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Wave energy conversion and the marine environment

Colonization patterns and habitat dynamics

OLIVIA LANGHAMER

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Abstract
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A wave energy park has been established on the Swedish west coast outside Lysekil and pioneer work about its interactions with the marine environment has been conducted. So far, little is known about the effects of offshore energy installations on the marine environment, and this thesis assists in minimizing environmental risks as well as in enhancing potential positive effects on the marine environment. The Lysekil research site is situated about two kilometres offshore and has been under development since 2005. During this time 26 "environmental devices", without generators, consisting of a steel buoy attached via a wire to a foundation on 25 m depth have been placed out for ecological studies on macrofauna in surrounding sediments and on colonization of the foundations and the buoys. Sediment samples to examine macrofauna in the seabed have been taken during five seasons. Biomass, abundance and diversity of infauna in the test site were generally low, but higher than in a nearby control site. The species composition was typical for the area and depth.

In addition to sediment analysis, the effect of wave power concrete foundations on the marine environment has been investigated by scuba diving. The surface orientation and its effect on colonization by sessile organisms was examined on the first five foundations, placed out in 2005, and observations of habitat use by fish and crustaceans were made. The results show a succession of colonization over time (three years of investigation) with a higher cover by sessile organisms on vertical surfaces. Mobile fauna abundance on and around the foundations was generally low.

Three months after the deployment of the 21 new foundations in 2007, assemblages of mobile organisms were examined visually. Also here, mobile species exhibit a low density, but still higher than on surrounding soft bottoms. The edible crab used artificial holes in the foundations frequently. The foundations were placed in two different clusters, north and south, and the degree to which early recruits covered the foundations and the succession of epibenthic communities were documented during two years. Sessile organisms colonized the northern foundations more rapidly, producing a higher diversity which suggests that the placement of wave energy devices affects colonization patterns.

Biofouling on buoys was examined and blue mussels, *Mytilus edulis*, dominated with a cover about 90%. Wave exposed buoys were particularly favoured by *M. edulis* which there had a higher biomass and larger shells compared to those on sheltered buoys. Biofouling on wave power buoys, independent whether these had a cylindrical or toroidal shape, was insufficient to markedly affect their energy production.

Finally, the thesis incorporates a review describing wave power projects in general pointing out the need of future research on for instance no-take zones, marine bioacoustics and electromagnetic fields. The main conclusions are that large-scale renewable wave energy conversion will cause ecological impact primarily by adding new hard substrate to an area but not by harming organisms or decreasing biodiversity within wave power parks.

Keywords: artificial reefs, benthos, biodiversity, biofouling, colonization, environmental impact, fish, shellfish, Mytilus edulis, renewable energy, wave power

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To my family
...and to a bright future, I hope

List of Papers

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

I Leijon, M., Boström, C., Danielsson, O., Gustafsson, S., Haikonen K, Langhamer O, Strömstedt E, Stålberg M, Sundberg, J., Svensson, O., Tyrberg, S., Waters, R. (2008) Wave Energy from the North Sea: Experiences from the Lysekil Research Site. *Surveys in Geophysics*, 29(3): 221-240.

II Langhamer, O. Effect of wave energy converters on macrofaunal species abundance in surrounding soft-bottoms (submitted manuscript)

III Langhamer, O., Wilhelmsson, D., Engström, J. (2009) Artificial reef effect and fouling impacts on offshore wave power foundations and boys – a pilot study. *Estuarine, Coastal and Shelf Science*, 82(3): 426-432

IV Langhamer, O., Wilhelmsson, D. (2009) Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes - a field experiment. *Marine Environmental Research*, 68(4): 151-157

V Langhamer, O The location of offshore wave power devices structures epifaunal assemblages (manuscript)

VI Langhamer, O. (2009) Colonization of blue mussels (*Mytilus edulis*) on offshore wave power installations on the Swedish west coast. Accepted for publication in Columbus, F. (editor) *Biofouling: Types, Impact and Anti-Fouling.* Nova Science Publishers, NY, invited

VII Langhamer, O., Haikonen, K., Sundberg, J. Wave power – sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters. (submitted manuscript)

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The author has also contributed to the following reviewed conference papers not included in the thesis. These papers are partially within the scope of this thesis and basically a summary of the above listed papers.

A) Sundberg, J., Langhamer, O. “Environmental questions related to point-absorbing linear wave-generators: impacts, effects and fouling” , Proceedings of the 6th European Wave and Tidal Energy Conference, August 28 - September 3, 2005, Glasgow, Scotland

B) Langhamer, O., Wilhelmsson, D. "Wave power devices as artificial reefs", Proceedings of the 7th European Wave and Tidal Energy Conference, September 11-13, 2007, Porto, Portugal

C) Tyrberg, S., Stålberg, M., Boström, C., Waters, R., Svensson, O., Strömstedt, E., Savin, A., Engström, J., Langhamer, O., Gravråkmo, H., Haikonen, K., Tedelid, J., Sundberg, J., Leijon, M. "The Lysekil Wave Power Project: Status Update", WREC X, July 21-25, 2008, Glasgow, Scottland

D) Langhamer, O., Wilhelmsson, D., Engström,,J. "Development of Invertebrate Assemblages and Fish on Offshore Wave Power", Proceedings of the 28th International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2009), May 31-June 5, 2009, Honolulu, Hawaii

E) Andersen, K., Chapman, A., Hareide, N.R., Folkestad, A.O., Sparrevik, E., Langhamer, O. “Environmental Monitoring at the Maren Wave Power Test Site off the Island of Runde, Western Norway: Planning and Design” Proceedings of the 8th European Wave and Tidal Energy Conference, September 7-10, 2009, Uppsala, Sweden

The author also contributed to following popular publications:

- Wilhelmsson, D., Langhamer, O. “Nya energikällor skapar nya livsmiljöer” HavsUtsikt, Issue 2/2009 (in Swedish)

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“If it seems like you
are playing around
and not practicing,
that's when you
know you really love
it.”

Jack Johnson

Introduction

In 2007 the UN climate panel reported that during the last hundred years there has been a serious climate change due to anthropogenic emissions of greenhouse gases, especially carbon dioxide (IPCC 2007). This change clearly depends on the global energy production that is mostly based on limited and ecologically harmful fossil fuel resources such as oil, gas and coal. If these emissions increase at the same pace, concentrations of carbon dioxide during the coming century are going to rise against 1000 ppm so that the effect of global warming will be even stronger. Rising temperatures, rising sea levels and increasing misery – the earth's climate is about to change. The last time this happened, 251 million years ago, almost 90% of all life on earth was wiped out (the Permian-Triassic extinction event or the "Great Dying"). That was the closest our planet has ever been to turn into a lifeless stone. Consequently, it is necessary to explore alternative and sustainable energy sources.

Oceans cover more than 70% of the earth's surface and hold a large amount of energy. Wave power is an unused energy source with high potential. Research in the area of energy conversion from waves is amongst others conducted at the Swedish Centre for Electric Energy Conversion (CFE) at Uppsala University. Two challenges need to find their solutions before we can capture the vast amount of energy in the oceans: engineering and the environment. Solutions on wave energy production in the future have to be practical, economic, safe and environmentally friendly. Work has started at different places around the world, mostly by entrepreneurs and researchers. It is important to consider interactions between the environment and wave power installations. This is a process that takes time, but as time passes by we get closer to useful applications for future conservational work.

Wave power

Uneven heating of the earth by the sun produces winds blowing from high to low pressure zones, thereby creating sea surface waves. Energy density raises from sunlight to waves, where ocean waves transport energy over long distances with minor losses. Some waves can travel thousand of kilometres before reaching a shore. Waves start to loose energy when the water depth decreases below one half wave length, and energy finally turns into heat through

breaking waves and friction against the seabed. Harnessing wave energy for electricity generation makes wave power an interesting renewable energy source. In general, large waves are more powerful, and anyone who has experienced such waves, understands the higher density of energy that can be extracted from waves than from wind or solar energy. The global energy potential in waves has been estimated to be around 1 TW, mostly concentrated in offshore locations (Fig.1) (Falnes & Løvseth 1991). Along the Swedish coast, predominantly smaller waves contribute to a milder wave climate with an annual average wave power density of only about 5.2 kW/m on the west coast and during 10% it gets above 13.5 kW/m (Waters et al. 2009).

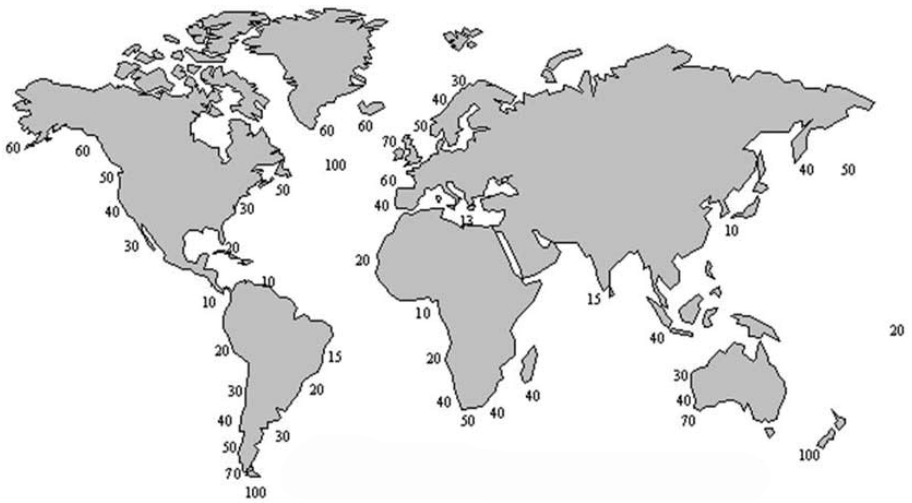
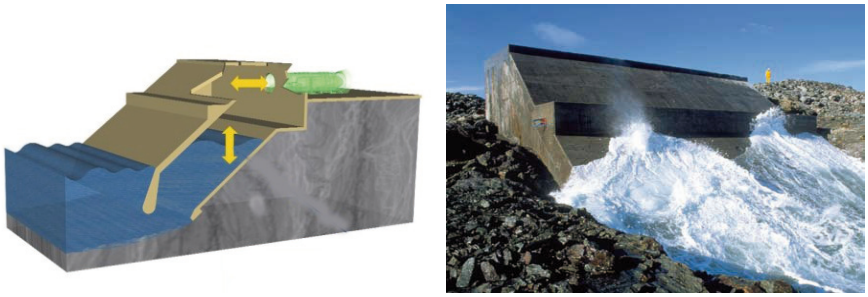


Figure 1. Wave power density (kW/m) of wave front for the various parts of the world.

Harnessing energy out of ocean waves is not a new idea. Wave energy conversion started with the intention of marking the presence of navigation buoys with lights. Still, there are no commercial plants in operation since technical difficulties must be overcome to make wave power an economically realistic energy source. Research on wave energy began in the 70s as a reaction to the oil crises at the time. Nowadays, wave energy is where wind power was 25 years ago due to less funding and the fundamentally bigger challenges it is facing in a harsh marine environment. Several concepts of wave energy converters have been developed based on three major principles:

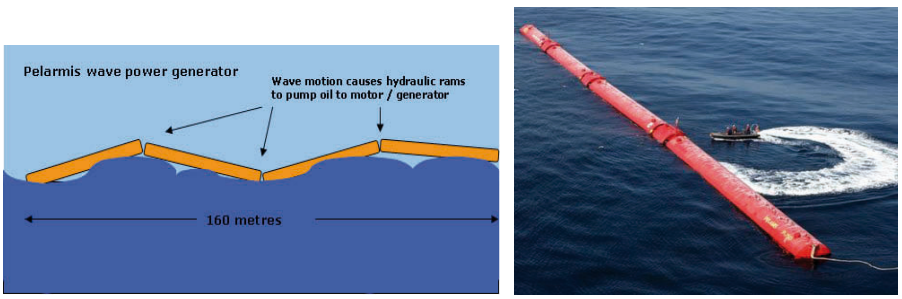
- Oscillating water column
- Overtopping systems
- Wave activated bodies

The oscillating water column is a low-pressure air turbine that is partly submerged and open below the water surface, so that an oscillating water pillar can pump air through a turbine. The Limpet plant is an example of a full-scale shoreline oscillating water column device (Fig. 2).



© Wavegen

© Wave Dragon



© Pelamis

Figure 2. Examples of concepts of wave energy converters that have developed to full scale devices. Top: Limpet. Middle: Wave Dragon. Bottom: Pelamis.

The second principle consists of reflectors or channels that direct waves towards a ramp. Behind the ramp, a large basin that is held above seawater level collects the directed water and leads it back via hydro-turbines. The Wave Dragon is a floating offshore wave energy converter constructed after the overtopping systems principle (Fig. 2). Wave activated bodies are floating structures with sections that move relative to each other induced by wave

motion e.g. Pelamis (Fig. 2). The relative motion is used to drive an electro-mechanical or hydraulic energy converter. Another example is the point absorber (Fig. 3) that has a relative small structure in comparison to the wave length. This is the concept presently researched and developed within the Lysekil Project run by the Swedish Centre for Renewable Electric Energy Conversion at Uppsala University. This thesis is the first step in order to investigate ecological effects of this concept.

Wave power installations and the marine environment

A great benefit of utilising wave power and other renewable energy sources is that the devices themselves do not have any harmful emissions or produce any greenhouse gases. As a result, wave energy is non-polluting, securing energy supply, and allowing economic growth independent from resource usage. Wave energy research and development is reaching a crucial stage, with the first full scale prototypes tested at sea and the first pre-commercial orders placed. All offshore energy conversion has some impact on the marine environment, but studies are needed to evaluate positive or negative effects. Furthermore, negative impacts should be reduced as far as possible by the developers since offshore structures are becoming common features of coastal waters close to urbanized areas. Environmental factors of concern can be divided into abiotic (e.g. water and air quality), biotic (e.g. marine flora and fauna) and socio-economic (e.g. restricted areas, visual impacts). Still, we find ourselves at an early stage of wave power development since test rounds only consist of small-scale deployments, and there can just be estimates about the possible impacts. Large arrays of wave energy converters may pose a conflict with nature conservation interests, either in terms of loss of species or habitat, barriers or threats to particular species. Nature conservation issues, such as habitat loss or extinction rates in marine organisms may not be easily predicted, and consequently demand long-time studies to be covered properly. Generally, there is a more limited ecological knowledge of the marine environment than of terrestrial ecosystems. Some lessons can be learned from other offshore projects, such as oil rigs, offshore wind and aquaculture farms. However, direct comparisons can mislead since effects are expected to be site as well as device specific and need to be determined and specified for each project.

Adjacent sediments

Artificial structures tend to change the seabed's topography and the hydrodynamics of the water around them, and thus affect the surrounding soft-bottom habitats. More than 80% of the ocean floor consists of soft bottom sediments, forming the most extensive biotope on earth (Lenihan & Micheli

2001). Coastal marine soft-bottoms are ecologically important components of the aquatic ecosystem with high biological activities and production. Economically important fish and shellfish use these shallow areas as nurseries (Pihl & Rosenberg 1982, Pihl & Wennhage 2002). Shallower areas are largely affected by incoming wind and waves, water level and temperature fluctuations. These natural disturbances are the major factors affecting the infauna. Thus, their biomass and species composition vary greatly with both time and space (Lenihan & Micheli 2001). Competition for space is less important than on rocky bottoms or coral reefs, since infaunal organisms inhabit a 3-dimensional space (Lenihan & Micheli 2001). Hard substrates on soft bottoms can work as stabilizers and protection for a variety of benthic organisms against wave action (Denny et al. 1985), ice scouring (Bergeron & Bourget 1986) or as shelter from predators (Ambrose & Anderson 1990, Kurz 1995). Artificial hard substrates also have indirect effects on benthic organisms by changing local currents, nutrient abundance and sediment coarseness (Abelson & Loya 1995). Moreover, organic material may accumulate through growth of epifauna on the artificial structures and algal detritus may become entrapped in the sediments, thereby changing activities and mortality of associated organisms. Thus the deployment of artificial structures contribute to changes in surrounding infauna communities, like changes in species diversity and species distribution (Davis et al. 1982, Ambrose & Anderson 1990). Infaunal organisms create much of the structure in soft-sediment habitats varying from micro-scale changes around burrowing individuals to complex reef-forming organisms. Macrobenthic organisms are optimal indicators for environmental change because they are relatively immobile, and their abundance and diversity may thus reflect the condition of the area (Reynoldson & Day 1993). Since these organisms are directly associated with the seabed habitats, any alteration in sediments tend to have an effect on the structure and composition of the benthic communities.

Colonization of wave power devices

Everyone who has observed the marine underwater world of the Swedish west coast, by diving or snorkelling is aware of entering a very lively and beautiful environment. Dominating in the upper, subtidal zone are green algae and deeper down brown and red algae are visible moving slowly with waves and currents. All hard substrate covered by water is colonized by organisms using tentacles, filtrating apparatus or bow nets for catching their prey. Hardly anyone is not impressed by that! A totally different reaction and feeling emerges when coming across exactly the same marine communities on boats, piers or buoys. Rather than reef communities, you regard those as obstacles since they are fouling communities.

Marine biofouling is the attachment and growth of marine organisms, such as algae, microorganisms and animals, on solid surfaces in the ocean water. For example, in the case of ships the unfavourable biological settlement leads to a reduction of their manoeuvrability and speed, and thus increased fuel consumption. For the industry, biofouling is expensive since it either requires costly anti-fouling measures in terms of increased maintenance or it can lead to undesired mechanic wear. Ideally, constructions should be made so that fouling has little impact on performance. Organisms taking part in marine biofouling are primarily the attached or sessile forms occurring naturally in shallow water along the coast (WHOI 1952). The formation of fouling communities depends on biotic and abiotic factors, such as predation, competition, geographic location, light levels, depth, temperature, salinity and local hydrodynamic regime, ice, bottom topography and substrate morphology (e.g. Dayton 1971, Mook 1981, Roughgarden et al. 1988, McCook & Chapman 1991, Pineda 1991, Denny et al. 1992, Miron 1995, Malm et al. 1999, Guichard 2001). Although about 4000 species have been identified on artificial offshore structures, this still includes a very small proportion of the known marine species (WHOI 1952). These organisms must have the ability to adhere hard enough to resist strong forces to avoid being washed off. Species with high tolerance to wide fluctuations in environmental conditions (e.g. temperature, salinity, water movement) dominate over more sensitive species and survive. The biofouling process involves many interesting steps, from initial conditioning of the surface by organic and inorganic molecules to the colonization by microorganisms and finally the establishment of macroorganisms (Davis 1995, Jonsson et al. 2004, Yerba et al. 2004). Common macrofouling communities are composed of organisms that secrete hard calcium carbonate tubes, shells or exoskeletons (e.g. barnacles, mussels, tubeworms, bryozoans and corals) together with soft organisms (e.g. algae, hydroids, sponges, ascidians). The extension of biofouling is dependent on a great number of different parameters, e.g. temperature, salinity, solar radiation and water depth. Fouling organisms grow larger in warmer regions with higher water temperatures; there is a clear relation between temperature, breeding period and growth rate in marine organisms. In colder regions with higher temperature variation typically only one generation can be produced during the short warm period.

Wave power structures will inevitably be colonized by sessile animals and algae. Assemblages of animals on artificial structures are often very different from those of surrounding natural, rocky reefs (Connell 2001, Bulleri 2005, Perkol-Finkel et al. 2006). Thus, introduction of artificial structures may change local diversity of the adjacent fauna. Biological changes might be alterations in biodiversity, species abundance and biomass (Johnson et al. 1994, Lozano-Alvarez et al. 1994, Ibrahim et al. 1996, Nelson 2003). Still, there are conflicting results regarding whether this increase in biodiversity is a result of aggregation from the surroundings or a true in-

crease in species and biomass (Bohnsack 1989, Bohnsack et al. 1997). Higher species abundance due to artificial reefs has been suggested to be related to better protection from predation, new food sources, increased feeding efficiency and an enhancement in larval recruitment (Sánchez-Jerez et al. 2002). On the other hand, the introduction of new substrates may also introduce new species which might influence the existing ones through other patterns of competition, predation and parasitism (Thompson et al. 2002).

It is also possible to influence the composition of fouling assemblages on energy installations. Protuberance, depth, age, shade orientation, complexity and texture of substrata all influence species composition (Potts & Hulbert 1994, Connell 2001, Glasby & Connell 2001, Spieler et al. 2001, Svane & Petersen 2001, Andersson 2005, Atilla et al. 2005, Perkol-Finkel et al. 2006). Position in the water column and orientation of the substrate could for example be adapted to specifically cater for macroalgae or filtrating animals (e.g. mussels) (Petersen & Malm 2006, Wilhelmsson & Malm 2008). A complex substratum increases the spatial heterogeneity which can increase the species diversity of an area by providing more ecological niches, thus allowing more animals to recruit (Menge 1976). The value of structural complexity seems to be related to several things such as ambush possibilities for predators, shelter for prey, the presence of organisms attached to or hiding between the structures that may serve as food, or a combination of these factors (Cocheret de la Morinière et al. 2004). It is important to know the species that normally inhabit an area and the prevailing environmental factors of an area prior to developing artificial reefs. To a large extent, this will dictate which species will likely be attracted to or found associated with an artificial reef. Flat, featureless bottoms provide an excellent opportunity for the application of artificial reefs to alter/enhance the environment, thereby providing habitat for a variety of fish and invertebrate species.

Overall objective

The central aim of this thesis was to gain knowledge on how the deployment of wave power devices affects the surrounding marine environment as well as colonization patterns and biofouling on the devices themselves. In total 26 devices for environmental studies have been installed at the Lysekil research site. These are comprised of a buoy connected via a wire to a concrete foundation. Thus, they resemble real wave energy converters, without a generator. In general, the research site may continue to serve as a model to larger, commercial wave power parks for observing ecological interactions. There are no earlier studies on environmental impacts of offshore wave power devices, and studies on offshore installations and colonization processes in temperate waters below 15 m are rare.

More specifically the aims of the different studies on which the thesis is based were:

1. Document the development of the Lysekil research site (**Paper I**)
2. Evaluate potential effects on the surrounding marine environment by the deployment of wave energy converters (**Paper I** and **II**)
3. Investigate the colonization patterns of fish and invertebrates on wave power devices (**Paper III, IV** and **V**)
4. Estimate fouling impacts on wave energy converters (**Paper III** and **VI**)
5. Recommend important marine environmental aspects involved with the deployment of wave energy converters (**Paper VII**)

The Lysekil Project

The Lysekil Project started 2002 with the aim to, under realistic and natural conditions, and over a longer time period, test the concept for wave energy conversion developed at the Swedish Centre for Electric Energy Conversion (CFE) at Uppsala University. This concept is based on a linear wave power generator, where a translator is moving up and down instead of rotating, standing on a foundation on the seabed (Fig. 3). The idea was to have an as simple solution as possible since ocean waves make up a harsh environment, where there are challenging conditions and high risks. The linear direct driven wave generator uses energy from slow motions, does not contain any intermediate system (gearboxes or energy storage) and is anchored on a concrete foundation on the seabed, thus avoiding the extreme forces of waves at the surface. The generator is connected via a wire to a buoy that floats on the surface and absorbs about 20% of the incoming wave energy (Waters 2008).

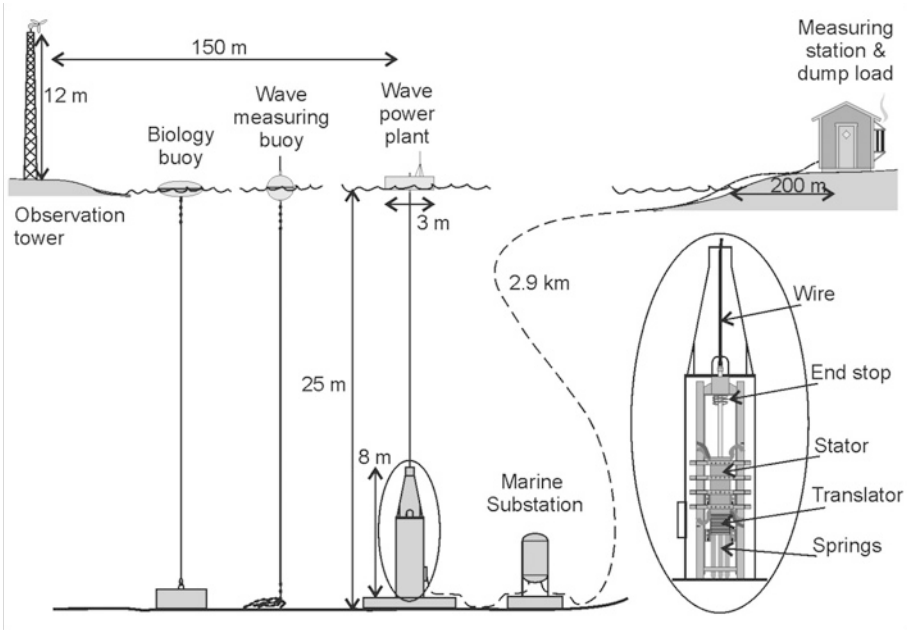


Figure 3. Schematic overview of different devices installed at the Lysekil research site, and a more detailed illustration of the Lysekil generator.

The capacity of the Lysekil generator is in the size of 10 kW to match the expected average wave height which is about 2 m (Paper I). The electricity is transmitted to land by a sea-cable. The whole system has only a few moving parts and thus potentially a smaller need of maintenance and higher survival. Experiments within the Lysekil Project have been conducted both in the workshop at the Ångström laboratory in Uppsala, with mostly an engineering focus, and out at sea at the Lysekil research site to study the technique as well as marine ecological aspects. There is a broad research team working on different parts in the project (Fig.4).

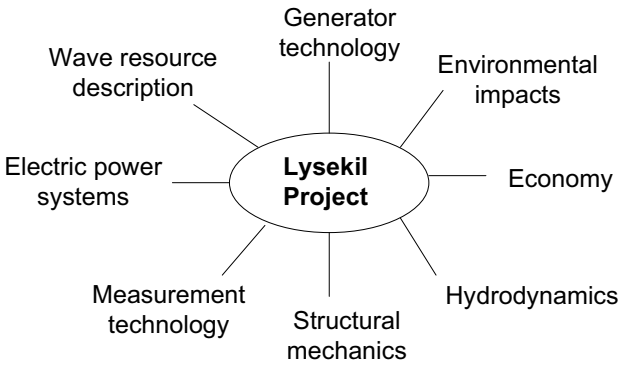


Figure 4. Areas of research within the Lysekil project

The Lysekil research site

The Lysekil research site is situated on the Swedish west coast, about 100 km north of Gothenburg, near the municipality of Lysekil (Fig. 5). The site is located 2 km offshore, between a northern (58° 11′ 850 N; 11° 22′ 460 E) and a southern (58° 11′ 630; N 11° 22′ 460 E) navigational marker signalling the research area to avoid interference with shipping. It covers an area of 40,000 m^2 and will by 2013 contain approximately 40 buoys: ten with generators, an additional 30 for environmental impact studies (Sundberg & Langhamer 2005), and two substations.

The entire Skagerrak region is a productive transitional zone connecting the cold and highly saline North Sea with the more low-saline Kattegat. The salinity is around 24‰ at the surface and around 33‰ at 30 m depth. The temperature of the surface water is in the range of 15-20°C in the summer and 0-2°C in the winter, and covering ice occurs on the upper regions of the shores on average every forth year (Åberg 1992). The average tidal ampli-

tude is only about 0.3 m, but depending on changes in air pressure and wind directions water levels can fluctuate up to 2 m (Johannesson 1989). The shoreline of the area is characterised by rocky slopes covered by algae, with sandy and muddy bottoms below the rocky outcrops (Cato & Kjellin 2008).

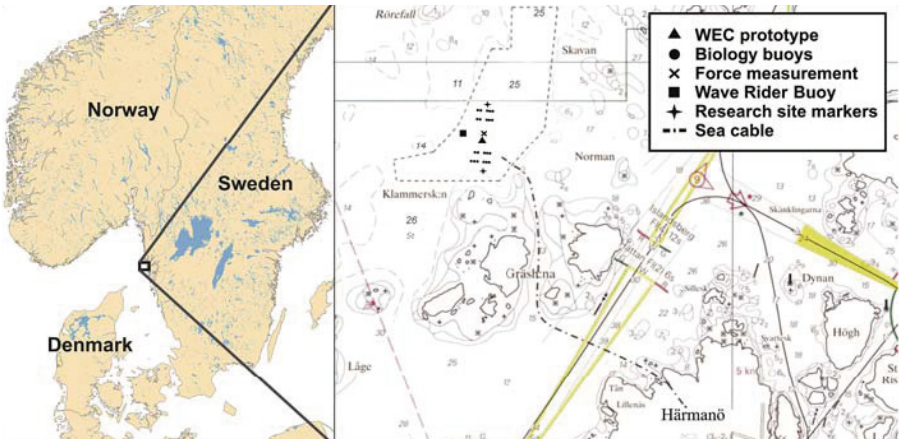


Figure 5. Map of the Lysekil research site including different devices and sea cable to land. Black numbers indicate different depths (m) and are surrounded by grey depth-contours.

The water depth in the research site is 24-25 m. The bottom material consists mainly of sandy silt and some smaller areas are covered with rougher material. The silt/sand layer is about 1 m thick. **Paper I** deals with the properties of the project, results on wave characteristics and wave absorption in the research site. The limited water depth at the site allows divers to perform regular inspections of devices placed at the seabed and marine environmental studies. The research site is situated only eight km from Kristineberg Marine Research Station (Gothenburg University) and Klubban Biological Station (Uppsala University), where well-equipped research facilities and larger boats are available. Also, smaller boats are available for more regular visits and work in the project area.

Brief research site history

- **Spring 2002**: start of the project at the Division for Electricity, Uppsala University
- **Summer 2003:** Location- and bottom surveys in the area outside Islandsberg at the Swedish west coast
- **April 2004:** a Datawell wave rider buoy is installed at the Lysekil research site to take measurements of incoming waves and the wave climate
- **Oktober 2004:** the Swedish Maritime Administration places two markers at the site
- **November 2004:** sediment cores are taken to study the marine infaunal assemblages in the research site. After that samples are taken yearly.
- **March 2005:** the first devices are put out in place consisting of four environmental wave power devices and one extra buoy connected to springs for measurements of the maximum line force
- **Summer 2005:** the first diving investigations at the wave power foundations are conducted to study colonization by marine organisms. After that the foundations are investigated every summer.
- **February and March 2006:** a measuring station is built on Härmanö to where the power cable is connected
- **March 2006:** first wave energy converter, including the sea cable to shore, is placed out
- **Summer 2006:** SGU (Geological Survey of Sweden) conduct geological surveys on the seabed
- **March and May 2007:** 21 additional environmental wave power devices are placed out
- **July 2007:** a 12 m high observation tower mast is installed at Klammskär, a small nearby island, equipped with a camera and a weather station for monitoring of the buoy motions in the research site
- **May 2008:** a toroidal (ring shaped) buoy is installed at the wave energy converter (Fig. 11)
- **February 2009**: two more wave energy converters are deployed
- **May 2009:** a marine substation is deployed transmitting the total power of the three installed wave energy converters
- **2005-2009** due to design problems with the mooring system some environmental buoys get loose and float away during autumn, winter and spring storms.

Wave power buoys

Different designs of wave power buoys are in use in order to study wave motions, wave absorbance and biofouling impacts (Fig. 11). The first "environmental buoys" for studying interactions with the marine environment were placed out in 2005. They were 1.5 m in diameter, 0.8 m high and had a weight about 400 kg. In 2006, the first wave energy converter was deployed in the research site. The buoy, attached to rope to measure the maximum line force, was cylindrical with a diameter of 3 m, 0.8 m high and had a weight of 1 t. In **Paper I** we measured forces on and acceleration of the buoy to provide detailed information on the operation of the wave energy converter. The cylindrical buoy was also used in **Paper III** to calculate the impact from biofouling on the buoy's energy absorption. The 21 environmental buoys that were installed in 2007 were 2 m in diameter, 0.8 m high and had a weight of about 700 kg including extra ballast. In 2008, a toroidal buoy was installed at the first wave energy converter to test its dynamics and ability to extract energy from ocean waves. That ring-shaped buoy was used in **Paper VI** for calculating biofouling impacts on the buoy's hydrodynamic forces. The buoy had a weight of 2.2 t and is a hexagonal ring with six sections, each 2.57 m along the centre-line and with a diameter of 0.71 m (Fig. 11).

Foundation design

In the Lysekil Project we use wave power generators attached to foundations that are placed on the seabed. We used concrete for the foundations for different reasons:

- *Function*: different materials function differently in attracting and holding marine organisms. An ideal material provides habitat for small organisms, attaching epifauna, and larger species that are important to the ecosystem. Concrete provides excellent surfaces and habitat for the settlement and growth of encrusting or fouling organisms, which in turn provide food and refuge for other invertebrates and fish.

- *Compatibility:* When there are documented environmental risks associated with the usage of a specific material, those risks should be known and steps taken to minimize them. Concrete is extremely compatible with the marine environment. The flexibility to cast concrete into a great variety of forms makes the material ideal for developing prefabricated units.

- *Durability:* The marine environment is hard on artificial structures. Therefore, artificial materials should be selected for their resistance to

chemical and physical forces that will be in constant action in the marine environment. Durability is specifically related to how long a material will last in the marine environment in a form that will maintain its function and compatibility.

- *Stability:* this is related to a material remaining in its original configuration and on the permitted site. This is especially important when artificial structures are subjected to strong storms. Concrete is highly durable, stable, and readily available.

In **Paper III**, we observed the first installed wave power foundations in the Lysekil research site. The set-up consisted of 4 cylindrical 10 t concrete foundations with a diameter of 2.5 m and a height of 1 m each and one bigger quadratic foundation with a weight of 40 t and an area of 16 m^2 (Fig. 11). Three of these foundations were constructed with holes intended to house fish, crabs and lobsters, and two without holes. Foundations were placed between 100 m and 300 m apart. In April 2007, another 21 environmental foundations were placed out in a northern and a southern cluster within the Lysekil research site. They measured 3 m in diameter, were 1 m high, and weighed 10 t each. These 21 foundations were used in **Paper IV** to survey associated fish assemblages and in **Paper V** to study recruitment and succession of benthic macrofauna and algae. The distance between modules was 15-20 m. Eleven of the foundations were each perforated with 26 rectangular holes, 12 cm x 15 cm x 30 cm (width x height x depth). Thirteen of the holes were made in the lower edge of the structure, so that the seabed constituted the floor of the holes, while 13 holes were shaped on the vertical side of the foundation, 50 cm above the seabed (Fig. 11). The foundations were designed for extreme wave conditions and lifting forces from the environmental buoys.

Study organisms

Infaunal macrobenthos

The seabed in the Lysekil research site consists of soft sediment and the deployment of wave energy converters will add a hard bottom substrate in this area and cause a small loss of soft bottom. Therefore, eventual biological changes in the sediment have to be monitored. Furthermore, infaunal organisms are perfect indicators for environmental changes in the sediments. Thus they have been studied in **Paper I** before placing out the wave energy converters and in **Paper II** before and during the deployment of wave energy converters in order to observe changes in macrofauna. Sediment cores were taken with a Hapscore sampler that has a bottom area of 0.015 m^2 once

yearly between 2004 and 2008. I sieved all samples through a 1 mm mesh, identified all macroorganisms found in the samples down to the lowest taxon possible and weighed them. In **Paper II**, I divided all infaunal organisms into five taxonomic groups: *Crustacea, Echinodermata, Mollusca, Polychaeta* and *Varia* (including fish, cnidarians, nemertines) and into the following trophic types; deposition feeder, predator and suspension feeder.

Sessile macrobenthos and algae

> *"In the remote coral reefs, marine biologists sometimes use dynamite…for the purpose of scientific study it is the only method for taking a census of all the varieties in an area"*
>
> Jacques-Yves Cousteau, 1956

In the studies conducted by me and colleagues, scuba diving and photographing were useful non-disturbing biological survey tools that provided an accurate method of studying epibenthic organisms colonizing wave power foundations (Bohnsack 1979). In both **Paper III** and **Paper V** we studied cover by macrobenthic organisms on wave power foundations by taking underwater-photographs of 7.0 cm × 10.6 cm big areas while scuba diving. In **Paper III** 10 vertical and 10 horizontal surfaces were sampled on each foundation from the same, evenly distributed, positions during three years. Vertical surfaces only were sampled in **Paper V** on foundations clustered in northern and in the southern locations of the research site. 10 surfaces were sampled from the same spot on each foundation. Invertebrate taxa were identified to the lowest taxonomic level practical. Epifauna that could not be identified to species from photographs were assigned a higher taxonomic level (e.g. hydroids, bryozoans).

In order to estimate biofouling on different kinds of wave power buoys I used marking buoys for maritime shipping situated in Brofjorden north of Lysekil in **Paper III** and **Paper VI**. The reason for sampling outside the wave power park was that no buoys were out there from the beginning. All samples from the marking buoys were taken by scraping a 20 cm × 30 cm area about half a meter below the sea surface with a scraper into a 1 mm mesh net. The location of the sampling area was randomly determined and three samples were taken per buoy. The collected material was taken directly to the lab, weighed, counted and identified down to family or species level if possible. In **Paper VI**, only blue mussels, *Mytilus edulis* > 0.5 cm were counted, their wet weight was taken, their shell-length measured and divided into 3 size classes; 0.5 – 2.5 cm, 2.5 – 5.5 cm and > 5.5 cm. Subsamples were taken to estimate number and weight of *M. edulis* < 0.5 cm if they appeared in high quantities (> 500 individuals per scraping area).

Motile bottom-dwelling fauna

> *"The best way to observe a fish is to become a fish"*
> Jacques-Yves Cousteau

In **Paper III** and **IV** we observed fish and other motile fauna visually during scuba diving. This is a commonly used method to study reef-associated motile organisms (Sale & Douglas 1981). Fish, crabs, lobsters and other motile organisms were recorded on the foundations and on the surrounding bottom within 1 m distance. Control areas 8 m from each foundation were examined for comparison to the newly added hard bottom habitats. These control areas had the same total area as on and around the foundations (12 m^2). On each foundation, the top of the structure was surveyed first. After that, the sides, the holes if present, and the adjacent bottom were surveyed by slowly circulating around the foundations. The controls were studied in the same way as the foundations, although these were predominantly two-dimensional (flat sand bottom). During a single dive we were able to study one foundation and one control site. Each census of either a foundation or a control took approximately 8 minutes.

Statistical approaches

This thesis contains a variety of statistical methods for both uni- and multivariate data. Among univariate methods, I used single factor analysis of variance (**Paper I, IV**), and multifactor analysis of variances (**Paper II, III, V, VI**). Analysis of multivariate patterns were applied using non-parametric multivariate analysis of variance (**Paper I, II, III, V**) and non-parametric analysis of similarities (**Paper II**, **III, V**). Most statistical analyses were carried out using STATISTICA™ v6-8 and PRIMER ™ v6.

Main findings and discussion

Benthic infauna and influences from wave energy converters

Sediments in the test park showed a higher species abundance and diversity compared to the control area prior to deployment of the wave energy converters, and the areas differed significantly (ANOSIM, $R_{2004} = 0.26$, $p = 0.004$) (**Paper I**). With the deployment of the first wave energy converter and the environmental devices the pattern of higher biomass in the test park did not change (ANOSIM, $R_{2005} = 0.2$, $p = 0.005$) (**Paper II**): The overall most abundant taxonomic group are polychaetes with about 50% higher biomass and there was an overall pattern of a higher biomass in the test park compared to the control area (Fig. 6).

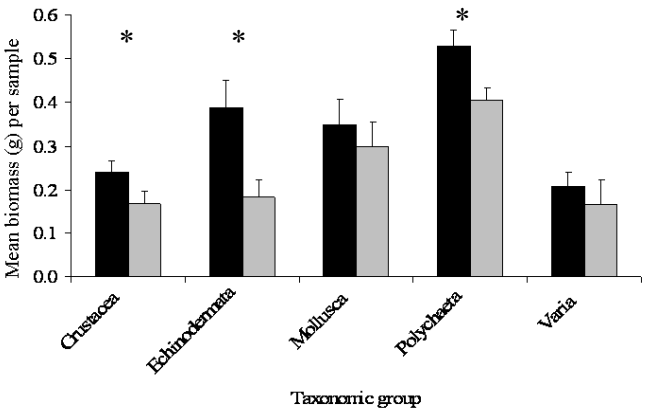


Figure 6. Mean biomass (g) ± SE per sample (0.015 m^2) in the taxonomic groups, *Crustacea, Echinodermata, Mollusca, Polychaeta* and *Varia* found in the Lysekil research site (black) and in the control area (grey). * = $p < 0.05$

The higher biodiversity found in the test park can be explained by differences in the sediment substrates between areas. Sediments in the test park contains both silt, sand and shell gravel whereas the control area only contains silt and shell gravel. Silt is mostly relatively oxygen deficient and thus only a few organisms are adapted to these extreme conditions. The biodiversity in sandy sediments with medium grain size is most often higher than in

other soft bottom types (Van Hoey et al. 2004). In general, the infaunal samples reflect a rather low abundance of mostly juvenile, small-sized organisms compared to other findings at the Swedish west coast (Josefson 1981, Rosenberg & Nilsson 2005).

In **Paper II**, the infauna differed during the first years of sampling (2004-2006) with overall more species in the test park (Fig. 7). The main contributors to the dissimilarities between the test park and the control area are polychaetes: about 20% more were found in the test park where *Glycera alba* was present in all the samples of 2004-2006. A dominance of polychaetes, high diversity and species richness of infaunal assemblages has been observed in earlier studies (Rabaut et al. 2007, Fukunaga & Bailey-Brock 2008). The species of the infaunal communities in the surrounding of the wave energy converters are mainly typical for the area and depth outside the Swedish west coast (Agrenius 2002, Rosenberg & Nilsson 2005). However, the total mean biomass was low as mostly small, juvenile organisms were found. One reason may be frequent and powerful mixing of the bottom layers by waves, disturbing the seabed with its inhabitants.

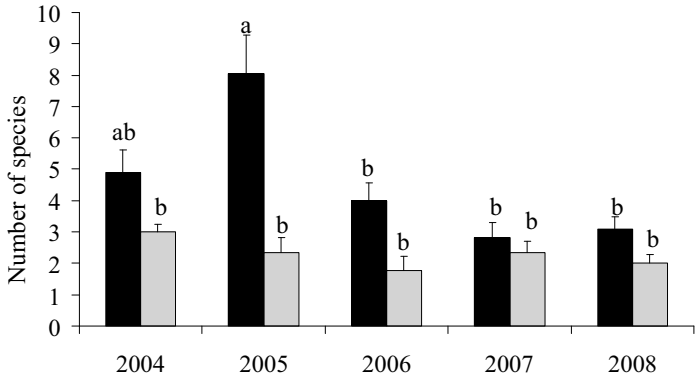


Figure 7. Calculated mean total number of species± SE per Hapscore-sample (0.015 m^2) of infauna in the test park (black) and in the control area (grey). Letters above bars indicate significantly different means based on Tukey's post-hoc comparisons.

Another factor of disturbance can be commercial trawling that occurred in the area before 2004. Trawling has immense influences on soft sediment communities (Dayton et al. 1995, Jennings et al. 1998). The negative impact can last long and have large influences on ecological processes in the seabed (Lenihan and Micheli 2001).

Still, wave energy converters may partly affect infaunal assemblages. The infaunal biodiversity differed between years and sites (ANOVA, $F_{4, 110} = 3.4$, $p = 0.01$). On the other hand, wave energy converters may have stabilizing effects on the seabed and thus can contribute to positive long-term effects to infaunal biomass, diversity, and in that way contribute to environmental recovery.

Artificial reef effect of wave power foundations

Paper III and **V** show that the succession of epifaunal macroorganisms on wave power foundations is initiated by only a few species, mostly calcareous tubeworms (*Pomatoceros triqueter*) and barnacles (*Balanus sp.*) (Table 1). Both species usually produce many larvae and are capable of colonizing and taking advantage of empty niches. During the second year of foundation deployment, the total cover by epifaunal organisms increased strongly, mostly due to sea squirts (*Ascidiacea sp.*) since they are more competitive, resistant to predation, and invest more energy into reproduction than tubeworms and barnacles do (Table 1) (Barnes & Hughes 1999).

Table 1. Comparison of epifaunal assemblages on wave power foundations between the northern and southern location, during 2007 and 2008 using similarity of percentage (SIMPER). Listed taxa contributed to at least 90% of dissimilarities between locations.

Taxa	Average coverage degree (%)		Contribution (%)
	North	South	
2007			
Pomatoceros triqueter	0,26	0,21	44,62
Balanus sp.	0,12	0,03	22,15
Hydroidea sp.	0,09	0,06	20,83
Asterias rubens	0,01	0,05	5,31
2008			
Pomatoceros triqueter	3,73	2,03	36,14
Ascidiae	0,84	0,81	18,63
Balanus sp.	1,15	0,31	15,55
Hydroidea sp.	0,97	1,17	12,80
Bryozoa sp.	0,36	0,34	8,16

The species composition on the foundations resembles that on natural hard bottoms of the Swedish west coast at similar depths. This shows that concrete is suitable as foundation material resembling a natural environment (see Gislén 1930). The strong increase of epifaunal organisms during the second year can be explained by sediment depositions of faecal matters and organic litter (probably mostly from biofouling on buoys), that can enrich the habitat with food.

In **Paper III** we show that vertical surfaces were preferred by epifaunal organisms and more densely colonized than horizontal surfaces. More species were found and a higher biodiversity was attained on vertical surfaces (Fig. 8). Studies in shallower waters in other regions showed the same patterns on differing surface orientations (Glasby & Connell 2001, Knott et al. 2004). An explanation for this pattern may be sedimentation processes, since horizontal surfaces tend to retain sediments and colonizing organisms are therefore under greater sedimentary stress. However, small filamentous red algae

grew on horizontal surfaces. The location of the foundations together with a high water turbidity causes low light intensities and that has a major effect on algal growth (D'Anna et al. 2000).

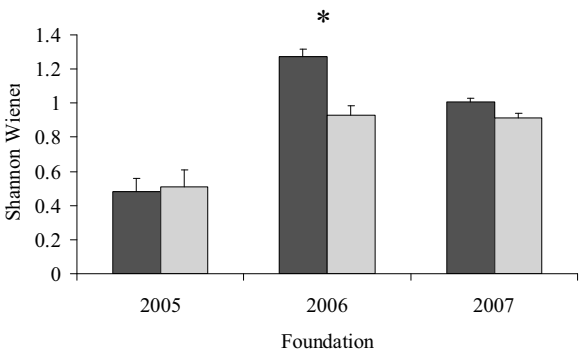


Figure 8. Mean Shannon-Wiener diversity index ± SE in epifaunal assemblages on vertical (black) and horizontal (grey) sides of wave power foundations. * = $p < 0.05$

Paper V shows that the locations of the wave power foundations differed significantly from each other in terms of total number of species (ANOVA, $F_{1, 175} = 16.6$, $p < 0.001$), total individuals (ANOVA, $F_{1, 175} = 63.8$, $p < 0.001$) and Shannon-Wiener diversity (ANOVA, $F_{1, 175} = 11.4$, $p < 0.001$). These were higher on foundations placed in the northern location. An interaction between years and location can be explained by an asymmetric increase in total individuals with time (ANOVA, $F_{1, 175} = 58.0$, $p < 0.001$). Mostly, calcareous serpulid polychaetes and ascidians contributed to the differences with a higher cover on northern foundations (Table 1). Due to strong waves and winds, predominantly from the west and northwest, the northern location is more exposed which may have an impact on colonization success. In natural habitats, higher biomass of filter feeders has frequently been recorded at exposed, compared to sheltered, natural rocky reefs. A higher water turnover influences the flux of phytoplankton and nutrients and consequently increases the food supply (Kautsky 1982, Bustamante & Branch 1996, Frandsen & Dolmer 2002).

Since the wave power foundations serve as substrate for epibiota, they also gather motile species that typically associate with hard bottom substrates (**Paper III, Paper IV**). In comparison to the control areas, higher average abundances and more fish species occurred on foundations (Fig. 9).

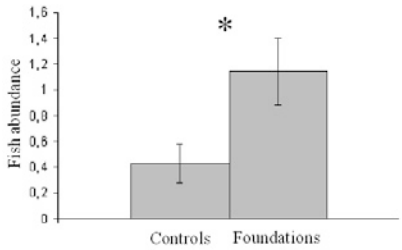


Figure 9. Average fish abundance (± SE) on foundations and controls. * = $p < 0.05$

The fish abundance was generally low compared to other complex structures previously investigated (Wilhelmsson et al. 2006), which suggests low complexity of the foundations apart from the holes. Yet, fish rarely used holes and, if so, they preferred holes along the bottom to holes up on sides (4 versus 0) (**Paper IV)**. Certain fish species have been suggested to seldom enter holes with only one opening, where escape options and water circulations are limited (Dean 1983, Spieler et al. 2001). In general, colonization of artificial reefs happens quickly (i.e. in a few days to months) so that fish abundance and species numbers may not increase notable with time after reef establishment.

The scarcity of fish can also be due to the frequent use of holes by the edible crab, *Cancer pagurus* (Fig. 11). They commonly used side-holes above the bottom for shelter (Fig. 10) and their carapace size generally matched the size of the holes well (**Paper IV)**. The preference of *C. pagurus* for these holes may be due to less sediment build-up compared to the holes along the bottom and thus less maintenance work required, less disturbance from lobsters, and enhanced protection from predators.

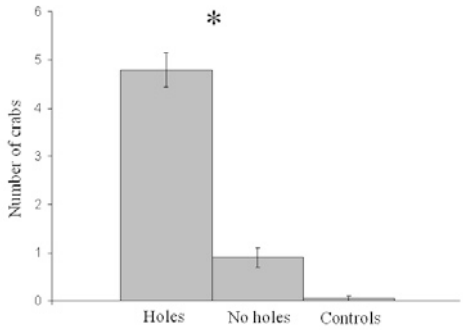


Figure 10. Average number of (± SE) edible crabs (*Cancer pagurus*) on foundations with and without holes, and in controls. * = $p < 0.05$

The spiny starfish, *Marthasterias glacialis*, and the sand star, *Astropecten irregularis*, were affected by the foundations (**Paper IV)**. The abundance of *M. glacialis* was significantly higher on the non-complex foundations and is potentially a result of the significantly increased predator abundance (i.e. *C. pagurus*) on the foundations with holes (holes: 1.4, no holes: 0.2). The negative effect on abundance of the sand star on the foundations could simply be due to the loss of soft-bottom area. Over the entire test park, however, soft-bottom loss amounted to only 2%, so this effect is negligible.

The impact from biofouling on wave power buoys

In **Paper III** we showed that epifaunal species colonizing and growing on buoys consisted of algae, crustaceans, echinoderms, molluscs, tube-building polychaetes and varia (hydroids, bryozoans, sponges), in order of wet weight biomass. Furthermore, the total biomass was 13.4 ± 3.0 kg/m^2. Assuming that all cylindrical wave power buoys would be covered by the same amount per square meter, each would carry a biomass of about 137.5 ± 15.7 kg. Simulations on the cylindrical buoys` dynamic behaviour gave the results that an added biofouling of about 140 kg would decrease the energy absorption with about 5%. That means that we could not find any substantial negative effects regarding the dynamics of the wave power buoys due to biofouling.

The blue mussel, *Mytilus edulis* (Fig. 11), was found to be the species that contributed with about 85% of the biomass of fouling organisms. The mean biomass of blue mussels was 11.3 ± 3.2 kg/m^2, and exposed buoys carried a significantly higher amount and larger mussels (**Paper VI**). The dominance of mussels in general can be explained with their broad distribution over wide geographical regions, since their larval development takes around one month and gives long time for dispersal (Gosling 1992, Seed 1992, Seed & Suchanek 1992). Their lower abundance on wave-sheltered buoys may be an impact of predation by the common sea star and eiders (Dare 1982, Saier 2001), drain of food in cavities and depressions (Frandsen & Dolmer 2002), parasite infections (Buck et al. 2005) or ice cover (Gutt 2001). In **Paper VI** I furthermore calculated that if the toroidal buoy would be covered by *M. edulis*, it will lift an extra weight of 408.4 kg ± 56.2 kg. Still, this would increase the buoy's heave period with only a minor percentage, since the total weight of a translator/buoy with mussels is approximately 10 t. Thus, any mass increase through fouling is too small to have any major effect regarding the dynamic behaviour of the buoy.

Nature conservation issues

Ocean reserves are constrained in terms of both resources and space, and thus comprehensive integrated approaches are fundamental to manage all human marine activities. Most renewable energy (RE) conversion could be labelled as "outspread" infrastructure projects and are relatively new challenges for integrated coastal management strategies and marine spatial planning policies. In **Paper VII** we review potential conflicts with other marine interests, such as fishing, and identify conservation matters that to some extend are valid independent on RE-technique. Yet, ongoing environmental baseline studies are taking an advantage from experiences from other offshore ventures, i.e. choice of suitable areas, study methods or estimation of environmental impacts on specific sites (WaveHub 2006). Large knowledge gaps exist, however, which impede environmental impact assessments and issuing of permits (Gill 2005).

One aspect is the provision of no-take zones that are becoming a growing demand from most conservationists and ecologists as most oceans are overexploited. RE-conversion will hinder most commercial fishing, especially with trawls and nets, and hence be positive for fishery management strategies (Sanchirico et al. 2006).

Other aspects that we highlight in **Paper VII** are disturbance effects that are main concerns for the marine environment, such as underwater noise and electromagnetism. The construction phase of wave energy parks will inevitably generate some noise from seabed preparation, placement of foundations, as well as boat traffic. In the Lysekil research site, work related to placing of foundations on the seabed may have a low effect on acoustically sensitive organisms. Harbour seals have regularly been observed at the research site and may be affected during construction as several haul-out sites, i.e. rocks and isles used for resting exist within a short distance. Electromagnetic fields from the power transmission cables are a topic of concern and local disturbances on foraging and navigation of electro-sensitive species, such as sharks, rays and eels cannot be ruled out. With the use of a better cable technique the electromagnetic fields only affect the nearest surroundings, however. In fact, the background earth magnetic field usually becomes more prominent only a few decimetres from the cable. In combination with cables buried into the seabed this problem might disappear. Some opportunities are mentioned in **Paper VI** about plans for combining RE- production with offshore aquaculture activities, especially blue mussels. Thereby rough offshore areas could be made available for this sector, in which requirements for space and water quality are restraining factors (Buck et al. 2004).

Finally, consideration of impacts should begin at the initial stages of planning and incorporate the entire life of the wave power park. Therefore, all elements of the exploration, construction, operation, maintenance and shutting-down of wave power and any proposed extensions of the project in

the future should be considered. Importantly, we list in **Paper VII** dedicated baseline surveys to assess the use of the area by marine wildlife and, in particular, the significance of the area for breeding, feeding or migration. Actual lack of knowledge of environmental impacts should result in the application of a forehanded course of action based on "Before-After/Control-Impact" (Underwood 1994), in particular where large scale projects are under consideration.

Figure 11. Collection of pictures from the practical work within the Lysekil Project. **1st row:** Blue mussels on a buoy, juvenile whiting passing buoy line, ascidians on foundation. **2nd row**: biofouling on buoy line, sea anemone growing on foundation, construction of environmental buoys. **3rd row:** environmental buoy from above, seas star on foundation, environmental buoys and foundations. **4th row:** lobster under foundation, 40t foundation, wave power generators. **5th row:** edible crab at foundation, work on environmental buoys, toroidal buoy.

Conclusions & future directions

Research performed within the Lysekil Project aims to understand and evaluate the wave energy concept from a physical, technological, economical and ecological perspective. The ecological results, presented in this thesis, provide an emerging picture of the interactions between wave energy converters and the marine environment. The thesis contributes work on succession and colonization, with regard to species composition, distribution and dynamics of macrobenthos, crabs and fish on wave power devices in general, but specifically in temperate waters. The focus on the effect of fouling and artificial reefs provides knowledge important both for project builders as well as for conservationists.

Wave power devices may be extensively and rapidly colonised by organisms occurring on natural hard-bottom areas and used as new habitats. Wave power foundations, as well as added structural components, could both enhance abundances of associated fish and invertebrates, but may have adverse effects on local numbers of certain species. Thus, it seems possible that the overall effect of wave energy converters on marine fauna will be positive. Most coastal seas are already seriously destroyed habitats, but wave energy converters have the capacity to enhance biodiversity in degraded marine habitats, thus representing a perfect instance of "win-win ecology".

Scuba diving and photography are useful non-invasive biological survey tools which provide an accurate method of studying epibenthic communities on and around wave power devices. Both are recommended methods applicable for other offshore energy devices in shallower waters, such as wind power turbines. Wave power buoys will be subjected to biofouling dominated by blue mussels (about 90%), but calculations showed that an increase of mass by biofouling is too small to have any major effect on the energy absorption by the buoys. Consequently, cleaning of wave power buoys from biofouling may not sufficiently enhance performance of devices to be cost effective. If there is an economical pay-off in harvesting the blue mussel clumps growing on wave power buoys, it may be a possible secondary use of wave power installations.

The thesis is the first ever that gives an early insight into changes induced by wave power devices on sessile and motile organisms living in the Lysekil research site. Infauna in the research site was generally low in abundance, biomass and diversity and dominated by juvenile polychaetes. Comparisons between the test site and the reference site showed an effect, which may

depend on the deployment of foundations or a reference site out of place. There was, however, a positive effect comparing the sediments before and after deployment of the first devices, but this was followed by a negative effect after deploying some additional devices. This was probably due to variations between years. Thus, the deployment of wave energy converters in the Lysekil research site may have minor ecological impact on the sediments, much below the level of natural variation. Random dynamics in space and time strongly control processes causing environmental dynamics or physical processes and are major factors structuring soft-bottom communities (Lenihan & Micheli 2001).

However, the project is still under development, planning a deployment of 7 more wave energy converters and about 10 more environmental buoys. Thus, there is still insufficient scientific knowledge concerning effects of large scale deployments in the research site under a longer time-scale. Future research would greatly benefit by further focusing on:

- sediment transport and hydrodynamic processes
- long-term studies of infaunal assemblages after disturbance by wave energy converters with at least one more comparable reference site
- the effect of no-take zones on eventual biological restoration
- how habitat complexity through structural design of wave power foundations can improve for instance fish, crab and lobster abundance
- assessment of how noise and vibrations from whole wave power parks affect organisms
- effects on birds, pelagic fish and sea mammals in relation to wave power
- large scale effects (>100 wave energy converters) on bottoms of greater depth where commercial wave power parks commonly will be established

It is only through experience and research that we will be able to construct wave power parks in an environmental friendly way. Given time, wave energy has the potential to be one of the most effective, environmentally and economically promising ways to produce electricity.

Vågenergiomvandling och den marina miljön

Koloniseringsmönster och habitatdynamik

FN:s klimatpanel rapporterade 2007 att det har förekommit allvarliga klimatförändringar orsakade av mänskliga utsläpp av växthusgaser, speciellt koldioxid under de senaste 100 åren. Dessa förändringar beror till största delen på den globala energiproduktionen som i huvudsak är baserad på icke förnyelsebara och miljöfarliga fossila bränslen som t.ex. olja, gas och kol. Koldioxidhalten i atmosfären har ökat med drygt 35% sedan mitten av 1800-talet (från ca 280 ppm år 1850 till 379 ppm år 2005). Redan nu observeras stigande temperaturer, höjda havsnivåer och ökad svält – jordens klimat håller på att förändras.

Om utsläppen fortsättningsvis ökar i samma takt kommer koldioxidhalten att uppgå till 1000 ppm under det kommande seklet, vilket kommer att leda till fortsatt uppvärmning. Senaste gången något liknande hände var för 251 miljoner år sedan (perm-trias utdöendet) då nästan 90% av allt liv på jorden blev utplånat. Det var det närmaste vår planet någonsin har varit att omvandlas till en livlös sten. Följaktligen är det nödvändigt att utveckla alternativa och miljömässigt hållbara energikällor.

En hittills outnyttjad energikälla med hög potential finns i våra hav i form av vågenergi. Denna kan bidra med en betydande del av världens energiproduktion. Enbart i Östersjön beräknas potentialen vara 24 TWh, vilket är långt mer än Sveriges planerade utbyggnad av förnybar elenergi under de närmaste 5-10 åren och motsvarar 20% av den totala elanvändningen i Sverige 2007 (Bernhoff et al. 2006). Olika uppskattningar visar att potentialen för vågenergi i världen ligger mellan 1 TW och 10 TW.

Vid Uppsala universitet studeras energiomvandling ur vågor med hjälp av en ny typ av vågkraftverk där linjärgeneratorer är direkt kopplade till bojar som drivs av vågorna. Istället för att anpassa vågkraftverken till en konventionell, roterande generator, anpassas här generatorn till vågornas långsamma rörelse. Utöver teknisk/funktionell verifiering och utveckling av systemet utvärderas detta även vetenskapligt från ekologiska aspekter. Framtida lösningar på utvinning av vågkraft behöver vara robusta för att klara de stora påfrestningar som uppstår till havs, praktiska, ekonomiska, säkra, och miljövänliga. Entreprenörer och forskare jobbar med detta på flera olika platser runt om i världen. Det är i sammanhanget viktigt att tänka på interaktioner mellan den marina miljön och vågkraftsanläggningar. Med fortsatt forskning

kommer vi att få en bra överblick över vågkraftens möjliga inverkan, samt en tillförlitlig teoretisk bakgrund för att kunna beräkna denna.

Den största fördelen med att utnyttja vågkraft är att själva anordningarna inte orsakar några farliga utsläpp eller producerar växthusgaser. All havsbaserad energiomvandling har dock en förväntad inverkan på den marina miljön och om denna inverkan är positiv eller negativ måste följas upp. Miljöpåverkan från vågkraft kan indelas i abiotisk påverkan på vatten- och luftkvalitet, biotisk påverkan på den marina floran och faunan samt socioekonomisk påverkan på till exempel skyddsområden, fiske eller upplevda synintryck. Rent generellt är den ekologiska kunskapen om den marina miljön mycket mer begränsad än för terrestra ekosystem.

Denna avhandling beskriver studier av interaktioner mellan en nyetablerad vågkraftsanläggning vid Sveriges västkust utanför Lysekil och den marina miljön. Lysekilparken ligger ca två km från kusten och har utvecklats kontinuerligt sedan 2005. Under denna tid har 26 ”ekologiska vågkraftverk” lagts ut. Dessa enheter består av en stålboj på havsytan som med en stålvajer förankrats till ett betongfundament på botten. Alla dessa konstruktioner är utplacerade enbart för miljöstudier och fundamenten ligger på 25 m djup. Hälften av fundamenten har håligheter för att kunna fungera som gömställen för rörlig fauna.

Jag har tagit sedimentprover årligen mellan 2004 och 2008 för att studera makrofaunan i områdets mjukbotten. Jämförelsen av faunan i sedimenten före och efter utplaceringen visade först på en positiv effekt efter utlägget av de första fem fundamenten och sedan en negativ effekt efter utlägget av de 21 nya fundamenten, vilket kan bero på fundamenten eller, mer troligt, på slumpmässiga skillnader mellan åren. Artsammansättningen var typisk för denna typ av habitat. En jämförelse mellan ett område med fundament och ett kontrollområde visade på en negativ effekt i fundamentområdet, vilket kan bero på fundamenten eller troligen på ett olämpligt kontrollområde. Sammantaget har utplaceringen av vågkraftfundament troligen ingen effekt på sediment utöver den naturliga variationen.

Förutom dessa sedimentstudier, som avser påverkan på det befintliga habitatet, har jag undersökt effekten av tillkomsten av ett nytt habitat i området: vågkraftfundamenten liksom bojarna utgör en sorts hårdbotten, en habitattyp som inte fanns här innan utplaceringen av vågkraftaggregaten. Detta har jag undersökt genom dykning, undervattensfotografering och visuella observationer. Fundamenten koloniserades av en stor mängd fastsittande organismer, framförallt på vertikala ytor, men mängden av rörlig fauna som attraherades av fundamenten var generellt rätt låg.

Tre månader efter utlägget av 21 nya fundament undersöktes förekomsten av alla rörliga organismer med hjälp av dykning och visuella observationer. Vågkraftfundamenten visade sig attrahera fisk, och hål i fundamenten samt hålens placering påverkade bl.a. mängden krabbtaskor. De 21 fundamenten var utplacerade i två grupper inom vågkraftparken, en nordlig och en sydlig.

Under två år studerade jag vilka arter som koloniserar dessa fundament och hur successionen av dessa arter sker. Organismsamhället på de nordliga fundamenten hade en högre biologisk mångfald. Detta tyder på att den påverkan som vågkraftfundamenten kan ha är väldigt platsspecifik eftersom de fysiska och ekologiska faktorerna varierar från plats till plats.

Påväxt på vågkraftbojar skulle kunna vara ett problem när det gäller elkraftproduktionen – dämpas den av djurens tyngd? För att svara på denna fråga har vi studerat påväxtorganismer på bojarna och visat att artsammansättningen dominerades av blåmusslor, *Mytilus edulis*, som utgjorde nästan 90% av biomassan. Vågexponerade bojar blev särskilt koloniserade av blåmusslor, med högre biomassa och större musslor än mer skyddade bojar. Beräkningar visade dock att påväxt på vågkraftsbojar inte har en märkbar inverkan på kraftverkens energiproduktion.

Sammanfattningsvis fann jag att vågkraftverken i Lysekilsparken troligen inte, eller i mycket ringa grad, inverkade på de mjukbottnar där de placerades. Däremot ökade tillkomsten av ett för området nytt hårdbottenhabitat, bestående av betongfundament och vågkraftbojar, den biologiska mångfalden markant. Fiskar, krabbor, blåmusslor och fastsittande organismer som tidigare varit så gott som frånvarande i området ökade dramatiskt. Liknade effekter efter utplacering av ”artificiella rev” är kända från andra studier. Således hade vågkraftverken en övervägande positiv effekt på biodiversiteten i området. En möjlig negativ ekonomisk följd av vågkraftsutbyggnad är att fiske inom parkerna omöjliggörs. Parkerna kommer således att fungera som fredade zoner för fisk- och skaldjurspopulationer, vilket i långa loppet dock kan snarare gynna kommersiellt fiske i näraliggande områden på grund av ett möjligt överskott av fisk och skaldjur i vågkraftparken.

Ökologische Auswirkungen von Wellenkraftwerken

Kolonisierungsmuster und Habitatdynamik

Der Weltklimarat (IPCC) fasste 2007 in einem Report zusammen, dass der Klimawandel durch Emission anthropogener Treibhausgase, speziell durch den erhöhten CO_2-Austoss der letzten 100 Jahre, verursacht wird. Dieser Wandel wird durch das Verbrennen fossiler Brennstoffe wie Öl, Gas und Kohle bedingt, die als Grundbausteine für die globale Energieproduktion dienen. Der CO_2-Gehalt in der Atmosphäre ist seit 1850 um 35% angestiegen (von ca. 280 ppm auf 378 ppm im Jahre 2005). Sollten die Emissionen im gleichen Takt ansteigen, wird der CO_2-Gehalt im kommenden Jahrhundert bei 1000 ppm liegen und der Treibhauseffekt wird sich drastisch verstärken. Als Folge der erwarteten Erderwärmung um durchschnittlich 1,8 bis 4,0ºC muss, Forschern zufolge, mit steigenden Temperaturen, einem Anstieg der Meeresspiegel, dem Abschmelzen von Gletschern, Dürreperioden, und Hungersnöten gerechnet werden. Eine ähnlich starker Klimawandel ereignete sich vor 251 Mio Jahren (Perm-Trias Grenze), wobei ca 90% alles Lebens auf der Erde ausradiert wurde. Um eine Wiederholung dieses Ereignisses zu vermeiden, ist es von absoluter Notwendigkeit den Ausstoss von Treibhausgasen zu minimieren, alternative Energiequellen zu erforschen und nachhaltig zu nutzen.

Unsere Weltmeere bedecken mehr als 70% der Erdoberfläche. Die Bewegung dieser Wassermassen in Form von Wellen ist bisher eine unausgenutzte Energiequelle mit hohem Potential und Wellenkraft kann einen bedeutenden Beitrag zur Energieproduktion auf der Welt beisteuern. Nach Berechnungen des internationalen Weltenergierates in London könnten Wellen- und Gezeitenkraftwerke 15% des weltweiten Strombedarfs decken (diese Berechnung berücksichtigt allerdings nur küstennahe Standorte). Allein in der Ostsee beträgt die errechnete Leistung 24 TWh, was etwa 20% des schwedischen Stromverbrauchs von 2007 entspricht (Bernhoff et al. 2006).

An der Universität Uppsala wird mit Hilfe eines neu konzipierten Wellenkraftwerks die Energiegewinnung durch Wellen studiert. Das hier angewandte Konzept basiert auf einem linearen Generator, der direkt an eine Boje gekoppelt ist, die durch Wellen in Bewegung gebracht wird. Anstatt das Wellenkraftwerk an konventionelle, rotierende Generatoren anzupassen,

wird der lineare Generator an die langsamen Auf- und Abbewegungen der Wellen angepasst. Neben technischer und funktioneller Eignung Leistungsfähigkeit und Weiterentwicklung dieses Systems werden auch meeresbiologische und -ökologische Aspekte wissenschaftlich untersucht.

Wellenkraftwerke der Zukunft müssen ökonomisch, umweltfreundlich und robust sein, um den grossen Kräften des Meeres standzuhalten. Weltweit haben Forscher in Zusammenarbeit mit privaten Unternehmen an verschiedenen Standorten begonnen, die Möglichkeiten der Energiegewinnung aus Wellen zu erforschen. Der grösste Vorteil der Energieausuztung aus Wellenkraft ist, dass die Kraftwerke selbst keine Luftverunreinigungen oder Treibhausgase produzieren. Dennoch hat jeglicher Ausbau von Kraftwerken, der auf offener See stattfindet, einen gewissen Einfluss auf Meereslebewesen, und ob dieser positiv oder negativ ist, kann sich erst nach gründlichen Studien und Auswertungen herausstellen. Um die ökologischen Auswirkungen von Wellenkraftwerken auf die angrenzende Tier- und Pflanzenwelt beurteilen zu können, gilt es, einen umfassenden theoretischen Hintergrund aufzubauen. Umwelteinflüsse von Wellenkraft können in abiotische Faktoren (Wasser-, Luftqualitet), biotische Faktoren (Meeresflora und -fauna) und sozioökonomische Faktoren (Naturschutzgebiete, visuelle Einflüsse) aufgeteilt werden. Im allgemeinen ist das Wissen über die Ökologie der Meereslebewesen viel lückenhafter als über Landlebewesen.

Diese Doktorarbeit beschreibt die Wechselwirkungen zwischen einem etablierten Wellenkraftpark und der Meeresumwelt ausserhalb der Stadt Lysekil an der schwedischen Westküste. Der Lysekilpark wurde 2005 in Betrieb genommen und seitdem regelmässig bautechnisch erweitert. Während dieser Zeit wurden ausserdem 26 „ökologische Wellenkraftwerke“ gebaut, an denen ausschliesslich der Einfluss auf die Umwelt untersucht werden sollte. Diese ökologischen Wellenkraftwerke sind vereinfachte Kraftwerke, bestehend aus einer schwimmenden Stahlboje, die durch ein Stahlseil an einem Betonfundament in 25 m Tiefe, verankert ist. Die eine Hälfte der Fundamente hat Hohlräume, so dass sich Fische und Krustentiere dort verstecken oder diese bewohnen können.

Um zu erforschen, welche Organismen die Sedimente im Testpark bewohnen, und um Veränderungen zu dokumentieren, wurden zwischen 2004 und 2008 jährlich Sedimentproben genommen. Die vorkommenden Arten waren typisch für diesen Lebensraum. Die Sedimentfauna wurde erst positiv durch die Auslegung der ersten fünf Fundamente, doch später negativ durch weitere 21 Fundamente beeinflusst, was evtuell durch die Fundamente oder möglicherweise durch jährliche Schwankungen verursacht wurde. Der Vergleicht zwischen dem Testpark und dem Kontrollgebiet zeigte einen negativen Effekt, was entweder von den Fundamenten oder einem ungünstig gewählten Kontrollgebiet abhängen kann. Zusammenfassend hat die Auslegung der Fundamente eher geringere Auswirkungen auf die Meeresfauna als das Mass an natürlicher Variation.

Ausser Sedimentuntersuchungen habe ich die Einwirkungen von Wellenkraftfundamenten auf die Meeresumwelt durch Tauchgänge, Unterwasserfotografie und Beobachtungen dokumentiert. Um die Lebensraumnutzung von Fischen und Krustentieren und die Kolonisierungsprofile festsitzender Arten zu untersuchen, führte ich eine Pilotstudie an fünf Fundamenten, die 2005 ausgelegt worden waren, durch. Ein Resultat war, dass Fundamente von festsitzenden Organismen kolonisiert und vor allem die vertikalen Oberflächen dicht besiedelt wurden. Fische und Krustentiere um und auf den Fundamenten wurden nur spärlich vorgefunden.

Drei Monate nach Installation der 21 neuen Fundamente im Jahre 2007 konnte gezeigt werden, dass Fische die Fundamente aktiv aufsuchen und dass in den Hohlräumen, die in einigen Fundamenten angebracht worden sind, Taschenkrebse aufzufinden waren. Ein Einfluss der Lage und Ausrichtung der Hohlräume auf die Verteilung der Taschenkrebse und Fische konnte gezeigt werden. Die 21 Fundamente waren auf zwei Lokale innerhalb des Testparks, Nord und Süd, aufgeteilt worden. Zwei Sommer lang habe ich untersucht, welche festsitzenden Arten die Fundamente besiedeln und in welcher Reihenfolge sich Arten ansiedeln (Sukzession). Ich fand eine höhere Biodiversität auf den nördlichen Fundamenten, welches darauf schliessen lässt, dass der Einfluss eines Fundamentes auf festsitzende Organismen stark abhängig von dessen Plazierung ist, denn physische und ökologische Faktoren unterschieden sich zwischen den Fundamenten.

Biofouling (ungewollter Aufwuchs von Organismen) an Wellenkraftbojen kann die Energieproduktion beeinträchtigen und somit zu erheblichen Problemen führen. Deshalb habe ich Aufwuchsorganismen an Bojen zusammengestellt und konnte zeigen, dass die Artzusammensetzung des Aufwuchses von Miesmuscheln dominiert wurde, die 90% der Biomasse ausmachten. Bojen, die stärkeren Wellen ausgesetzt waren, wurden von den Muscheln deutlich bevorzugt. Berechnungen zeigten, dass Biofouling an Wellenkraftbojen jedoch keinen beträchtlichen Einfluss auf deren Energieproduktion hatte.

Zusammenfassend fand ich heraus, dass die Wellenkraftwerke im Lysekilpark kaum oder nur einen sehr geringen Einfluss auf die umgebenden Sedimente hat. Dagegen erhöhte die Anlegung von neuem Hardsubstrat, aus Betonfundamenten und Wellenkraftbojen bestehend, die Artenvielfalt makrant. Fische, Krabben, Muscheln und festsitzende Organismen, die hier früher nicht vorkamen, haben beträchtlich zugenommen. Dieselben Auswirkungen von Auslegungen künstlicher Riffe ist aus anderen Studien bekannt. Demzufolge haben Wellenkraftwerke einen überwiegend positiven Effekt auf die biologische Vielfalt im Wellenkraftpark. Eine mögliche negative ökonomische Folge vom Parkausbau wäre, dass der Fischfang innerhalb des Parks nicht möglich ist. Dadurch fungieren solche Wellenparks als Küstenschutz, wo die Ausnutzung von Meeresressourcen verboten. Dies kann jedoch durch eventuellen Űberschuss an Fisch und Krustentieren im Park umliegende Gebiete und somit zukünftigen Fischfang in der Umgebung langfristig begünstigen.

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