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Environmental Effects from Wave Power

Artificial Reefs and Incidental No-take Zones

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Abstract

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Marine renewable technologies have rapidly been developing over the past decade. Wave power is one of the renewable sources and has the potential securing the renewable electricity production. However, all renewable energy extraction affects the environment in some way and for a true sustainable energy generation, environmental effects need to be investigated. Beside uncertain effects from the technologies to habitats or organisms e.g., collision risks, electromagnetic fields, noise, past studies have also shown benefits on diversity, size and abundance of species around marine renewable technologies as a result of habitat creation by the devices and fishery exclusion in designated offshore park areas.

This thesis deals with environmental effects from heaving point-absorber wave energy converters developed at Uppsala University and deployed on the Swedish west coast at the Lysekil research site and the Sotenäs Project wave power park over a period of four years. The scope was the investigation of artificial reef effects from wave power foundations on local mobile, mega and macrofauna during visual inspections using scuba diving on the first hand. On the second hand, the effects from the incidental no-take zone on decapods and two sea pen species were investigated applying cage fishing and ROV seabed surveys. A third focus was on environmental monitoring around MRE sites and monitoring of MRE installations, both in an experimental and theoretical approach.

In the Lysekil research site, the results highlight that abundance and diversity can be enhanced locally around wave power foundations compared to control areas. The abundance and size of decapods were not significantly different within the wave power park and up to a distance of 360 m outside of it. In the Sotenäs Project wave power park a positive effect on *Nephrops norvegicus* size and burrow density but not on abundance was found on a scale of up to 1230 m. Sea pen abundance was enhanced inside the wave power park. However, interannual variation was strong.

In conclusion, wave power foundations can influence abundance and diversity of marine organisms around foundations on a very local scale (meters). With the methods in this study, the investigations did not reveal strong effects on the abundance and size of decapods on a larger scale up to 1230 m away from foundations as a result of the no-take zone. However, a focus should be put on a further development of environmental monitoring routines around MRE sites and their evaluation.

Keywords: Marine renewable energy, Wave power, Environmental monitoring, Artificial reef, No-take zone, Decapods, Nephrops norvegicus, ROV, Cage fishing

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To Juan and Lucía,
to my German and my Spanish family.

“It takes as much courage to have tried and failed
as it does to have tried and succeeded.“

—Anne Morrow Lindbergh

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. **Bender, A.**, Langhamer, O., Sundberg, J. Colonisation of wave power foundations by mobile mega- and macrofauna – a 12 year study.
Marine Environmental Research, (2020) 161(105053) doi.org/10.1016/j.marenvres.2020.105053

II. **Bender, A.**, Langhamer, O., Molis, M., Sundberg, J. Effects of a Wave Power Park with No-Take Zone on Decapod Abundance and Size.
Journal of Marine Sciences and Engineering, (2021) 9(864); doi.org/10.3390/jmse9080864

III. **Bender, A.**, Sundberg, J. Effects from wave power generators on the distribution of two sea pen species on the Swedish west coast.
13th European Wave and Tidal Energy Conference Series, EWTEC (2019)

IV. **Bender, A.**, Langhamer, O., Molis, M., Sundberg, J. Effects of distance from a wave power park with no-take zone on *Nephrops norvegicus* abundance, size, and burrow density.
In Manuscript

V. **Bender, A.**, Sundberg, J., Effects of Wave Energy Generators on *Nephrops norvegicus*.
4th Asian Wave and Tidal Energy Conference Series, AWTEC (2018)

VI. **Bender, A.**, Francisco, F., Sundberg J. A review of Monitoring Methods and Models for Environmental Monitoring of Marine Renewable Energy.
12th European Wave and Tidal Energy Conference Series, EWTEC (2017)

VII. Rémouit, F., Chatzigiannakou M. A., **Bender, A.**, Temiz, I., Sundberg, J., Engström, J. Deployment and Maintenance of Wave Energy Converters at the Lysekil Research Site: A Comparative Study on the Use of Divers and Remotely-Operated Vehicles.
Journal of Marine Science and Engineering (2018), 6, 39; doi:10.3390/jmse6020039

VIII. Francisco, F., **Bender, A.**, Sundberg, J. Use of Multibeam Imaging Sonar for Observation of Marine Mammals and Fish on a Marine Renewable Energy Site.
Submitted to PLOS ONE

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Contents

Abbreviations

Abbreviation	Description
ANOSIM	Analysis of similarities
AUV	Autonomous vehicle
CE	Control east
CW	Control west
H	Holes
IWP	Inside wave park
MPA	Marine protected area
MRE	Marine renewable energy
NH	No holes
OSPAR	Oslo Paris
ROV	Remotely operating vehicle
SDG	Sustainable Development Goal
WEC	Wave energy converter

1. Introduction

The global demand for electricity has risen continuously over time and predictions call for a further increase in the future [1]. Development of new electricity consuming technologies, process engineering and industrialization contribute to the rising demand for electricity. At the same time an awareness of climate change and the need to take action is a widespread topic in society and politics. There is a loud call for a change towards a sustainable electrical production and a generally sustainable development. The United Nations has set up 17 Sustainable Development Goals (SDG) to be achieved by 2030. Among those SDG, two are interlinked; focus on sustainable electricity production to attenuate climate change: *Affordable and Clean Energy* (Goal 7) and *Climate Action* (Goal 13) [2]. Among other aims of the SDG is a substantial increase in the share of renewable energy in the global energy mix and an enhancement in international cooperation to facilitate access to clean energy research and technology, including renewable energy [2]. Furthermore, affordable, scalable solutions are now available to enable countries to leapfrog to cleaner, more resilient economies. The pace of change is quickening as more countries are turning towards renewable energy utilisation and a range of other measures that will reduce emissions and increase adaptation efforts. The transition from conventional energy sources towards renewable energies contributes to Goal 7 as well as to Goal 13 [2]. Marine renewable energy (MRE) development, such as offshore wind, wave and tidal energy, is driven by the need to meet rising energy demands but also decrease greenhouse gases. Many countries include the development of MRE projects in their strategy to secure future energy demands. However, the expansion of MRE can create conflicts, such as competition for space in an already busy marine environment and environmental compatibility of these relatively new technologies should be secured including environmental monitoring along the development.

1.1 Marine Renewable Energies – Wave power

Marine renewable energy is harvested from ocean waves, tides, currents, ocean temperature and salinity gradients. Ocean waves originate from the asymmetrical irradiation of the sun on the earth's surface. The result is a variation in temperature followed by an atmospheric pressure change which induces motion of air masses and wind is thereby created. The wind transfers its energy into the waves blowing over the ocean surface. Ocean waves have the potential to contribute significantly to global electricity production (Figure 1). The global gross resource of energy from the ocean waves has been estimated to be around 3.7 TW [3]. The distribution of waves, and thereby wave energy, is uneven over the world including seasonal variation. This is a common feature of all renewable energy resources.

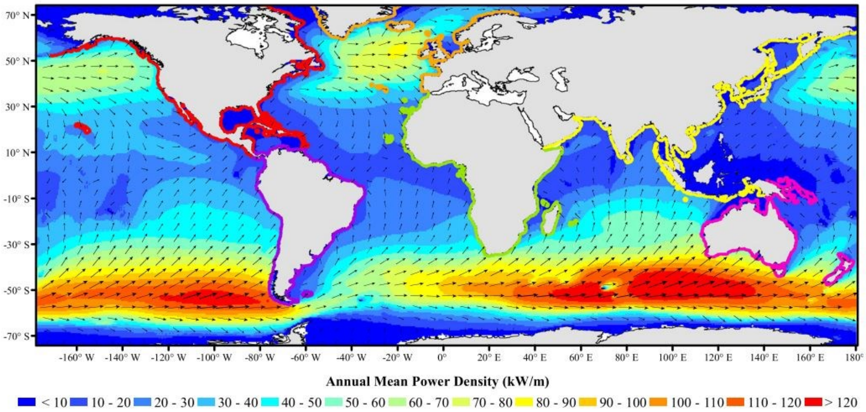

Figure 1. Average annual wave power density (color code) and average annual direction of the power density (vectors) (Source [4]).

Since the beginning of modern wave power research in 1970ies (as a reaction to the oil crisis) various types and designs have been developed [5]. Designing a wave energy concept includes several challenges. The structure has to be resistant to the rough conditions of a long-term deployment in the ocean (e.g., hydrodynamical forces, saltwater, scouring, erosion, biofouling, ice formation) and different coastal locations with different wave climates may require different types of technologies. Additionally, the system needs to be economically viable and be suitable to handle the huge changes in power input. It is thus not a big surprise that many designs have not reached the commercialization stage or have not even been built or tested in full scale and real conditions. However, there remain a substantial number of new wave energy converter (WEC) designs under consideration. The developed of this multitude of WEC concepts can be roughly classified into the following groups, based on their working principle: oscillating water column [6], overtopping devices [7], oscillating bodies and wave-activated bodies – e.g. linear generator point absorber at Uppsala University [8–10].

1.2 Environmental interactions around offshore renewable energies

The transition from conventional energy sources towards MRE does not automatically guarantees environmental compatibility. Although, MRE supports climate change mitigation, a true sustainable transition includes extensive, geographically adapted, monitoring programs and mitigation processes during all phases of the realization process in order to minimize eventual negative environmental impacts.

For a better understanding and assessment of the potential risks, a commonly used method is the investigation of the interaction between stressors and receptors. For MRE, commonly suggested stressors are the marine renewable energy device or system itself; this may stress or harm the environment, even kill the organisms or disturb and destroy their habitats. Elements of the MREs that may cause these problems include such parts as the moving blades of a tidal turbine, mooring lines, power cables anchors and foundations [11]. Receptors are organisms, species, individuals, habitats or ecosystem elements in the area or traversing the area of MRE projects and with the potential to response to the stressor [12]. The list of potential influences from wave power devices for the marine environment is long, and threats and impacts may vary among construction, operational and decommissioning stages [13,14]. Possible negative impacts may come from habitat loss or degradation, collision risk or entanglement, noise, visual impacts and electromagnetic fields. However, past studies could reveal positive environmental effects as a result of appropriate siting, design and management [15].

In the following chapter, this research focuses on two features. One is the potential of MRE devices to contribute positively to biodiversity, abundance and size of organisms, as a result of the artificial reef effect from for example the foundations. Another focus is on the possible beneficial effects on organisms from incidental no-take zones or *de facto* marine protected areas (MPA) as a result of the new infrastructure.

1.2.1 Artificial reef effects, structural complexity thereof and no-take zones

In this chapter, the focus is on changes in benthic and pelagic habitats caused by marine renewable energy devices with particular focus on artificial reef effects and incidental no-take zones.

1.2.1.1 Artificial reef effects and structural complexity

Submerged artificial structures have been reported to attract and concentrate fishes and invertebrates [16–21]. For centuries, humans have taken advantage of the behaviour of commercially interesting aquatic organisms, such as fishes and lobster, to be attracted to submerged objects and this knowledge was previously used in small-scale artisanal fishing. This phenomenon can be called the *artificial reef effect*. MRE installations act like artificial reefs and attract mobile organisms like decapods, demersal and pelagic fishes. This effect has been found and measured on wind power devices where fish species aggregated around offshore wind turbine foundations [22–28], but also on and around wave power installations [29–31]. By increasing the complexity of the seafloor, the aggregation behaviour can be explained by several reasons such as additional shelter against currents and predators, additional food sources, increased feeding efficiency and provision of nursery and recruitment areas [32]. This can potentially lead to changes in abundance, diversity and size of the local community [29,33–38].

Structural complexity and habitat characteristics are well known to play an important role in community structure [39–41]. The complexity of the structure itself can have an influence as well by modifying a number of ecological processes such as resource availability, recruitment and predation [42]. This knowledge is used in artificial reef designs for conservation purposes and management tools [43]. In the MRE sector, effects of different degrees of complexity have been investigated and differences in abundance were found for mobile species. Wind power foundations with a larger degree of complexity such as scour protection on monopiles compared to jacket foundations, showed increased numbers of brown crabs, *Cancer pagurus*, or cod, *Gadus morhua* [34]. Similar effects were found in a wave power site for brown crabs, which showed significantly higher abundances on more complex foundations [29,44].

MRE installations are often deployed on soft bottom substratum [11]. As more MREs are deployed the amount of artificial structures increases, and questions on their effect on the biodiversity, abundance and size of organisms rise. Investigations of simple but effective modifications of, for example, foundations could contribute to environmental benefits and even support specific species. Because the construction of MRE will add additional amounts of hard substrate to the marine environment, concerns have been expressed about MRE devices providing a colonization opportunity for non-native species or function as stepping stones [45]. However, investigations until now do not imply a higher risk for invasions compared to other marine installations such as marinas or coastal protection structures [11].

1.2.1.2 No-take zones and marine protected areas (MPAs)

As a result of the new infrastructure of an MRE site, human activities such as boat traffic or fishing, are often restricted or prohibited in or near such areas. These restrictions can create a *de facto* marine reserve through the creation of incidental no-take or exclusion zones. This incidental marine reserve can be beneficial for the recovery of the local populations, habitats, vulnerable species or local fisheries and even support adjacent areas if spill-over occurs [46].

This may be especially true for species inhabiting soft muddy or sandy sediments, which can benefit from exclusion zones in the form of no-take zones or MPAs, where destructive demersal fishing like trawling was previously conducted. The associated sea pen and burrowing megafauna, such as the Norway lobster (*Nephrops norvegicus*) communities are of key conservation importance as defined under the case report for the Oslo Paris (OSPAR) list of threatened and / or declining species and habitats and in the Background Document for Seapen and Burrowing megafauna communities [47,48].

Knowledge about the positive effect of no-take zones or areas with restricted activities is used in marine conservation activities and spatial planning. The strength of protection may vary, with a no-take zone being a strong level of protection, followed by spatial and temporal exceptions for fishing and other activities. No universal formula exists for a successful MPA, but characteristics such as large size, old age, magnitude of enforcement (e.g., fishing restrictions) and isolation of the area are shared by many successful MPAs [49].

Site section of new MRE projects focuses on suitability for energy extraction; however, both pelagic species and benthic species can benefit from areas with restricted activities which were previously exposed to invasive bottom fishing techniques such as trawling. Although not the main intention, positive effects on organisms inside MRE sites as results of restricted activities have been documented and the benefit of a no-take zone has proven to increase size, biodiversity, body mass and reproductive potential as a direct result of protection [26,50,59,60,51–58].

Clearly, the main focus of these structures is the successful harvest of energy and not the protection of species or habitats. However, in an already busy marine environment co-location of MPA projects can be a key to reducing competition for ocean use and conservation needs.

1.2.2 Environmental monitoring and monitoring around offshore renewable energy sites and devices

Technological development of MRE devices is progressing rapidly but non-technological barriers can hinder the development of the wave energy sector [61]. One of these non-technological barriers is the potential environmental risk and the uncertainties regarding the potential environmental impacts produced by MRE farms. As a relatively new technology, MRE devices require extensive monitoring programs as part of their consenting process. Installations need to comply with environmental regulations which are often based on "the precautionary principle," meaning the prohibition of installations of devices where scientific data do not permit full evaluation of environmental risks. The remaining uncertainties around the environmental impacts of MRE devices contribute to the perception by regulators and stakeholders that those technologies are risky. The European Marine Strategy Framework Directive (Directive 2008/56/EC) and ecological risk assessments [61], for example, are tools to identify interactions between human activities and pressures to ecosystem components.

At this stage, there are only a few cases in which a negative impact on organisms from MRE devices has been observed or measured [11,62]. A negative impact indicates here a number of animals negatively affected by a device or system. However, each MRE site and its associated organisms are unique and standardized monitoring techniques barely exist. Research is still needed to achieve a common standardized methodology for ecological risk assessments for MRE projects [28,63,64]. Many questions of environmental effects around this relatively young technology are still up to date and long-term investigations are scarce [62]. The key is to understand how the device may interact with the environment to help define the monitoring needs [65].

2. Aim of the thesis

The central aspect of my thesis deals with environmental effects and impacts from heaving point-absorber wave energy converters developed at Uppsala University and deployed at the 1) Lysekil research site and 2) at a second wave power park, Sotenäs Project wave power park, on the Swedish west coast.

In the Lysekil research site, the aim was to investigate the long-term artificial reef effect on mobile mega- and macrofauna by of the ecological foundations (foundations without generator for ecological studies in the Lysekil research site, hereafter also referred to as foundations), including differences between more complex and non-complex foundations. Evaluation of the effects of the incidental no-take zone on the abundance and size of the decapod community on a mid-term scale was another core aspect.

In the Sotenäs Project wave power park, the aim was to investigate the influence of the incidental no-take zone on the abundance, size and burrow density of the economically important and ecologically interesting decapod species *Nephrops norvegicus* and on the abundance of the locally abundant sea pen species *Virgularia mirabilis* and *Pennatula phosphorea*.

An overarching aspect of my thesis work has been environmental monitoring around MRE sites and monitoring of MRE installations. This was conducted both, in an experimental as well as more theoretical approach. The experimental execution was realised using a multifunctional environmental monitoring platform based on sonar systems for ocean energy applications and the more theoretical approach was implemented in reviewing methods and models for MRE monitoring and environmental monitoring.

3. Study area and methods

3.1 The Lysekil project − Uppsala University wave power research

The Lysekil project was started in 2002 by the Division of Electricity at Uppsala University. The main purpose was the development of a robust but effective and sustainable wave power generator. As a result, a heaving point-absorber wave power generator was developed (Figure 2). The research comprises of different fields such as power systems and generators, hydrodynamic modelling, and environmental impact of wave energy parks. The concept of the converter is based on simplicity and consists of only a few moving parts. The buoy at the sea surface is moved by the motion of the waves and has a connection via a line to the direct driven linear generator on the seabed. The absorbed power is transferred to the translator inside the generator where the motion is converted to electricity with the help of the movement of the translator relative to the fixed stator. More detailed information about the Lysekil project can be assessed in [8,66]. During the time period of this study the wave power generators were not connected to wave buoys, no electricity was generated and thus the park can be referred to as inoperative during the study period.

Figure 2. Uppsala University linear Wave Energy Converter (WEC) on foundation, without buoy, onshore before deployment.

Previous research at Uppsala University on wave power, conducted from 2006 to date, resulted in the following doctoral theses produced by the wave energy group of the Division of Electricity:

- Wave Energy Conversion, Linear Synchronous Permanent Magnet Generator, Oskar Danielsson, 2006
- Electric Energy Conversion Systems: Wave Energy and Hydropower, Karin Thorburn, 2006
- Modelling and Experimental Verification of Direct Drive Wave Energy Conversion. Buoy-Generator Dynamics, Mikael Eriksson, 2007
- Energy from Ocean Waves. Full Scale Experimental Verification of a Wave Energy Converter, Rafael Waters, 2008
- Wave energy conversion and the marine environment: Colonization patterns and habitat dynamics, Olivia Langhamer, 2009
- Ocean Wave Energy: Underwater Substation System for Wave Energy Converters, Magnus Rahm, 2010
- Electrical systems for wave energy conversion, Cecilia Boström, 2011
- Hydrodynamic Modelling for a Point Absorbing Wave Energy Converter, Jens Engström, 2011
- Buoy and Generator Interaction with Ocean Waves, Simon Lindroth, 2011
- Experimental measurement of lateral force in a submerged single heaving buoy wave energy converter, Andrej Savin, 2012
- Submerged Transmission in Wave Energy Converters: Full Scale In-Situ Experimental Measurements, Erland Strömstedt, 2012
- Experimental results from the Lysekil wave power research site, Olle Svensson, 2012
- Full scale applications of permanent magnet electromagnetic energy converters, Boel Ekergård, 2013
- Offshore marine substation for grid-connection of wave power farms - An experimental approach, Rickard Ekström, 2014
- Buoy geometry, size and hydrodynamics for power take off device for point absorber linear wave energy converter, Halvar Gravråkmo, 2014
- Underwater radiated noise from point absorbing wave energy converters: Noise characteristics and possible environmental effects, Kalle Haikonen, 2014
- Grid connected three-level converters: studies for wave energy conversion, Remya Krishna, 2014
- Modelling wave power by equivalent circuit theory, Ling Hai, 2015

- Grid connection of permanent magnet generator based renewable energy systems, Senad Apelfröjd, 2016
- Sea Level Compensation System for Wave Energy Converters, Valeria Castellucci, 2016
- Numerical Modelling and Mechanical Studies on a Point Absorber Type Wave Energy Converter, Yue Hong, 2016
- Theoretical and experimental analysis of operational wave energy converters, Erik Lejerskog, 2016
- Numerical Modelling and Statistical Analysis of Ocean Wave Energy Converters and Wave climates, Wei Li, 2016
- Demagnetization and Fault Simulations of Permanent Magnet Generators, Stefan Sjökvist, 2016
- Cooling Strategies for Wave Power Conversion Systems, Antoine Baudoin, 2017
- Multilevel Power Converters with Smart Control for Wave Energy Conversion, Deepak Elamalayil Soman, 2017
- Automated Production Technologies and Measurement Systems for Ferrite Magnetized Linear Generators, Tobias Kamf, 2017
- Wave Loads and Peak Forces on Moored Wave Energy Devices in Tsunamis and Extreme Waves, Linnea Sjökvist, 2017
- Wave Energy Converters: An experimental approach to onshore testing, deployments and offshore monitoring, Liselotte Ulvgård, 2017
- Modelling and advanced control of fully coupled wave energy converters subject to constraints: the wave-to-wire approach, Liguo Wang, 2017
- Robotized Production Methods for Special Electric Machines, Erik Hultman, 2018
- Automation of underwater operations on wave energy converters using remotely operated vehicles, Flore Rémouit, 2018
- Adapting sonar systems for monitoring ocean technologies, Francisco Francisco, 2019
- Offshore deployments of marine energy converters, Maria Angeliki Chatzigiannakou, 2019
- Adaptation of wave power plants to regions with high tides, Mohd Nasir Ayob, 2019
- Grid Integration and Impact of a Wave Power System, Arvind Parwal, 2019
- Wave Power for Desalination, Jennifer Leijon, 2020
- Numerical and experimental modelling for wave energy arrays optimization, Marianna Giassi, 2020

- On the System Optimization of Magnetic Circuit with Alternative Permanent Magnets and its Demagnetization, Jonathan Sjölund, 2021
- In the Air Gap of Linear Generators for Wave Power, Anna Frost, 2021

3.1.1 The Lysekil research site

The Lysekil research site is situated on the west coast of Sweden approximately 5 NM south of the city of Lysekil. A northern (58° 11’ 850’’ N; 11° 22’ 460’’ E) and a southern (58° 11’ 630’’; N 11° 22’ 460’’ E) navigational buoy marks the research area to help prevent interference with boat traffic. The rocky shorelines are covered by algae and the sea floor below the rocky slopes are soft [67]. The water depth is around 25 m with a tidal range of 0.3 m [68]. Water surface temperatures range between 15–20°C in the summer months and 0–2°C in winter, and salinity averages 25 ‰ [69]. The wave climate is considered to be mild with an estimated energy flux of around 5 kW/m [70].

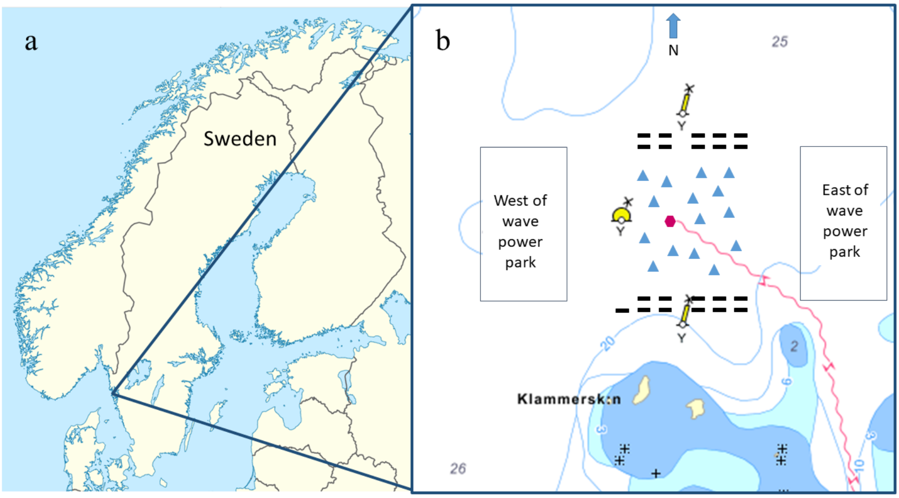

Figure 3. (a) Location of the Lysekil research site on the Swedish west coast. (b) Sea chart of the wave power park, marked with two yellow rod-shaped sea markings. The yellow buoy between the two rod-shaped sea markings indicates the position of the wave-measuring buoy. The red line indicates the position of a sea cable. Blue triangles mark the position of generators, black rectangles mark ecological foundations, and the red hexagon indicates the position of the marine substation. Sampling locations east and west of the wave power park are marked as squares. Numbers indicate water depth and light-yellow areas represent islands. Note: size and position of symbols are not to scale.

In 2006, the first full-scale generator was deployed at the Lysekil research site followed by further generator deployments in the following years [8,66,71]. A total of 21 ecological foundations were deployed at the site in 2007 to conduct studies on environmental impacts (Figure 3). Each foundation is cylindrical, ca. 3 m in diameter, 1 m in height and with a weight of 10 tons (Figure 4). Eleven of the 21 foundations are perforated on the lateral side of the cylinder with 26 rectangular holes measuring 12 cm in width, 15 cm in height and 30 cm in depth (Figure 4). Those reflect the more complex foundations. Half of the holes are situated on the lower edge of the cylinder and the other half are in the upper third.

Figure 4. Two ecological foundations for environmental and ecological studies in the Lysekil research site. The upper ecological foundation includes manufactured holes for increased complexity, and the lower foundation resembles a non-complex foundation.

3.1.2 Environmental studies in the Lysekil project

Environmental studies on possible environmental impacts from the devices on marine organisms were part of the Lysekil project from the beginning to achieve the goal of developing sustainable wave power. For that purpose, accompanying studies were conducted in relationship with the generator research. The focus of past projects included benthic assemblage investigations around the wave power areas, studies of the reef effect from foundations and generators and biofouling assessments on foundations and buoys [72]. In a second project the noise characteristics of the units and its possible effects were studied [73]. The purpose of the third project was the development and use of a sonar system platform for environmental monitoring and monitoring of the MRE device [74].

3.1.3 Study species

In the Lysekil Project, the study focus was on the local mobile fauna associated with the ecological foundations and in the nearby control areas assessed visually during scuba diving inspections. Observed species were primarily decapods, fishes and echinoderms, but polychaetes, bivalves and molluscs were also sporadically observed. Among the most abundant species were the brown crab (*Cancer pagurus*), the cod (*Gadus moruha*), the spiny starfish (*Marthasterias glacialis*) and the common starfish (*Asterias rubens*) A complete species list can be found in Paper I.

The investigation on the abundance and size of the decapod community in and around the wave power park was conducted with two cage models (Paper II). Among the most abundantly caught decapods were the brown crab, the shore crab (*Carcinus maenas*) and the sandy swimming crab (*Liocarcinus depurator*). Other less abundant species were the great spider crab (*Hyas araneus*), common hermit crab (*Pagurus bernhardus*), the hermit crab (*Pagurus pubescens*), a squat lobster species (*Galathea* spp.), and the European lobster (*Homarus gammarus*).

3.1.4 Methods

During my project, two methods were applied in the Lysekil research site. During the four study years 2016–2019 the ecological foundations were sampled in July and August using scuba diving for visual inspections on the ecological foundations (Paper I). All mobile fauna associated with the foundations and within 1 m from the foundations were recorded during visual censuses. The same procedure was applied for a nearby control areas in approximately 10 m distance to the foundations. Species richness, total number of individuals, Shannon-Wiener biodiversity 'H' ($H = \sum [(pi) \times \ln (pi)]$ (pi = abundance of a species/total abundance; ln = natural log)) and Pielou's evenness 'E' ($E = H/HMAX$ (H = Shannon-Wiener Diversity index; HMAX = the highest possible diversity for that sample (calculated by ln (richness)) were calculated for the foundations and controls. Abundances of brown crabs (*Cancer pagurus*) were compared between the complex and the non-complex foundations. Multivariate and univariate analyses were conducted in PRIMER v.7.0. Other analyses were performed with R (Version 3.5.1, R core team 2018) enabled via RStudio (version 1.1.463, Vienna, Austria) [75].

During the same time period, cage fishing for decapods was carried out with two cage models (Figure 5a and b) inside the wave power park, east and west of it along a gradient up to 360 m away from the foundations (Paper II). The cages were baited with half a salted herring before their 24 h deployment. GPS positions of each cage were taken during deployment and the distance to the closest foundation was calculated. The cages were used to assess and compare the abundance and size of the decapod community in and outside the park. All individuals were identified to species, documented and the carapace width of all captured decapods was measured. All individuals were marked with a t-bar anchor to detect possible recaptures. Individuals were returned to respective sampling locations after the procedure. A linear model (R base v 3.5.1, function: "lm") [75] was used to fit the number of decapods and average carapace width per cage as a function of distance to the closest ecological foundation for both cage types independently, either for each year separately, or combined for all years. All analyses were conducted using statistical software R (version 3.5.1, Vienna, Austria), enabled via RStudio (version 1.1.463, Vienna, Austria) [75].

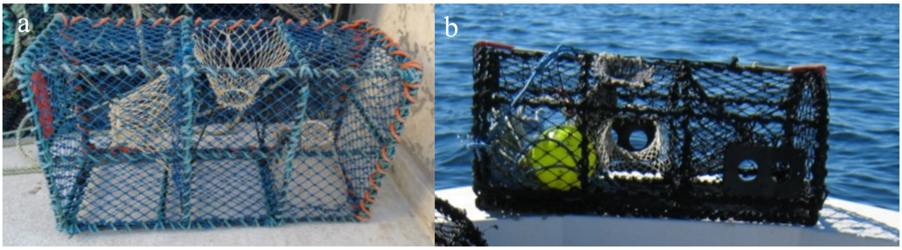

Figure 5. (a) Small cage type, with two entrances one on each long side (white funnel-shaped net); (b) large cage type, with two entrances, one on each long side (white funnel-shaped net). The yellow surface buoy and line are stored in the left chamber of the cage.

3.2 Sotenäs Project wave power park

The Sotenäs Project wave power park is located 5 km offshore the west coast of Sweden, near the municipality of Smögen (Figure 6a). The seafloor at the site is at a depth of around 50 m and the area has a homogenous flat muddy seabed with little relief. Rocky slopes characterize the nearby shore line and the winds and waves come predominantly from the west. The tidal range is ca. 0.3 m [68] and average salinity in the area is approximately 25 ‰ [69]. In 2014 and 2015 a total of 36 gravity-based heaving point-absorber wave power generators were deployed at the site in a circular arrangement in the south eastern corner of the designated park area (Figure 6b) [76]. During the years of the study, 2016−2020, no buoys were connected to the linear generators, thus the wave power park can be referred to as inoperative during the study period.

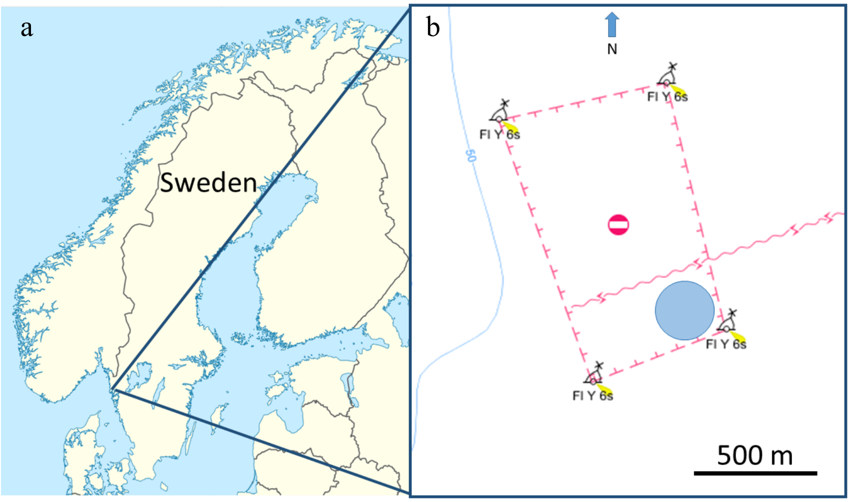

Figure 6. (a) Location of the Sotenäs Project wave power park on the Swedish west coast; (b) Sea chart of the wave power site, marked with four yellow sea marking buoys. Blue circle inside the wave power park indicates the location of the 36 circular arranged gravity based linear generators. The sea cable is represented as the red waved line Note: size and position of symbol are not to scale.

3.2.1 Study species

In the Sotenäs Project wave power park, the study focus was on the economically and ecologically important Norway lobster, *N. norvegicus* (Figure 7) and on two species of sea pens *Pennatula phosphorea* and *Virgularia mirabilis* (Figure 8). All three species are burrowing megafauna inhabiting soft muddy or sandy habitat which is considered of key conservation importance by the OSPAR convention [47,48].

N. norvegicus belongs to the family of Nephropide, occurs at a depth between 20−800 m and requites a specific sediment composition of clay and silt to excavate its burrows (Figure 8). The Norway lobster is territorial and does not migrate far from its burrow after settlement. This behavior can be taken advantage of for investigations on abundances among different areas.

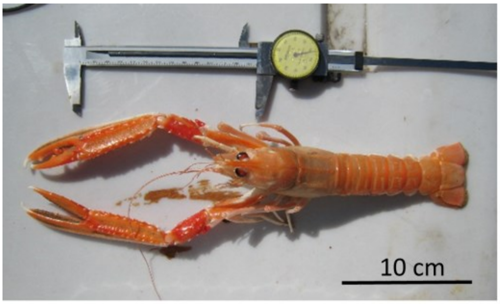

Figure 7. Norway lobster, *Nephrops norvegicus*, during measuring procedure.

Two sea pen species are abundant along the Swedish west coast. *Pennautla phosphorea* can grow up to 40 cm in length (including the peduncle), with only around half of this protruding above the sediment. The axial polyp is firm and fleshy and contains red sclerites, which give it its red colour and also the Latin name (Figure 8). It can retract to some extent into the sediment [77] and has been recorded in sandy or muddy sediments between 15 m and 100 m depth. *Virgularia mirabilis* is a long and slender sea pen, up to 60 cm in length and usually off-white to beige in colour (Figure 8). This species of sea pen has a highly muscular peduncle allowing it to burrow and retract completely into the sediment [78].

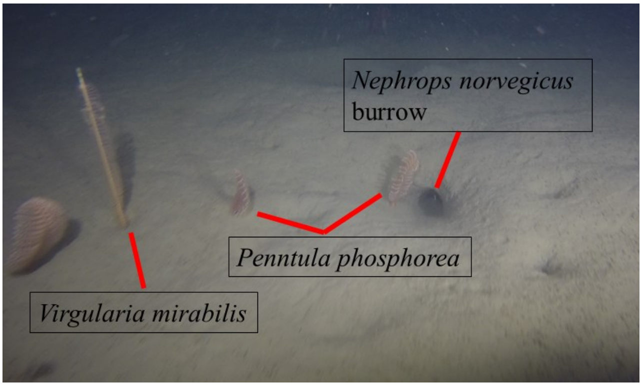

Figure 8. Photograph of a Norway lobster burrow and two sea pen species during the ROV survey 2017. Dark spot at the right site of the picture indicates a Norway lobster burrow. Long, slender beige sea pen is *Virgularia mirabilis*. The three, red, shorter, feather like sea pens are *Pennatula phosphorea*.

3.2.2 Methods

In the Sotenäs Project wave power park, two methods were applied complementary in the same area. Cage fishing for Norway lobster was conducted during the years 2016−2018 and in 2020 using cages for Norway lobster (Figure 5a). Sampling occurred always between late April and late May once a year to ensure comparable seasonal conditions (Paper III, IV and V). Cages were applied in the wave power park, and east and west of it. They were baited with a herring before its 48 h deployment. Captured Norway lobster were measured (carapace length), tagged with a t-bar anchor to identify potential recaptures and after the procedure returned to the respective sampling location. GPS positions were taken and the distance of the cages to the center of the circular arrangement of the gravity-based foundations (hereafter referred to as center of the foundations) were calculated (up to 1230 m). A linear model (R base v 3.5.1, function: "lm") [75] was used to fit the number of Norway lobsters and the average carapace length per cage as a function of distance to the center of the foundations, both for each year separately or combined for all years. All analyses were conducted using statistical software R (version 3.5.1, Vienna, Austria), enabled via RStudio (version 1.1.463, Vienna, Austria) [75].

ROV surveys were conducted complementary during two years, 2016 and 2017, each time between early June and early July (Figure 9). With the help of the ROV, recordings of the seabed inside the wave power park, along with areas east and west of it were conducted. Norway lobster burrows and sea pens were counted for each video section and number per m^2 calculated (Paper III, IV and V). GPS positions were taken and the distance of the video sections to the center of the foundations were calculated. All analyses were conducted using statistical software R (version 3.5.1, Vienna, Austria), enabled via RStudio (version 1.1.463, Vienna, Austria) [75] and PRIMER v.6.0.

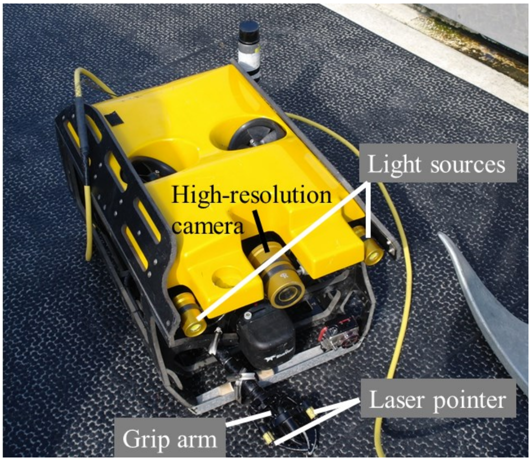

Figure 9. Medium size ROV, attached with grip arm, laser pointer, high-resolution camera and tether.

3.3 Monitoring and environmental monitoring around MRE sites and devices

This section will not focus on specific methods used in the Papers VI-VIII. A sustainable implementation of MRE is a key and therefore a need exists to investigate more about the prerequisites and consequences ocean energy can have on the marine environment. Reliable, cost effective and all-over environmental monitoring frameworks are a necessary support and safeguard for ocean energy operations. The harsh conditions in where MRE devices are often placed reflect a challenge for the monitoring equipment, that need to withstand and survive the marine conditions with fast moving water and high waves beside the ability to manage power to operate instruments and onboard data acquisition systems.

Technological advancements in different instrument classes and the improvement of methodologies have helped the understanding of MRE devices on the marine environment and some of these technologies are also used to monitor and enable maintenance for the devices themselves. Common instruments to observe interactions of MRE devices and marine organisms are passive and active acoustic instruments and optical cameras such as hydrophones, sonars or high-resolution optical cameras, which are often used and combined in multipurpose platforms or packages. However, most of today's multipurpose platforms and instruments are developed for research purposes and additional effort need will be needed to assure the use on a commercial and large scale for future MRE projects.

A paragraph about challenges and the necessity of standardized monitoring methods, the further development and need to mature existing technologies to be able to compare results, process data volumes thereof and finally simplify and speed up consenting processes, where applicable, is discussed in chapter 4.3.

4. Synthesis of main results and discussion

4.1 Artificial reef effect and complexity as a feature to enhance abundance

Artificial reef effect

The foundations in the Lysekil research site act as artificial reefs. Twelve years after deployment the species richness, number of individuals, and Shannon-Wiener biodiversity all increased on and around the foundations compared to that at the control sites (Paper I). Pooled data of the study years (2016−2019) showed significantly larger species richness, number of individuals, and higher biodiversity on the foundation (2016−2019) compared to the first two years after deployment (2007, 2008). The control sites between the two study periods did not differ significantly in species richness, number of individuals, and biodiversity (Figure 10 and Table 1). The evenness decreased significantly from the first to the second study period (Figure 10 and Table 1). No non-native species were found at any time.

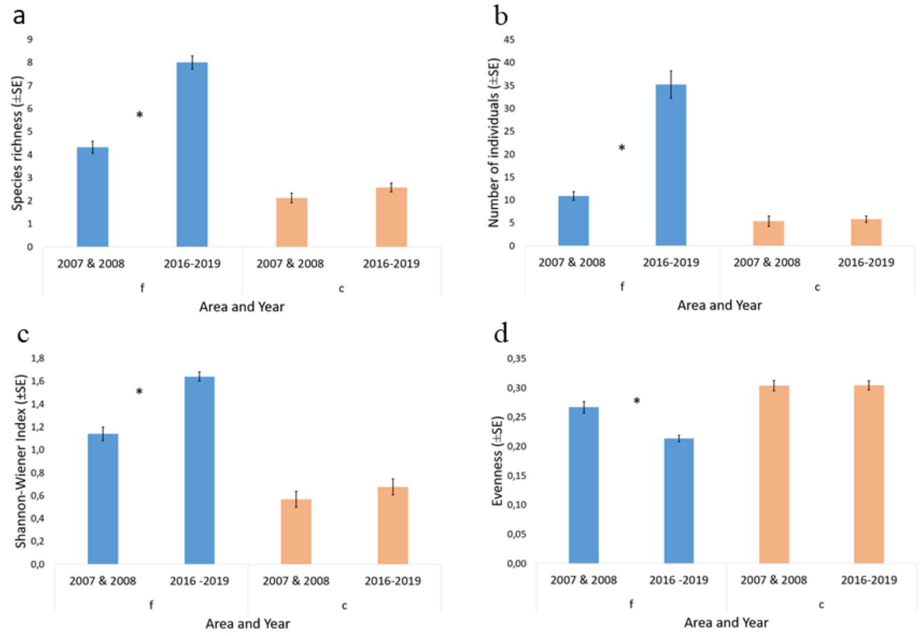

Figure 10. Average (a) Species richness (±SE), (b) Total number of individuals (±SE), (c) Shannon-Wiener biodiversity index (±SE), (d) evenness (±SE) on y-axis, respectively, of pooled data from 2007 and 2008 and 2016–2019 comparing wave power foundations, blue bars, (complex and non-complex foundations combined) and controls, orange bars, of both survey periods on x-axis. * indicates $p < 0.05$.

Table 1. Mann-Whitney U tests (mean value ± standard error (SE) and p-value) for comparison of pooled abundance of species richness, total number of individuals, Shannon-Wiener biodiversity index and evenness between foundations 2007 and 2008 and foundations 2016–2019 and controls 2007 and 2008 and controls 2016–2019.

Mann-Whitney U test	2007 & 2008	2016-2019	
Species richness	Mean ±SE	Mean ±SE	p-value
Foundations	4.33 ± 0.26	8 ± 0.29	< 0.001
Controls	2.13 ± 0.21	2.58 ± 0.2	0.117
Total number of individuals	Mean ±SE	Mean ±SE	p-value
Foundations	10.88 ± 0.97	35.23 ± 2.99	< 0.001
Controls	5.35 ± 1.14	5.82 ± 0.68	0.224
Shannon-Wiener biodiversity index	Mean ±SE	Mean ±SE	p-value
Foundations	1.14 ± 0.06	1.64 ± 0.04	< 0.001
Controls	0.57 ± 0.07	0.68 ± 0.07	0.285
Evenness	Mean ±SE	Mean ±SE	p-value
Foundations	0.27 ± 0.01	0.21 ± 0.01	< 0.001
Controls	0.3 ± 0.01	0.3 ± 0.01	0.851

The larger species richness, number of individuals, and Shannon-Wiener biodiversity on and around the foundations compared to controls can be explained by the additional structures, the foundations, acting as artificial reefs. Those structures provide substrate, shelter, and additional food sources by the epibenthic growth [16,22,30,79–81]. Furthermore, studies comparing communities on artificial reefs with communities on natural reefs or in randomly chosen control areas almost always showed larger density and biomass (e.g., Wilhelmsson et al. (2006) [82]), where vertical artificial structures had a positive effect on fish abundance, which is in accordance with our findings [83]. The sandy seabed areas of the controls reflect a well establish and old habitat compared to the foundations, where high evenness would be expected. Evenness shows higher values for the control sites compared to the foundations, both for the pooled data and individual years. One likely explanation why this is the case is the general low species richness and low number of individuals in the control sites and the way of calculation for evenness. The decrease in evenness on the foundations from the first study period to the second study period can be explained by the occurrence of single individuals in the later years which did not reside on the foundations earlier. In the second sampling period (2016−2019), foundations were populated to a larger extent by echinoderms and crustaceans and general species abundances were larger. Colonisation of newly introduced habitat occurs gradually but is also dependent on installation season [28]. Establishment of less mobile species such as echinoderms and nudibranchs for example requires sufficient food sources, cover of epibenthic communities and appropriate habitat with shelter opportunities to hide from predators [16,30,79,81].

Structural complexity

During all years (2007, 2008 and 2016−2019), but one (2018), the numbers of *Cancer pagurus* were up to three times greater on complex foundations compared to non-complex foundations (Figure 11, Paper I). In 2018 the number of brown crabs were still 1.5 times greater than on non-complex foundations. A three-way crossed multivariate Analysis of similarities (ANOSIM) revealed a significant difference between the complex foundations and non-complex foundations (global R =0.581; $p < 0.0001$) but not between the years (global $R = 0.166$; $p<0.0002$) nor between the geographical position (location of foundations in either northern or southern part of the wave power site (Figure 3b)) in the wave power site (global $R = -0.08$; $p < 0.927$).

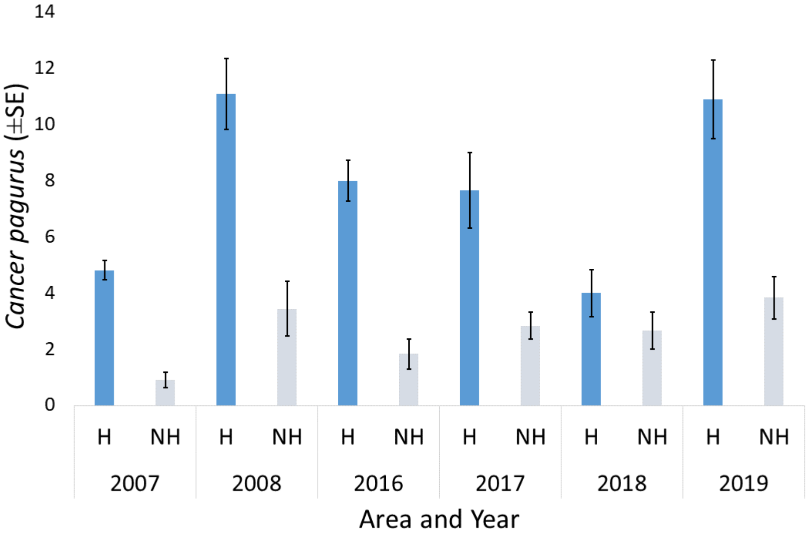

Figure 11. Mean number of *Cancer pagurus* (±SE) on y-axis comparing complex foundations with holes (H) and non-complex foundations with no holes (dark blue bars) and (NH) for all years (light blue bars) on x-axis.

Manufactured holes in the foundations reflect a more complex habitat which brown crabs are attracted to. As an example, shortly after deployment the side holes of the foundations were frequently used by *Cancer pagurus* [30]. During the second period of the investigations (2016−2019), occupancy was still large. The preference of *C. pagurus* for the holes may be due to the holes' shelter function and enhanced protection from predators, as well as due to the rich epibenthic growth on the foundations which provided additional food sources, which has been found to be of crucial importance in other studies [32,84].

4.2 No-take zones / Marine Protected Areas

4.2.1 No-take zone − Lysekil research site

Two cage types were applied to investigate the potential effects of the wave power site as an incidental no-take zone on the decapod community (Paper II). No clear pattern in the number of individuals could be found among the two cage types, results were mainly non-significant, indicating only a small difference in abundance with distance to the foundations.

The results of the decapod abundance for the large cage type are presented in the following section. The number of decapods caught with the large cages was on average 1.7 individuals per cage. Pooled data of all years (2016−2019) showed a decrease, on average, by 0.02 individuals for every additional 100 m away from the ecological foundations (linear model: abundance = -0.0002 * D + 1.69), indicating a statistically non-significant relationship (F (1,170) = 0.06; p = 0.81) (Figure 12). The variation in decapod abundance was large and is also reflected by a low level of explained data variance by the model (r^2 = 0.04%). Linear regression of single years indicated a non-significant relationship between decapod abundance and distance to the ecological foundations (Figure 12 and Table 2). When data were analyzed for each year separately, the number of captured decapods increased every 100 m away from the wave power park by 0.2, 0.1, and 0.01 individuals in 2016, 2017, and 2019, respectively. In 2018, the number of captured decapods decreased every 100 m away from the wave power park by 0.2 individuals. The relationship between decapod abundance and distance to the ecological foundations was non-significant for all years and pooled data of all years.

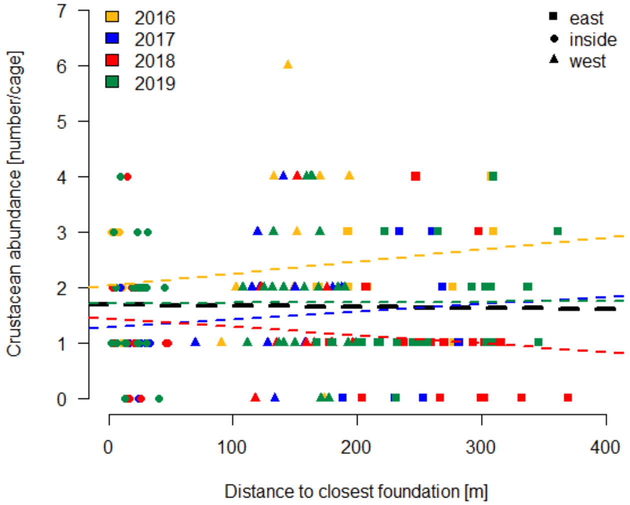

Figure 12. Number of decapod individuals captured with cages in 2016–2019. Black dashed line represents pooled regression line of all years. Fitted values of single years are represented by dashed lines in colors according to years in the legend. Each symbol represents a single cage, with circles, quadrats, and triangles indicating cages positioned inside, to the east, and to the west of the wave park, respectively.

Table 2. Results of the linear models with number of decapods per cage as a function of distance to the closest ecological foundation (= D) for the different year and all years pooled.

Large Cages	Number of cages	F-statistic	r^2	p-value	Linear model
2016	32	0.87	0.03	0.359	0.002 * D + 2.04
2017	36	0.50	0.015	0.482	0.001 * D + 1.29
2018	41	1.01	0.03	0.321	-0.002 * D + 1.45
2019	63	0.01	0.0001	0.931	0.0001 * D + 1.71
Pooled	172	0.06	0.0004	0.81	-0.0002 * D + 1.69

The non-significant results of the decapod abundance on a larger scale (up to 360 m away from the foundations) can have several explanations. With an area of only 0.5 km^2, the wave power park in our study is comparably smaller than most MPAs in Europe, where mean size of MPAs are 55 km^2 [51]. Small MPAs have also been found to be less effective than larger protected areas [49]. Foundations reflect artificial reefs and are known to attract organisms [85–87], however, predators of decapods such as seals and larger fish like cod could also be among the attracted organisms (Paper VIII) which could compensate for a potential increased number of decapods in the wave power park. Furthermore, recreational fishing inside the wave power park, even though undesired, has occurred throughout the study years (personal observation). The coastal habitats on the Swedish west coast are extensively used by recreational fisheries [88] and recreational fisheries have been shown to contribute to mortality of marine mobile fauna and may also have contributed to mortality of decapods [89,90] and thereby compensate eventual increased decapod abundances. The Lysekil research site did not significantly influence the abundance of decapods in the park and up to 360 m around it. The results suggest that the incidental no-take zone plays a limited role as an additional benefit for the decapod community in terms of abundance.

4.2.2 No-take zone – Sotenäs Project wave power park

Sea pens (*Virgularia mirabilis* and *Pennatula phosphorea*)

Sea pens are benthic organisms which can potentially benefit by the incidental no-take areas of wave energy sites and analyses of two species were conducted in the site Sotenäs Project wave power park (Paper III). The investigations on two sea pen species (*Virgularia mirabilis* and *Pennatula phosphorea*) in the Sotenäs Project wave power park with a two-way crossed ANOSIM revealed a significant difference between sites, inside wave power park, east and west of it (global $R = 0.642$; $p = 0.001$) and between years (global $R = 0.576$; $p = 0.001$). Significant differences were found between all pairwise comparisons of the three locations, inside wave power park and control area west ($R=0.602$; $p<0.001$), inside wave power park and control area east ($R=0.842$; $p<0,001$) and between the two control areas ($R=0.49$; $p<0.001$). Abundance of sea pens for year 2016 was largest inside the wave power site as it was for year 2017 (Figure 13). However, the abundances between the years for each site differed for the location west and inside the wave power park.

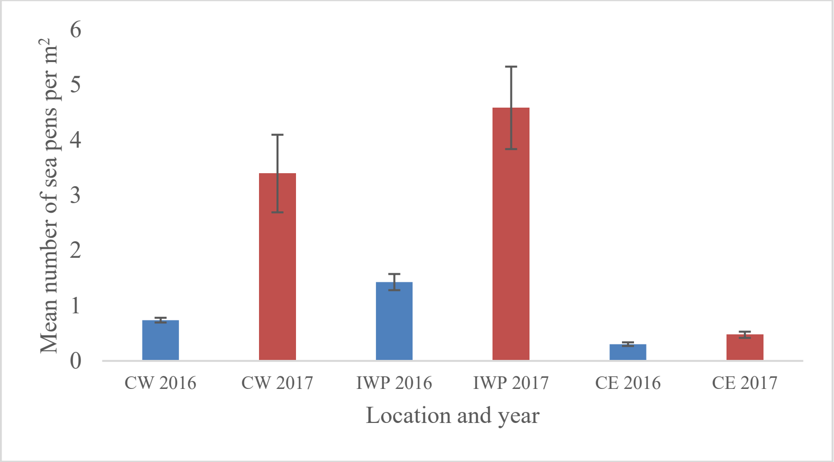

Figure 13. Mean abundance (±SE) per m^2 of the two sea pen species on y-axis for the three locations inside the wave park (IWP), and the two control areas east (CE) and west (CE), and the two years 2016 (blue bars) & 2017 (red bars) on x-axis.

Restriction of marine activities inside MRE sites, such as fishing and boat traffic of designated areas, could be beneficial for benthic organisms [51,58,91]. Slow-growing benthic species such as sea pens can benefit from *de facto* no-take zones of MRE sites especially since damaging fishing methods such as trawling can be destructive to both seabeds and associated organisms. Analyzing both years independently, the abundance of sea pens was always largest inside the wave power park (Figure 13). Although this met the expectations, it does not explain the large differences between the two years for the location inside the park and the control area west. An explanation for the difference in abundance between the years could be the withdrawal behaviour. Both investigated sea pens species, *Virgularia mirabilis* and *Pennatula phosphorea*, are capable of withdrawing into their tubes in the soft bottom [77,78]. However, sea pens closely passed by the ROV did not show this behaviour. Sea pens are slow growing organisms and thus the sudden increase in abundance from one to another year cannot be explained by a recruitment event. Even though sampling locations were chosen to resemble similar conditions, patchiness could occur and the control east may have provided less favourable conditions for sea pens and thereby been inhabited by lower densities compared to the control location west of the wave power park and inside.

Another reason could be an inaccuracy in video analyses due to the higher speed of the ROV in 2017 compared to 2016. Transects were approximately taken in the same location in both years, however, working at a depth of 50 m, the scanned area can be easily shifted by a few meters, also influencing the abundance by scanning a different area and resulting in the discrepancy between the years.

Norway lobster (*Nephrops norvegicus*)

Nephrops norvegicus, is an ecologically relevant and economically important species, which could benefit from no-take restrictions in MRE parks. Potential positive effects on size, abundance and burrow density at the Sotenäs Project wave power park were investigated using cage fishing and ROV seabed surveys (Paper IV and V).

Averaged over all years, max. carapace length of *N. norvegicus* was 6.39 cm and the range was 3.49 – 9.97 cm (Figure 14). Pooled overall years, max. carapace length of individuals decreased by a negligible 0.01 cm with every 100 m distance to the center of the foundations (F (1,328) = 0.38, p = 0.377, Figure 14 and Table 3). Maximum carapace length in 1 km distance to the foundations were, on average 1.2 % smaller than individuals in the park, pooled for all years. Natural variation in *N. norvegicus* carapace length was relatively large and is also reflected by a low level of explained data variance (r^2 = 0.2%) by the model. In 2016 and 2017, *N. norvegicus* max. carapace length decreased significantly, on average, by 0.06 and 0.1 cm, respectively, with every 100 m distance to the foundations (Figure 14 and Table 3). Hence, individuals in 1 km distance to the wave park were, on average, 9 and 10.6 % smaller than conspecifics living inside the wave park in 2016 and 2017, respectively. Yet, distance to the wave park is a relatively weak predictor of change in carapace length as it only explained 18 and 13 % of the variance in 2016 and 2017, respectively. In 2018 and 2020, *N. norvegicus* max. carapace length decreased, on average, by 0.01 cm and increased, on average, by 0.004 cm with every 100 m distance to the foundations (Figure 14 and Table 3). Variation in carapace length was large in 2018 and 2020 and is also reflected by a low level of explained data variance (r^2 = 0.6 % and 0.08 %, respectively) by the model.

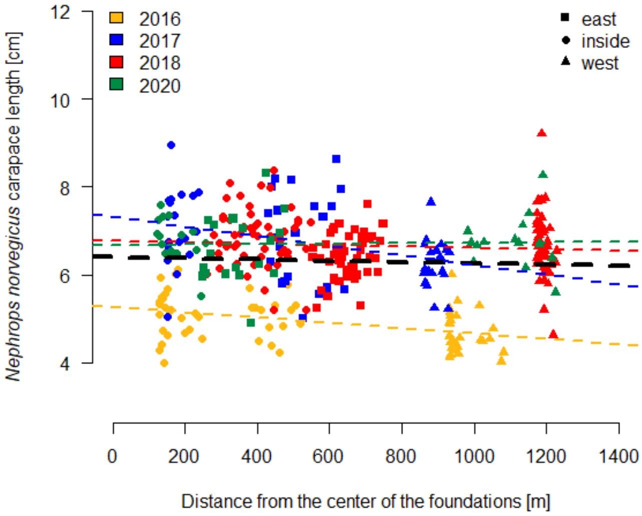

Figure 14. Maximum carapace length of *Nephrops norvegicus* averaged per cage in 2016–2018 and 2020. Black dashed line represents a pooled regression line for all years. Fitted data of single years are represented by dashed lines in colors according to years in the legend. Each symbol represents a single cage, with circles, quadrats, and triangles indicating cages positioned inside, to the east, and to the west of the wave park, respectively.

Table 3. Results of the linear models with carapace length of *Nephrops norvegicus* as a function of distance from the center of the foundations (=D) for all years pooled and each year separate.

Years	Number of cages	F-statistic	r^2	p-value	Linear model
All years	330	0.38	0.002	0.377	-0.0001 * D + 6.4
2016	67	13.83	0.18	0.0004	-0.0006 * D + 5.26
2017	61	8.74	0.13	0.004	-0.001 * D + 7.31
2018	153	0.99	0.006	0.321	-0.0001 * D + 6.76
2020	45	0.037	0.0008	0.849	0.00004 * D + 6.68

The mean number of *N. norvegicus* burrows per m^2 was 8.6, calculated for all years, and the range of burrows between years per m^2 was 2.2–22.7 (Figure 15). The number of N. norvegicus burrows pooled for both years decreased, on average, by 0.7 burrows for every 100 m away from the center of the foundations (Figure 15), illustrating a significant relationship between burrow density and distance from the center of the foundations (Table 4). Number of burrows at 1 km distance from the wave park were, on average, 38.4 % larger than number of burrows inside the wave park, pooled for both years. Yet, distance to the wave park is a relatively weak predictor of change in burrow density as it only explained 11.8 % of the variance (Table 4). In 2016, the change in *N. norvegicus* burrow density showed a negligible negative trend with increasing distance from the center of the foundations (Figure 15) and was statistically non-significant (Table 4). Variation in *N. norvegicus* burrow density was large in 2016 and is also reflected by a low level of explained data variance ($r^2 = 9.6$ %) by the model (Table 4). In 2017, the number of *N. norvegicus* burrows decreased, on average, by one burrow per m^2 with every 100 m distance from the center of the foundations (Figure 15). This trend was statistically significant, yet distance to the wave park is a relatively weak predictor of change in burrow density as it only explained 20.1 % of the variance (Table 4). Variation of distance-dependent change in burrow abundance resulted in 26.1 and 45.2 % more burrows in 2016 and 2017, respectively.

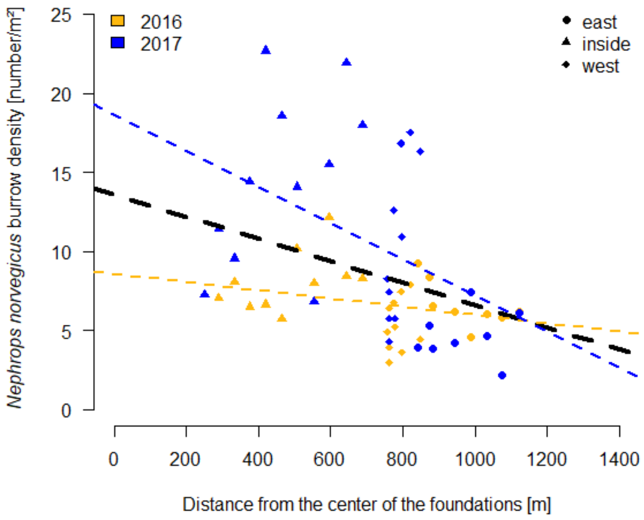

Figure 15. Number of *Nephrops norvegicus* burrows of the year 2016 and 2017. Black dashed line represents pooled regression line of both years. Single years are represented by dashed lines in colors according to years in the legend. Location of video transects are represented by symbols, whereas circles indicate sections of the transects inside the wave power park, quadrats transects east of the wave power park and triangles transects west of the wave power park.

Table 4. Results of the linear models with number of *Nephrops norvegicus* burrows as a function of distance from the center of the foundations (=D).

Year	Number of video sections	F-statistic	r^2	p-value	Linear model
2016 & 2017	58	7.47	0.118	0.008	-0.007 * D + 13.62
2016	29	2.88	0.096	0.102	-0.003 * D + 8.59
2017	29	6.99	0.201	0.013	-0.011 * D + 18.66

While these results are often consistent with expectations, they are somewhat weaker than expected. One explanation for the non-significant results could be the size of the wave power park, that is the size of the incidental no-take zone. The size of an MPA or a no-take zone is one of the key characteristics that contribute to the efficiency and success and larger sizes of the protected areas are known to be more effective [49,92]. A study on benthic species in a small MPA (2.1 km^2) on the eastern coast of Canada indicated a limited influence by the MPA [93]. In an investigation using 58 datasets from marine reserves one key finding was the importance of larger reserve size on the increase of commercial fish species [92]. The biological mechanism behind this size-dependent effect can also be applied for the species in our study. Despite the territorial and stationary behaviour of *N. norvegicus* it is easy to imagine that individuals could move distances of 300 m. This reflects the longest the distance an individual would need to move to reach outside the wave power park and thereby exit the no-take area. This motility could contribute to the weak effect of the number of burrows in 2016.

ORE parks are usually designed and sited with no intent to conserve biodiversity or enhance individuals. However, as incidental no-take zones or MPAs, they still have been shown to protect organisms. In the future, ORE sites will most likely continue growing to secure a sustainable energy supply. This can provide a chance to further investigate the potential of purposeful co-location of MPAs and ORE sites to enhance abundance, biomass density, and biodiversity.

This study highlights especially the need of longer-term investigations, as results of single years could have over- or underestimated the results. The results suggest that the small incidental no-take zone can affect *N. norvegicus* size and burrow density positively. Furthermore, natural interannual variation is an important factor to consider when interpreting the data and designing the study.

4.3 Monitoring around MRE sites and devices

The attention of paper VI-VIII in this thesis is on environmental monitoring and its challenges around MRE sites. Paper VI provides an overview of environmental monitoring methods and technologies that are commonly used to evaluate the impact of wave and tidal power on the marine environment. Mentioned methods include conventional techniques such as fishing with nets and cages or visual survey methods but also unmanned monitoring tools like ROVs and autonomous vehicles (AUV) or mathematical and numerical models as a complementary cost-effective tool. Paper VII reflects a case study on the deployment, monitoring and maintenance of the WEC type developed by Uppsala University. It compares three different methods used for underwater operations on the WECs: the first uses divers only, the second is a combination of divers and ROVs conducted procedures, and the last one is a fully ROV assisted method. Paper VIII focused on the observation of fishes, seals and larger marine mammals at the Lysekil research site, using a multibeam sonar system integrated to a standalone monitoring platform.

The focus of this section will highlight the necessity of standardized monitoring methods and the further development and need to mature existing technologies to be able to compare results, process data volumes and help to facilitate further MRE deployments.

Each wave power park location and its associated organisms are unique and extensive monitoring programs are often necessary to fulfil the consenting requirements and many environmental studies are conducted with only this purpose. Furthermore, monitoring during deployment and maintenance often reflects a challenge, both financially and in the practical realization. Several challenges must be met to enable monitoring in dynamic marine environments with high energy waters, where harvesting of wave and tidal energy is usually conducted on the one hand, but also to fit the target of interest. This is the case for environmental monitoring aiming to detect short- or long-term effects on the ecosystem but also for monitoring during deployment and maintenance phases or even to detect failures of devices.

Monitoring of MRE devices either as part of maintenance routines, or in case of failure, comes along with high costs including vessel charter, equipment costs and personnel salaries. Where applicable, the method of using divers implies additional high risks and danger to life [94]. In the offshore wind sector robotics such as ROVs are regularly used for monitoring and for inspection purposes [94]. Those vehicles can be used for many applications such as inspections (valve position and gauge reading), monitoring (check for leakage, surface conditions, acoustic anomalies), maintenance (cleaning or sampling), and heavier operations, such as drilling, welding, or cutting [95]. However, in the wave energy sector, partly due to the diversity of device types, the use of underwater robots is still limited [94].

The overriding question in environmental monitoring, if an observed effect is positive or negative, is dependent on scale and context. To answer this question, however, scale and context need to be defined first. Sonars for monitoring can be a helpful tool and in the last decade several attempts have been made to develop a platform with integrated sonar technique [74,96]. Sonars have been used for species monitoring but also to monitor the physical environment and have been used for site selection [97–100]. Major challenges are still the deployment in high energetic waters, data handling and processing, biofouling and power supply [62,74,101].

Many questions still exist regarding the environmental effects surrounding this relatively young technology and long-term investigations are scarce [11]. However, the extent of the monitoring can be reduced by understanding the relevant changes that are site specific from what can be learned by following previous deployments. The nature of the effects caused by marine energy converters will be similar for devices that have similar components, and the understanding of these effects can be transferred from one project to another. The key is to understand exactly how a device is interacting with the environment – the stressor, what the disturbance is, and then this can be applied to each location with its specific receptors such as species and habitats. This approach would help define what type of monitoring needs to be undertaken to quantify the relevant and quantifiable changes, and therefore understand the impacts on marine organisms or habitats from MRE [65]. One instrument or method alone cannot provide all the answers. Rather, a suite of methods, instruments, and study designs must be employed to come closer to capture a more complete picture of how MRE devices interact with their environment.

5. Conclusions

During the time period of the studies for my PhD project, the focus was on the investigation of mobile fauna, with a particular focus on decapods in and around MRE sites from a local scale within meters to a broader scale up to 1230 m.

In conclusion, compared to surrounding soft sea floors, offshore renewable energy foundations in cold temperate regions can locally enhance the biodiversity, abundance of specific reef species and total number of individuals with a successional increase over time. Thus, the provision of ecosystem services such as goods and benefits humans derive from nature as production of food, materials and energy might be positively affected [28]. A focus should be given to the improvement of complexity of the different renewable offshore foundations to widen the spectrum for species colonisation. A further increase in structural complexity such as different sizes and depth of holes in the foundations but also channels and corridors for individuals to pass through and possibilities for escape could be implemented to increase the benefit for various species and sizes of individuals.

The results of the studies of the incidental no-take zone imply that the restricted area can play a role as an additional benefit for the decapod community in terms of abundance and size but may be dependent on species and area. For the Lysekil research site our study generally revealed no significant differences in abundance and size of decapods in and around the park, more than 15 years after the wave power park construction. For the Sotenäs project wave power site our results suggest that the small incidental no-take zone can affect *N. norvegicus* size and burrow density positively. The use of ROVs for the sea bed monitoring of sea pens and Norway lobster burrows is a suitable method. However, abundances can be biased by quality of recordings, habitat patchiness, specific species behaviours such as withdrawal behaviour of sea pens, fishing pressure and violation of fishing ban in designated areas. Year to year and natural variation may have a large influence and need to be considered in the monitoring and temporal set up.

In summary, wave power foundations can influence abundance of marine organisms on a very local scale (meters). With the methods in this study, the investigations did not reveal strong effects on the abundance and size of decapods on a larger scale up to 1230 m away from foundations. However, a focus should be put on a further development of environmental monitoring routines around MRE sites and their evaluation.

6. Limitations & Future work

This chapter covers limitations of the studies and suggests future directions and developments of the work.

The investigations have been conducted at inoperative wave power parks. Both wave power sites, the Sotenäs Project wave power park, as well as the Lysekil research site, have been to the vast majority without buoys connected neither to the generators nor to the ecological foundations and can thus be referred to as inoperative. For an all-embracing investigation, a fully operating wave power park would be beneficial. However, the focus of the investigation of the studies was on characteristics such as artificial reef effects and effects from incidental no-take zones, which were not directly hindered by the absence of the buoys during the investigations.

Ecological field studies always reflect a compromise between the ideal number of samples, sampling years and the possibility within the limitations regarding financial, temporal and personnel resources.

Furthermore, each individual sampling method has limitations. The chosen methods for each study such as scuba diving, fishing with cages or the use of ROVs have known limitations. All these methods are, however, regularly used in marine ecological and monitoring studies and are therefore considered a suitable investigation tool.

The work of this thesis could be continued in the following directions:

- Studies in fully operative wave power parks
- Temporal continuation of the studies including investigations during night, rough weather conditions and all seasons
- Extension of sampling events, spatial and temporal

7. Summary of papers

This chapter summarizes the content of the eight papers (Table 5) on which this thesis is based on and describes the author's contribution to each paper.

Table 5. Schematic overview of the individual studies (spatial and thematically) comprising this thesis. Artificial reef effects in the site Lysekil (Paper I), effects of the incidental no-take zone in the Lysekil research site (Paper II), effect of the no-take zone in the Sotenäs Project wave power park (Paper III, IV and V). Studies with the broader focus on (environmental) monitoring around marine renewable energy (VI-VIII).

	Lysekil	**Sotenäs**
Artificial reef effect	I	
No-take Zone / Marine Protected Area	II	III, IV, V
(Environmental) Monitoring	VI, VII, VIII	

Paper I

Colonisation of wave power foundations by mobile mega- and macrofauna – a 12 year study

This paper presents a follow up study after 12 years on environmental impacts from wave energy generators at the wave power park Lysekil research site. The focus is on the artificial reef effect from the ecological foundations (foundations without generator for ecological studies) and the difference between the two different complexity types of foundations on the local mobile mega- and macrofauna community.

The author took part in the planning, preparation and execution of the experiment, analyzed the experimental data and wrote the paper.

Published in Marine Environmental Research, 161, 105053, 2020. doi.org/10.1016/j.marenvres.2020.105053

Paper II

Effects of a wave power park with no-take zone on decapod abundance and size

The work of paper II contains the investigation of the effects of an incidental no-take zone of the wave power park Lysekil research site on the size and abundance of the local decapods. With the use of two cage types the size and abundance of decapods were analysed inside the wave power park and up to 360 m east and west of it.

The author took part in the planning, preparation and execution of the experiment, analyzed the experimental data and wrote the paper.

Published in the Journal of Marine Science and Engineering, 2021, 9, 864. doi.org/10.3390/jmse9080864

Paper III

Effects from wave power generators on the distribution of two sea pen species on the Swedish west coast

This paper presents the investigation of the effects of an incidental no-take zone of a wave power park on the Swedish west coast on two sea pen species. A ROV was used to record the seabed inside and outside the wave power park. The abundance of the two sea pen species between the different areas was analysed.

The author took part in the planning, preparation and execution of the experiment, analyzed the experimental data and wrote the paper.

Presented by the author at the 13th European Wave and Tidal Energy Conference in Naples, Italy, EWTEC 2019 and published in the conference proceedings.

Paper IV

Effects of distance from a wave power park with no-take zone on *Nephrops norvegicus* abundance, size and burrow density

Paper IV investigates the effects of an incidental no-take zone of a wave power park on the size and abundance of the economically and ecologically important species *Nephrops norvegicus*. Two methods, the use of a remote operating vehicle (ROV) and cage fishing were applied complementary to investigate the effects on size and abundance inside the wave power park and up to 1230 m away from it.

The author took part in the planning, preparation and execution of the experiment, analyzed the experimental data and wrote the paper.

Manuscript

Paper V

Effects of Wave Energy Generators on *Nephrops norvegicus*

Paper VIII investigates the effects of an incidental no-take zone of a wave power park on the burrow density of the economically and ecologically important species *Nephrops norvegicus*. With the help of a remote operating vehicle (ROV) seabed survey were conducted to evaluate the *Nephrops norvegicus* burrow density inside the wave power park and adjacent control areas. This study can be seen as a preliminary assessment for parts of the content in Paper IV.

The author took part in the planning, preparation and execution of the experiment, analyzed the experimental data and wrote the paper.

Presented by the author at the 4th Asian Wave and Tidal Energy Conference in Taipei, Taiwan, AWTEC 2018 and published in the conference proceedings.

Paper VI

A review of Monitoring Methods and Models for Environmental Monitoring of Marine Renewable Energy

This paper provides an overview of the state of the art of environmental monitoring methods and technologies that are commonly used to evaluate the impact of wave and tidal power on the marine environment.

The author contribution was the overall conception of the manuscript and the main writing of chapter I, II and V.

Presented by the author at the 12th European Wave and Tidal Energy Conference in Cork, Ireland, EWTEC 2017 and published in the conference proceedings.

Paper VII

Deployment and Maintenance of Wave Energy Converters at the Lysekil Research Site: A Comparative Study on the Use of Divers and Remotely-Operated Vehicles

This paper is a case study on the deployment and maintenance of the WECs developed by Uppsala University. The goal of the paper was to propose solutions in order to gradually automate the deployment and maintenance of the WECs. It compares three different methods used for underwater operations on the devices: one uses divers only, the second is a combination of divers- and ROVs-conducted procedures, and the last one is a fully ROV-assisted method. Moreover, a comparison of the cost efficiency of renting and of buying an ROV is presented.

The author contributed in writing and rewriting the paper and had a specific responsibility for the information on the diving work.

Published in the Journal of Marine Science and Engineering 2018, 6, 39; doi.org/10.3390/jmse6020039

Paper VIII

Use of Multibeam Imaging Sonar for Observation of Marine Mammals and Fish on a Marine Renewable Energy Site

This study focused to observe the occurrence of fish, seals and larger marine mammals at the Lysekil research site, using a multibeam sonar system integrated to a standalone monitoring platform.

The author took part in the practical part of the experiment, in rewriting and editing of the paper.

Submitted to PLOS ONE

8. Swedish summary – Svensk sammanfattning

Den globala efterfrågan på elektricitet har ökat kontinuerligt under de senaste årtiondena. Prognoser visar att ökningen kommer att fortsätta, bland annat genom utveckling av ny elberoendeteknik som processteknik eller allmänt framskridande industrialisering. Samtidigt är medvetenheten om klimatförändringar och behovet av att vidta åtgärder för att bromsa dessa ett utbrett ämne i samhället och politiken. Marin teknik kan bidra till en förnybar elproduktion, men utbyggnaden av marina energiparker kan skapa konflikter, såsom konkurrens om utrymme i en redan pressad marin miljö. Därför bör miljökompatibiliteten för dessa relativt nya tekniker säkerställas, inklusive miljöövervakning, under dess utveckling.

Det senaste decenniet har utvecklingen av förnybar marin energiproduktion gått snabbt. Vågkraft är en av de förnybara källorna som har potential att bidra till en hållbar elproduktion, men även förnybar energiutvinning kan påverka miljön på flera sätt. För att uppnå en hållbar energiproduktion behöver därför deras möjliga miljöeffekter utredas. Förutom eventuella negativa effekter på livsmiljöer eller organismer, t. ex. habitatförlust, kollisionsrisker, elektromagnetiska fält och buller, har tidigare studier även visat på positiva effekter i termer av ökad biologisk mångfald och individers större storlek kring energiparker, som följd av att nya habitat skapas av enheternas fundament och från uteslutning av fiske i t. ex. utsedda energiparkområden.

Den här avhandlingen visar på resultat från flera års studier av miljöeffekterna från punktabsorbatorer, en typ av vågkraftgeneratorer som är utvecklad vid Uppsala universitet. Punktabsorbator består av en flytande boj som är kopplad till en linjär elgenerator på havsbotten. Dessa finns utplacerade på den svenska västkusten vid de två vågkraftprojekten ”Lysekilprojektet” och ”Sotenäsprojektet”. Avhandlingen omfattar undersökningar av långtidseffekter av konstgjorda rev, uppkomna av vågkraftsfundamenten, på en lokal mobil mega- och makrofauna genom visuella undersökningar under dykningar i Lysekilområden. Förutom det, studerades effekterna av fiskeförbud i områden med flera arter kräftdjur (decapoda) genom burfiske. I Sotenäsområden undersöktes särskilt havskräftor (*Nephrops norvegicus*) samt två arter av sjöpennor genom burfiske och havsbottenundersökningar med hjälp av ROV (fjärrstyrd undervattensfarkost).

Resultaten av visuella undersökningar från ”Lysekilprojektet” visar att antalet individer och mångfalden av mobil mega- och makrofauna kunde förbättras lokalt på och runt vågkraftsfundamenten, jämfört med kontrollområden. I större skala, längre bort från fundamenten, visar resultaten från burfiske att skillnader i antal och storlek av tiofotade kräftdjur inte var signifikant i jämförelse mellan vågkraftsparken och ett avstånd om 360 m utanför parken. Vid vågkraftprojektet i Sotenäs såg vi en positiv effekt på havskräftors storlek och densiteten av bohålor, men inte på individtätheten, parkområdet i jämförelse med avstånd upp till 1230 m därifrån. Antalet sjöpennor var högre inne i vågkraftsparkensområdet än utanför, men den årliga variationen var stor.

Sammanfattningsvis fann vi att vågkraftsfundament kan öka antalet och mångfalden av marina organismer runt vågkraftsfundament, men inom en mycket lokal skala (meter). Däremot kunde vi inte, med metoderna i denna avhandling, finna några starka effekter på förekomsten och storleken av dekapoder inom en större skala, upp till 1230 m från fundament, trots fiskeförbud. En anledning till de svaga positiva effekterna kan vara vågkraftparkens ringa storlek men också den naturliga variationen i antal individer mellan åren.

Ett möjligt mål för framtida studier är att bidra med kunskap om hur man bäst kan förstärka den positiva artificiella reveffekten, och därmed öka komplexiteten på fundamenten, och uppnå ett bredare spektrum av artkoloniseringen. En ytterligare ökning av strukturell komplexitet av konstgjorda rev, såsom olika storlekar och djup av hål i fundamenten, men även kanaler och korridorer som möjliggör för individer att passera och möjligheter till flykt, skulle kunna implementeras för att gynna olika arter och storlekar av individer.

Det är också viktig att vidareutveckla befintliga rutiner, tekniker och metoder för miljöövervakning och utvärdering av marina energianläggningar. Studier och teknisk produktutveckling vi utfört visar att det går att möjliggöra detta genom teknikanpassningar och därmed underlätta för framtida hållbara förnybara offshoreprojekt där potentiella effekter på miljön minimeras.

9. German summary – Deutsche Zusammenfassung

Der weltweite Strombedarf ist in den vergangenen Jahren kontinuierlich gestiegen und Prognosen gehen von einem weiteren Anstieg in der Zukunft aus. Die Entwicklung neuer stromverbrauchender Technologien, wie Verfahrenstechnik und die fortschreitende Industrialisierung, tragen zum steigenden Strombedarf bei. Gleichzeitig ist das Bewusstsein für den Klimawandel und der damit verbundene Handlungsbedarf ein weit verbreitetes Thema in Gesellschaft und Politik. Erneuerbare marine Technologien können zu einer nachhaltigen Energieerzeugung beitragen, gleichzeitig kann dessen Ausbau auch Konflikte herbeiführen. Konkurrenz um Platz in einer bereits stark genutzten Meeresumwelt und die Umweltverträglichkeit dieser relativ neuen Technologie sind nur zwei von potenziellen Konfliktthemen.

Erneuerbare Meerestechnologien haben sich in den letzten Jahren rasant entwickelt. Wellenkraft ist eine davon und hat das Potenzial einen relevanten Beitrag zu der erneuerbaren Stromerzeugung zu leisten. Nicht nur die konventionelle Energiegewinnung, sondern auch die Gewinnung erneuerbarer Energie kann sich negativ auf die Umwelt auswirken. Eine wirkliche nachhaltige Energieerzeugung umfasst die Untersuchung von Umweltauswirkungen und die damit verbundenen Risiken dieser Technologien auf Lebensräume oder Organismen. Potenzielle Risiken können Kollisionen von marinen Säugern mit den Anlagen, elektromagnetische Felder oder Lärm sein. Bereits durchgeführte Studien haben aber auch Vorteile für die Biodiversität, Größe von Individuen und deren Abundanz rund um einige erneuerbare Meerestechnologien festgestellt. Die positiven Effekte können zum Beispiel durch die Schaffung von Lebensräumen durch die Fundamente der Anlagen und durch den Ausschluss der Fischerei in den ausgewiesenen marinen Parkbereichen kommen.

Diese Dissertation befasst sich mit den Umweltauswirkungen von Wellenkraftanlagen. Die untersuchten Wellengeneratoren bestehen aus einem linearen Generator, welcher an der Universität Uppsala entwickelt wurde. Über einen Zeitraum von vier Jahren wurden Untersuchungen mit dem Ziel potenzielle Riffeffekte von Wellenkraftfundamenten auf die lokale Mobil-, Mega- und Makrofauna an der schwedischen Westküste am Forschungsstandort Lysekil und im Wellenkraftwerkspark des Sotenäs-Projekts durchgeführt. Zu diesem Zweck wurden verschiedene Methoden wie visuelle Bestandsaufnahmen von Arten und Individuenanzahlen mittels Gerätetauchen angewandt. Zum anderen wurden die Auswirkungen der unbeabsichtigten Fangverbotszonen auf Dekapoden und zwei Seefederarten untersucht, indem Käfige zum Fangen der Dekapoden und Meeresbodenuntersuchungen mit Unterwasserrobotern (ROV) durchgeführt wurden.

Am Forschungsstandort Lysekil konnte eine Erhöhung der lokalen Diversität und Abundanz der mobilen Mega- und Makrofauna um die Wellenkraftfundamente im Vergleich zu Kontrollgebieten nachgewiesen werden. Häufigkeit und Größe von Dekapoden unterschied sich innerhalb des Wellenkraftwerks und bis zu einer Entfernung von 360 m außerhalb allerdings nicht signifikant. Im Wellenkraftpark des Sotenäs-Projekts wurde auf einer Entfernung von bis zu 1230 m ein positiver Effekt auf die Größe von Individuen und die Dichte der charakteristischen Bauten von *Nephrops norvegicus* festgestellt, jedoch nicht auf deren Häufigkeit. Die Abundanz an Seefedern war im Wellenkraftpark im Vergleich zu Gebieten außerhalb leicht höher. Natürliche Schwankungen in der Abundanz zwischen den Jahren waren jedoch stark ausgeprägt.

Zusammenfassend lässt sich sagen, dass Wellenkraftwerke die Häufigkeit und Vielfalt von Meeresorganismen in der Nähe der Fundamente auf sehr lokaler Ebene (innerhalb von Metern) beeinflussen können. Mit den angewendeten Methoden dieser Studie zeigten die Untersuchungen in größerem Maßstab bis zu 1230 m Entfernung von den Fundamenten keine starken Auswirkungen auf die Häufigkeit und Größe von Dekapoden als Folge der Fangverbotszone innerhalb des Wellenkaftparkes.

In Zukunft könnte ein Schwerpunkt auf der Verbesserung der Komplexität der Fundamente liegen, um das Spektrum für die Artenbesiedlung zu erweitern. Eine weitere Komplexitätserhöhung wie zum Beispiel das Einbauen unterschiedlich großer Löcher und Höhlen in den Fundamenten, aber auch Kanäle und Korridore für den Durchgang von Individuen und damit Fluchtmöglichkeiten könnten den Nutzen für verschiedene Arten und Größen von Individuen erhöhen.

Generell ist es jedoch wichtig, Routinen und Methoden der Umweltüberwachung rund um marine erneuerbare Energiestandorte weiterzuentwickeln und deren Bewertung zu standardisieren um zukünftige neue Projekte an geeigneten Stellen zu fördern, deren Bau zu beschleunigen und mögliche Auswirkungen auf die Umwelt trotzdem nicht zu unterschätzen.

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