences regarding impact could also be species dependent, according to the results, the positive effects of

Biorock could, in some cases, be due to a combination of the material, the electrical stimulation, the elevated position and the species. However, in order to find optimal conditions for the marine ecosystems and to make a possible implementation of Biorock more effective in terms of time, economy and resources, more knowledge about the actual reasons is fundamental. In a Swedish context, this knowledge will probably differ between the west and the east coast, to a large extent because of the different salinities.

6.2.2 Relevance to Swedish Environmental Status and Goals

Regarding the environmental status of marine ecosystems reported in section 4.1, it is clear that actions are required, not least concerning acidification based on the recent alarming changes in the planetary boundaries. However, based on the results, Biorock is not the solution for mitigating acidification on a large scale, both since the increase in pH from the electrolysis is described to be local at the cathode and since the produced hydroxide ions, causing the increased pH, are thought to be consumed in the precipitation reactions (Eq. 6 and 8). Therefore, the increased pH seems to contribute positively to the marine ecosystems, not primarily by directly preventing acidification but with local zones of refuge by providing precipitated building blocks for calcareous organisms and natural structures to settle on. In other words, despite being unsuitable for large-scale acidification prevention, Biorock can indirectly be part of the acidification solution for marine ecosystems by making them more prepared for and resilient to changes like acidification. This means that instead of altering the conditions of the ocean to benefit these ecosystems, Biorock equips the marine ecosystems for the existing conditions. However, Biorock structures are not suitable everywhere, meaning that Biorock is not a universal solution but, according to the results, useful in some cases as part of the solution. One area where Biorock could be used, based on the results of Biorock in alvar landscapes, is the Great Alvar on Öland.

Moreover, the fact that Biorock has had positive effects on calcareous organisms promises well for the proposal from HaV and the other four agencies. This especially concerns the calcareous organisms in the proposal, including calcareous algae, oysters and blue mussels, because of the support from Biorock in the precipitation of calcium carbonate building components. This ability of Biorock is also very timely due to the recent addition of blue mussels to the Red List. Additionally, the eelgrass and seagrass, also mentioned in the proposal, could be connected to the results from Goreau (2012) about different types of grasses growing in toxic and tough locations because of Biorock, as well as being less exposed to waves. Therefore, since seagrass and eelgrass bind carbon dioxide, termed blue carbon, and both these grasses, as well as mussels and oysters, purify water, Biorock could indirectly contribute to these ecosystem services by supporting the restoration projects of these grasses in Sweden. This resembles the planned Biorock project in the Balearic Islands, since this project also uses Biorock as a support to organisms with purifying abilities.

Moving on to other mentioned threats against the Swedish marine ecosystems, the identified ability of the Biorock material to sequester certain substances, such as phosphorus, could contribute to reducing eutrophication, although on a small scale. For this reason, Biorock could be a step on the way to GES. The urgency with eutrophication in the Baltic Sea, compared to the North Sea, is, however, an obstacle somehow because of the low salinity in the Baltic Sea. This is because of the higher resistance caused by the low salinity of the Baltic Sea, which would require higher electrical stimulation, but as long as this is available and affordable, Biorock works in low salinity electrolytes as well. Nevertheless, the balance between a harmless electrical level for marine ecosystems and an acceptable growth rate in

the Baltic Sea might be even more complicated than in more salty waters and therefore requires more experiments.

Concerning the threat from marine infrastructure, the suggestions in the results about incorporating Biorock structures with existing infrastructures, such as harbors, bridges and pipelines, can make infrastructures more adapted to marine ecosystems. To combine human infrastructure with ecosystems in this way could be seen as a kind of ecosystem-based marine management, as mentioned earlier for GES. This could include opportunities to involve local communities, like schools, to work with Biorock structures, with the aim of creating an urban ecosystem. Involvement can develop an interest and passion for preserving these ecosystems, especially when they become visible, which they do if the structures are placed close to the surface or in shallow waters, combined with information and events to raise awareness. This could, of course, be done with other types of artificial reefs than Biorock structures, but it is one example of how Biorock could be implemented. Besides, because of the pressure from the EU Biodiversity Strategy for 2030, it is reasonable to explore every available option.

6.3 Costs, Carbon and Applications

One interesting perspective would be to relate the cost- and energy-efficiency of the produced amount of material and captured carbon via Biorock to that of cement and other carbon capture technologies. Regarding the energy requirement, the study that most resembles the Swedish context is the one from Denmark by Margheritini et al. (2020), where 0.04 kg material was obtained per kWh, at 2.5 V for 9 months in 2.4-20 degrees, which equals 25 kWh/kg. This value is compared to that of cement in Table 9. The value for energy requirement for cement production includes both thermal energy and electricity (S&P Global, n.d.). This means that the corresponding values for concrete are considerably lower since cement is the energy-intensive ingredient of concrete. Moreover, the value for cement is based on the calcination, meaning the burning, of limestone, since the energy requirement and costs for the other steps in the production process, for example mining and transport, are very low in comparison. The estimated Swedish electricity spot prices used in the comparison are at around 0.55-1.2 SEK/kWh, based on the average price in 2026 (Elbruk, 2026). The energy tax for 2026 is 0.45 SEK/kWh, including VAT, (Energimarknadsinspektionen, 2025) which is also used in Table 9. For the cases when the VAT is compensated for, such as for municipalities, estimations with energy tax excluding VAT are included in the table. Based on Table 9, the values for Biorock are around 25 times as high as for cement, regarding both the energy requirement and cost. In other words, this emphasizes that the production of Biorock is not competitive compared to cement production. However, one interesting aspect is that maintenance costs are included in the values for Biorock, due to the electrical stimulation and the self-healing ability of Biorock, but not in the values for concrete.

Table 9. Energy requirement and costs for cement compared to Biorock, based on Swedish electricity spot prices and these spot prices combined with energy tax, including and excluding VAT (Elbruk, 2026; Energimarknadsinspektionen, 2025; Margheritini et al., 2020; S&P Global, n.d.)

	Cement			Biorock		
	Electricity spot price	Incl. energy tax, incl. VAT	Incl. energy tax, excl. VAT	Electricity spot price	Incl. energy tax, incl. VAT	Incl. energy tax, excl. VAT
Energy requirement (kWh/kg)	1			25		
Cost (SEK/kg)	0.55-1.20	1.00-1.65	0.91-1.56	14-30	25-41	22-39

When, on the other hand, including environmental costs, the production of cement becomes more expensive because of mining, transport, production and also the EU Emissions Trading System (ETS). Mining is not relevant for Biorock, because it grows in-situ. Moreover, since Biorock can be adapted regarding the carbon balance, the carbon footprint of Biorock is regarded as negligible. However, for cement, the climate footprint is 0.8-0.9 kg carbon dioxide per kg, released during the calcination due to both the limestone and the fossil fuel (Kullman, 2023). This is affected by the EU carbon permit price, because of ETS, at around 0.8-0.9 SEK per kg (Trading Economics, n.d.). For comparison, the carbon footprint for the low-carbon concrete C20/25 ECO4, with a market price of 0.75 SEK/kg and a compressive strength of 20 MPa, is 0.05 kg/kg concrete (K. Tammo, personal communication, May 26, 2026). In a market price, the EU carbon permit price and energy tax are usually included.

Estimates of the costs for Biorock, cement and the low-carbon concrete as a result of these carbon footprints are compared in Table 10. From the table, it is clear that the benefits of Biorock regarding carbon footprint do not compensate for its high production costs. However, since environmental costs include more than carbon permits, Biorock might be able to compensate in other areas than the economic, such as its benefits on marine ecosystems, which are not priced. The initiatives, in section 5.1, to reduce the carbon footprint from cement also need to be considered, but the price for carbon permits compared to for example CCS, together with the growing environmental demands, affect what is considered worth pursuing. Regarding transport, Biorock has the advantage of being grown in-situ. There are, however, options also for concrete with less transportation needs, like sprayed concrete (K. Tammo, personal communication, April 29, 2026). Nevertheless, even when carbon permits are considered, Biorock is not competitive relative to cement, as seen in Table 10. On the other hand, Biorock is not supposed, or able, to replace concrete on a large scale, but could in some cases be a suitable alternative or complement. Besides, although relatively small production volumes, it is not a disadvantage to have options, especially because of recent years' environmental scandals and the uncertainty surrounding permits in the cement industry.

Table 10. Carbon footprints and costs based on these footprints for cement and low-carbon concrete compared to Biorock (K. Tammo, personal communication, May 26, 2026; Kullman, 2023; Trading Economics, n.d.)

		Cement	C20/25 ECO4 Concrete	Biorock
Carbon footprint (kg CO ₂ /kg)		0.8-0.9	0.05	-
Cost (SEK/kg)	Incl. energy tax, incl. VAT + ETS permits	1.64-2.46	-	25-41
	Incl. energy tax, excl. VAT + ETS permits	1.55-2.37	-	22-39
	Market price (incl. ETS permits)	-	0.75	-

Since the carbon balance for Biorock showed that it can be carbon neutral or negative if a suitable pH level is achieved and if renewable energy sources are used, it is good news for Biorock that renewable energy has become cheaper lately. The fact that Biorock can be further converted into magnesium carbonate by absorbing carbon dioxide means that the capacity of Biorock to store carbon is both direct and indirect. These values are, however, based on a certain ratio between calcium carbonate and magnesium hydroxide used in the literature, which, as earlier emphasized, depends on several factors. Moreover, since the effects on the carbonate system from the hydrogen ions from the anode influence the carbon balance of Biorock, so that carbon dioxide could be released, the overall carbon balance is uncertain. However, most of the time, carbon stays in the form of bicarbonate instead of

carbon dioxide, resulting in a net carbon storage for Biorock. Another interesting approach is the possibility to increase the carbon storage together with the growth rate by injecting carbon dioxide, since this results in a stronger material faster than without this injection. This would mean that this process is conducted separately from marine ecosystems to prevent harmful effects on the ecosystems. If this was to be scaled up, there would be some losses in efficiency which are being estimated (A. F. Rotta Loria, personal communication, May 18, 2026). The main message is, however, that electrolysis of seawater can turn precipitation of calcium carbonate and magnesium hydroxide into a process that at least becomes carbon neutral.

Even if Biorock is proven to be able to store carbon, this ability is more of a positive side effect of Biorock than its main purpose. This becomes clear when comparing the energy requirement and costs of carbon storage of Biorock to some CCS approaches, presented in Table 11. The table shows energy requirements for the different steps in the CCS process, where the capture step requires significantly more energy than the other steps. The costs in the table are based on the earlier-mentioned Swedish electricity spot prices. This is except for the values for transportation and storage costs for pipelines respective ships, estimated by Smith et al. (2021), since the given units were USD and EUR. Norwegian Northern Lights uses ships as transportation means (Smith et al., 2021), which is included in the table. The carbon dioxide stored by Icelandic Carbfix comes from Direct Air Capture (DAC) but the given values for Carbfix do not include the energy requirement for this process step (Carbfix, n.d.), as seen in Table 11. However, combined with the estimated energy requirement for DAC (The International Energy Agency, 2026), the total energy requirement and corresponding cost can be estimated. As seen in Table 11, the total energy requirement for Carbfix is around 50 times as low as for Biorock. In Table 11, in the Biorock column, the low values in the ranges for both energy requirement and cost refer to the approach when carbon dioxide is injected, described in Devi et al. (2025), while the high values are without this injection, based on the values in Hilbertz (1991). With Biorock, there is no need for DAC or transportation since it is the locally existing carbon dioxide that is stored, which is why only values for the storage step are included for Biorock in Table 11. However, regarding the approach when carbon dioxide is injected, values for transportation might need to be added but since the values for Biorock are already significantly higher than for CCS, it would be preferable if the source of this carbon dioxide could be located close by. Despite not being competitive, this carbon storage aspect of Biorock provides a bonus feature regarding the climate perspective.

Table 11. Energy requirement and costs for some CCS approaches, divided into the process steps DAC, transportation and storage, compared to Biorock (Carbfix, n.d.; Devi et al., 2025; Hilbertz, 1991; Smith et al., 2021; The International Energy Agency, 2026)

	CCS							Biorock
	DAC	Transportation + storage		Storage (Carbfix)	Total			
		Pipe-lines	Ships (Northern Lights)		DAC + pipelines + storage	DAC + ships + storage (Northern Lights)	DAC + storage (Carbfix) (excl. transportation)	
Energy requirement (kWh/kg CO ₂)	1.8-2.6	*	*	0.04-0.08	1.8-2.6 (excl. transportation and storage)	1.8-2.6 (excl. transportation and storage)	1.84-2.68	50-81
Cost (SEK/kg CO ₂)	1.0-3.1	0.04-0.42	0.35-0.63	0.02-0.10	1.04-3.52	1.35-3.73	1.02-3.20	28-97

*Not available

Besides the ability to store some carbon, the observed self-healing ability is an attractive feature of Biorock since this would reduce maintenance costs. The earlier-mentioned corrosion protection provided by the growing material is another such cost-effective aspect of Biorock. The dual function of Biorock, as habitat for marine ecosystems as well as formation of material, could also be seen as economically effective. This includes the possibility of Biorock to result in soil cementation, since this could contribute to preventing erosion. Another example is the approach of reusing decommissioned platforms for recreational and ecological purposes instead of being removed at high costs. However, this approach is currently limited because of the OSPAR Decision 98/3, but the fact that Biorock could prevent harmful corrosion and sequester some possible pollution connected to these platforms could help this cause. Nevertheless, since Biorock could add a layer of nature-mimicking material on the surfaces of marine infrastructure, Biorock at least offers a way of making the sometimes necessary, and still commissioned, marine infrastructure more ecosystem-friendly, which is another benefit due to its dual function. Regarding the Swedish maritime spatial plans, this ecosystem-friendly conversion of marine infrastructure could facilitate the coexistence of these kinds of energy, transport and fishery facilities with the nature areas. Moreover, the risk for corrosion, both in the splash zone and where structures are added to existing infrastructure, could be an argument against adding Biorock structures onto existing infrastructure. On the other hand, because of its corrosion-protecting abilities and relatively high strength, Biorock could be suitable for this context.

The fact that alternating current density or voltage would probably be the most suitable solution for a Swedish implementation and that this affects the economic viability because of the significant increase in energy requirement, if pulses are used, could be an obstacle. On the other hand, the first step of an implementation might not have to be using pulses, and the other ways of alternating the electrical stimulations could be cheaper. Since low electrical stimulation is most suitable for both marine ecosystems and durable material, and since mild steel appears to be preferred for the structures, the costs for a pilot Biorock project seem to be quite low, indicating no large economic risk, especially if recycled steel structures are used. Nevertheless, because lower current densities than expected seem to be desired, the energy requirement decreases, meaning that it becomes cheaper to support marine ecosystems, even cheaper in Swedish colder waters. In other words, the results that the current densities should be low might not be bad news for Swedish implementations of Biorock. Since finer metal grids could result in a more continuous material layer, and maybe also compensate to some extent for the slow growth rate, finer metal grids are also a possible way to reduce costs regarding energy per mass of grown material. Another attractive aspect of Biorock is its proven contribution to knowledge on how to control electrolysis to minimize the growth of interfering materials and instead optimize production of hydrogen gas. Therefore, Biorock has a positive influence on a key technology for producing non-fossil fuels, indicating an indirect economic value of Biorock. Furthermore, the many sectors involved if Biorock is part of ecosystem-based management, probably means several different priorities to consider but also much knowledge available from experts in different fields which could make a project like Biorock more affordable and desirable.

6.4 Method Discussion

During the thesis process, the plan changed several times, which is reflected in the method. The original plan was focused on Biorock as a way to store carbon dioxide and enhance ocean alkalinity, besides its ecological purposes, because that was what I first read about this technology. The literature search terms were therefore based on these subject areas. As the

content of the literature instead showed results about these abilities being quite limited for Biorock compared to already existing technologies, the literature study was redirected which prolonged the search process.

One challenge with the literature search was to find an as broad variety of authors as possible since several authors reappeared in many articles, for example Goreau, Margheritini, Rotta Loria and Simonsen. However, in 20 of the 33 studies, none of these authors were included. Moreover, most of the articles had a positive approach towards Biorock, so the articles with a more skeptical point of view were useful for comparison, like Knoester et al. (2024).

Regarding the year of publication, 20 of the 33 studies were published in 2020 or later. The earlier studies were included mainly because they were conducted in colder waters than tropical ones, were written by Hilbertz or Goreau, or reappeared in many articles and therefore seemed important. Apart from authors and year of publication, the variation in location of the Biorock projects was quite limited because of their focus on shallow tropical coral reefs. However, studies in the Mediterranean Sea, Toronto, Denmark and Sweden provided some valuable information, which hopefully increased the generalizability of the study regarding Swedish implementations.

Since Biorock appeared to have many alternative names, as seen in section 3.1, which increased the search results as more such names were identified, it is very likely that some useful literature was excluded in the search because of unidentified names. Besides alternative names for Biorock, the choice of other search terms affected the results of the search. Hopefully, the literature search for this thesis gave an overview of the current selection of studies about Biorock.

The choice of dividing the results based on marine ecosystems and construction materials was generally useful. However, in some cases these two parts were interconnected in the literature which made it harder to describe one of them without relating it to the other, but, overall, my impression was that this structure was the most suitable for the purpose of the thesis.

Furthermore, this division is probably suitable for addressing possible stakeholders since the most relevant sectors seem to be within ecology and construction.

Part of the plan was also the possibility to visit places where Biorock is used, which in many cases are Indonesia. However, from the literature it became evident that the environmental differences between Indonesia and Sweden could mean that the applicable information from the Indonesian context to Sweden is too small compared to what it would take to go there regarding time and resources. Nevertheless, Biorock projects in the Mediterranean Sea were found as the search process continued, but one of them had already ended and the other one had not yet gained permission, so the possibilities of visiting a Biorock project turned out to be quite small. On the other hand, these projects were studied from afar through personal communication and by reading studies about them.

Besides the Biorock projects, personal communications proved to be a very important element since they provided depth, width and context to the literature, partly because the communication went from being one-sided with the literature to two-sided where questions were made possible. In some cases, this type of information was prevented because of unavailable contact information. Whether communication was possible or not, the time spent on trying to contact as many as possible was worth it.

7. Conclusion

Nature is filled with eco-friendly solutions, providing new perspectives, ready for us to learn from – biomimicry. The question is whether we can afford, or have the right, not to harness these solutions or return the favor when we have already been given, and taken, more than we need from nature. At the same time, economic and practical aspects need to be considered along with the Swedish context.

To answer the research questions, the effects of Biorock on marine ecosystems seem to be positive in terms of favorable changes in water chemistry, natural material and elevated position, although depending on many factors. There are, however, uncertainties regarding a suitable level of electrical stimulation for the sensitive Swedish ecosystems. Additionally, the effects of Biorock on acidification proved to be primarily indirect and on a very local scale at the cathode, nevertheless increasing the resilience of marine ecosystems against these threats. Overall, it seems to be something with Biorock that attracts marine organisms.

Regarding the research question on the material, several factors influence its growth process, composition and abilities, including voltage, current density, temperature, water chemistry and the structure. The abilities to store carbon as well as heal, strengthen and protect materials from corrosion are results of the material structure and the aragonite/brucite and calcium carbonate/magnesium hydroxide ratios, which are controlled by the growth process, and vice versa. Furthermore, the material growth rate appeared to be relatively low and non-linear.

Therefore, regarding the third research question on a Swedish implementation, many aspects need to be considered, especially the trade-offs between marine ecosystems and durable material regarding the electrical stimulation level and between growth rate and strength respective thickness. A promising solution is alternating the electrical stimulation. Moreover, Biorock can contribute to several areas in Sweden that are exposed to climate change. This is for example water status, threatened species as well as producing sustainable materials. Therefore, suitable Swedish Biorock applications include breakwaters, corrosion protection and restoration of threatened organisms, such as blue mussels and eelgrass, and as a complement to existing marine infrastructure. Thereby, Biorock could involve many sectors, like an ecosystem.

Despite its many possibilities, it became clear that Biorock is not an alternative to producing concrete on a large scale. Nor does carbon storage seem to be the strength of Biorock. Consequently, energy- and cost-effective material production and carbon storage are not the competitive aspects of Biorock but represent positive side effects of this technology. Proposals for future research, therefore, include examining a suitable electrical stimulation level in a Swedish context, estimating the growth rate in the Swedish seasonal waters, identifying the crucial beneficial factors on marine ecosystems and analyzing possibilities to make Biorock more energy- and cost-effective. However, from an environmental perspective, Biorock has already proven to be valuable.

To conclude and refer to the objective of this thesis, the potential of the Biorock-technology to contribute to favorable habitats for marine ecosystems and to eco-friendly materials in a Swedish context appears high but involves some trade-offs and need for further studies. Regardless of this potential, Biorock highlights the importance of finding new perspectives and learning from nature. By-products could be valuable resources, in more cases than regarding Biorock. This thought is part of a sustainable way, away from the climate crisis towards solutions, in accordance with C. S. Lewis's Great Story (1956). In a world in want of solutions, maybe this thought should be allowed to grow solid - like Biorock.

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