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Underwater radiated noise from Point Absorbing Wave Energy Converters

*Noise Characteristics and Possible Environmental
Effects*

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Abstract

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The conversion of wave energy into electrical energy has the potential to become a clean and sustainable form of renewable energy conversion. However, like all forms of energy conversion it will inevitably have an impact on the marine environment, although not in the form of emissions of hazardous substances (gases, oils or chemicals associated with anticorrosion). Possible environmental issues associated with wave energy conversion include electromagnetic fields, alteration of sedimentation and hydrologic regimes and underwater radiated noise.

Underwater noise has the potential to propagate over long distances and thus have the potential to disturb marine organisms far away from the noise source. There is great variation in the ability to perceive sound between marine organisms, one sound that is clearly audible to one species can be completely inaudible to another. Thus, to be able to determine potential environmental impact from WECs associated with underwater noise, the noise radiated from the WECs must be known. This thesis presents results from studies on the underwater radiated noise from four different full-scale WECs in the Lysekil Wave Power Project.

Hydrophones were used to measure the underwater radiated noise from operating point absorbing linear WECs. The main purpose was to study the radiated noise from the operating WECs with emphasis on characteristics such as spectrum levels, Sound Pressure Level (SPL), noise duration and repetition rate. This to be able to determine the origin of the noise and if possible, implement design changes to minimize radiated noise.

The results identified two main operational noises (transients with the bulk of the energy in frequencies <1 kHz). The SPL of the radiated noise fluctuated significantly, depending on wave height. Broadband SPL_{rms} of the measurements ranged between ~110 dB and ~140 dB re 1 μPa and SPL_{peak} of specific noises ranges between ~140 and ~180 dB re μPa. Audibility was estimated range from 1km to 15 km depending critically on species and on assumptions of propagation loss. The noise is not expected to have any negative effects on behaviour or mask any signals, unless in the vicinity (<150m) of the WECs in significant wave heights. No physical damage, even in close vicinity are expected on either fish or marine mammals.

Having the aim to have as little impact on the environment as possible, these studies are important. This way precautions can be implemented early in the technical development of this kind of renewable energy converters. The benefits from the WECs the *Lysekil wave power project* are believed to outweigh possible environmental impacts due to underwater radiated noise.

Keywords: Wave energy conversion, renewable energy, environmental impact, marine ecology, underwater noise

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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., Gustavsson, 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., **Haikonen, K.**, Sundberg, J. (2010) Wave power – sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters. *Renewable & Sustainable Energy Reviews*, 14(4):1329-1335.
- III **Haikonen, K.**, Sundberg, J., Leijon, M. (2013) Characteristics of the Operational Noise from Full Scale Wave Energy Converters in the Lysekil Project: Estimation of Potential Environmental Impacts. *Energies*, 6(5): 2562-2582.
- IV **Haikonen, K.**, Sundberg, J., Leijon, M., (2013) Hydroacoustic measurements of the noise radiated from wave energy converters in the Lysekil project and project WESA. *1st international conference and exhibition on Underwater Acoustics*, UA2013, Corfu, Greece, 23rd - 28th June 2013.
- V **Haikonen, K.**, Sundberg, J., Leijon, M., (2014) Underwater radiated noise from direct driven Wave Energy Converters: Sound Pressure Levels in relation to Significant Wave Height and Wave Steepness (*Submitted paper*).
- VI **Haikonen, K.**, Sundberg, J., Leijon, M. (2014) Underwater radiated noise from direct driven Wave Energy Converters: Comparison between Sound Pressure Levels, Spectral levels and Noise Duration of Specific Operational Noises (*Submitted paper*)

The author has also contributed to the following papers, not included in the thesis:

- VII. Lejerskog E., Boström C., Savin A., Strömstedt E., Gravråkmö H., Engström J., **Haikonen K.**, Rahm M., Ekergård B., Svensson O., Waters R., Tyrberg S., Ekström R., Kurupath V., Li W., Sundberg J., Leijon M., Baudoin A., Hai L., Krishna R. "Lysekil Research Site, Sweden: Status Update". In Proceedings of the 9th European Wave and Tidal Energy Conference, Southampton, UK, 5-9 September 2011
- VIII. **Haikonen K.** and Sundberg J. "Sound measurements on full scale Wave Energy Converters in the Lysekil project" *European Conference on Underwater Acoustics*, ECUA, Edinburgh, UK, July 2012.

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Abbreviations

3D	Three dimensional
AR	Artificial reef
dB	Decibel
DP	Double pulse
ESH	End stop spring hit
LRS	Lysekil research site
LVMS	Low voltage marine substation
LWPP	Lysekil wave power project
MT	Moving translator
MPA	Marine protected area
n	Number of samples
N	Spreading factor
NM	Nautical mile
pH	Acidity
OWC	Overtopping water column
Pa	Pascal
RL	Received level
RMS	Root mean square
SIL	Sound intensity level
SL	Source level
SP	Single pulse
SPL	Sound pressure level
Hs	Significant wave height
TL	Transmission loss
WEC	Wave energy converter
μ Pa	Micro Pascal

Nomenclature

ρ	kg/m ³	Density
α_2	-	Wave steepness
c	m/s	Velocity
d	m	Depth
D	Km	Depth
p	Pa or N/m ²	Pressure
p_i	Pa	Sound pressure
I	W/m ²	Sound power
K	Pa	Bulk modulus
f	Hz	Frequency
λ	m	Wavelength
R	m	Distance to sound source
α	dB/km	Absorption coefficient
S	‰	Salinity
γ	-	Heat capacity ratio
Z	-	Acoustical impedance
T	°C	Temperature

Introduction

August 19 2014 was Earth Overshoot Day, marking the date when humanity has exhausted nature's budget for the year. This means that for the rest of the year we will be operating in overshoot. The world's need for energy is increasing, between 2000 and 2013 the total energy consumption of the world increased with 40%¹. Fossil fuels (coal, natural gas, and oil) accounted for 87 percent of global primary energy consumption in 2012². These energy sources are associated with adverse environmental impacts such as air pollution, oil spills, and acid rain. Also, the topic *Peak oil* is being debated worldwide, will the oil run out or not? [1]. Renewable energy sources can be found all over the world (solar, wind, ocean waves, hydropower, biomass and geothermal) and the amounts of renewable energy on this earth is vast as they in principle can meet world's energy demand severalfold. Conversion of renewable energy into electric energy has existed for many years, some of the more established concepts include solar, wind and hydropower. However, in order to make renewable energy conversion truly sustainable and dependable there are several issues that have to be solved. One major problem with renewable energy is to convert the energy to electricity at a price that can compete with fossil fuel and nuclear energy conversion. As long as there is a cheaper alternative other than renewable energy, this is likely to be chosen more often.

It has long been known that there is tremendous power in ocean waves. This energy is a concentrated form of solar energy. Uneven distribution of heat radiation from the sun upon our planet creates wind. When wind blows over the oceans the friction creates waves. In each of these steps there is an increase in energy density. This results in a renewable energy source with high energy density, meaning that ocean waves could be an important source of energy if harnessed.

The conversion of wave energy will not have emissions associated to other forms of energy conversion (e.g. air pollutants from fossil fuels), but still there will be other effects on the marine environment when man-made (anthropogenic) constructions are deployed in the ocean [II]. Little is still known of the potential effects that marine renewables can have on the marine ecosystem. Suggested effects are artificial reef effect, electromagnetic fields and underwater noise. These effects need to be studied, not only to reduce uncertainties

¹ Enerdata, Global Energy Statistical Yearbook 2014: <http://yearbook.enerdata.net/> (17/10-14)

² Worldwatch Institute: <http://www.worldwatch.org/fossil-fuels-dominate-primary-energy-consumption-1> (17/10-14)

(are they positive, negative or neutral?) but also to be able to implement technical design changes to reduce or even eliminated possible adverse impacts.

1.1. Wave Energy Conversion

The fact that the oceans hold vast amounts of energy has led to great efforts in trying to harness it. Already in the end of the age of enlightenment (1799) techniques for wave energy conversion were patented (Girard & Son, France) [2]. Since then, both industrial and academic forces have tried to tame the power in the ocean waves. The global energy potential represented by ocean waves, predicted to be one Terawatt (TW) [3]. However it is very difficult (maybe even impossible) to state the amount of energy that is possible to harness since little is known about the efficiency of future Wave Energy Converters (WECs).

Wave energy conversion research gained momentum during the 70s (oil crisis). In the beginning of the 21st century there were more than 300 patents regarding wave energy conversion [2]. Over the years WEC concepts have come in many shapes and forms, but only a handful have left the drawing boards and test tanks to reach full-scale offshore testing. Some of these are closing in on commercial deployment [4-6]. Designing Wave energy conversion concepts have several challenges. The system has to be able to withstand the rough conditions that the ocean offers (e.g. salt water and biological fouling) and able to handle the enormous dynamics in power input, and at the same time being economically viable. The *Lysekil Wave Power Project* (LWPP) operated by the Division of Electricity at Uppsala University aims to design a wave energy conversion system that is simple, sturdy and environmental friendly in design and at the same time being economically feasible.

There are several different methods to convert wave energy into electric energy, and these systems can be classified into three categories based on their working principle: *Oscillating Water Column* (OWC) [7], *Overtopping devices* [8] and *Wave activated bodies* [4, 6, 9]. The concept in the LWPP is based on a point absorber system with directly driven longitudinal linear generators. A buoy on the surface absorbs power from heaving waves; the kinetic power in the buoy is transferred to a translator inside the WEC through a line. The vertical motion of the translator (magnet) in relation to a stator (coil) induces electricity [4]. The basic concept of the WECs in the LWPP is shown in fig 2.2.

1.2. Environmental Impact

As anthropogenic activities (e.g. fishery, shipping, extraction of natural resources, aquaculture, recreational activities) increase in the marine environment, more and more of the oceans are affected by humans [10-12]. The utilization of renewable energy is seen as one step closer to a sustainable society. Wave energy conversion has several benefits compared with fossil fuels: no emissions in form of sulfur dioxide, nitrogen oxides, hydrocarbons, carbon monoxide dioxide and carbon dioxide particulates. The aim of these projects is also to have no emissions in form of harmful substances such as lubrication oils and anticorrosion paints. As long as the sun heats our planet there will be winds and waves, a result of this could be clean, cheap and virtually limitless amounts of energy if converted in an efficient and sustainable manner. However, emissions of air pollutants and/or other pollutants associated with fossil fuels are not the only way to impact the environment; the growth of interest to exploit the ocean further has raised concerns about how marine energy conversion (wind, current, wave and tidal) will affect the marine environment. No matter where in the oceans these energy converters are placed, there will be some impact (positive and/or negative) on the marine environment, locally and maybe more widespread [III]. Large scale installations will add anthropogenic impact in the oceans, and therefore ecological costs and benefits must be determined [13]. Suggested and identified impacts on the environment from WECs include [14-16]:

- Artificial reef effect
- Electromagnetic fields
- Underwater noise
- Toxicity of paint, oils and other associated chemicals
- Alteration of seabed habitats
- Alteration of hydrologic regimes
- Suspension of sediments and contaminants
- Collision (aquatic organisms struck by moving parts)
- Habitat loss
- Collision/entanglement
- Non-indigenous species

All forms of offshore renewable energy conversion will inevitably have some impact on the marine environment. However, knowing an impact (positive or negative), the design of these energy converters can be changed to enhance, minimize or even neutralize the effect on the marine environment.

1.2.1 Underwater Noise

Background (ambient) noise levels in the oceans have increased significantly during the last decades. Anthropogenic activities in water produce underwater noise and shipping alone has contributed with an increase of 12 dB to ambient noise levels [11]. Most anthropogenic noises are in low frequencies <1000Hz, but there are also many sources (small boats, sonars, acoustic deterrent and harassment devices) that produce high frequency noise >1000Hz [11].

The use of underwater sound is common in marine organisms and can be used in a variety of ways such as communication, navigation, detection of prey and predators, and overall learning about their environment [17-21]. Underwater radiated noise is one of the suggested impacts that ocean based renewable energy converters will contribute with [II,15]. The characteristics of radiated noise from the installation (pile driving) and operation of offshore wind power installations are known (continuous low frequency noise) and its possible effects on marine mammals and fish have been studied [22-24]. Depending on the source (vibrations in gearboxes, translators, springs or other moving parts) of the radiated noise will differ in characteristics (frequency range, spectral levels, noise duration and repetition rate). Different wave energy conversion techniques are likely to radiate different kinds of noise, and thus have different impact on the environment; e.g. a technique that radiates a low frequency noise is more likely have an impact on species that are more sensitive to low frequency noises e.g. Atlantic herring (*Clupea harengus*) [25] and Atlantic cod (*Gadus morhua*) [26], and less impact on species that are less sensitive to low frequency noise e.g. Killer whale (*Orcinus orca*) [27]. How various species will be influenced by the noise from different operating renewable energy converters is a difficult question to answer; studies on the response has to be studied for the specific type of noise.

Sound, unlike light or other potential stimuli, has the ability to transmit very efficiently through water. Anthropogenic noise with low to moderate frequencies with high sound pressure level (SPL) at the source, can be detected 10-100 km from the source if conditions are right. As the anthropogenic noise has increased in the oceans, the concern about how this will affect marine organisms has also increased. The impact of underwater noise can be divided into four zones of influence: 1) *Audibility*: the SPL of the sound is high enough to be perceived. 2) *Masking*: the SPL of the sound is high enough to reduce (partially or entirely) the audibility of biological signals. 3) *Responsiveness*: the SPL is so high that it induces a response e.g. behavioral (avoidance) or physiological (stress). 4) *Hearing loss, injury, mortality*: the SPL of the sound is so intense that an animal exhibits hearing loss (temporal or permanent) or if the sound is received with a very high SPL it can damage in non-auditory tissues, or even lead to death (extreme cases) [28].

The hearing capabilities and tolerance to underwater noise varies not only between different species, but may also between different individuals, making it a difficult task to determine if there will be any impact. To be able to make

a good estimation how various species will be influenced by the noise from different operating renewable energy converters four variables are needed to be known 1) Characteristics of the radiated noise 2) Hearing capabilities of the species of interest 3) Noise tolerance of the species of interest and 4) Vocal capabilities of the species of interest.

Marine mammal species that populate the Swedish West coast include Harbor porpoise (*Phocoena phocoena*) and Harbor seal (*Phoca vitulina*). Both species are protected and listed as vulnerable by the Swedish Species Information Centre. On the Swedish West coast there are about 110-130 different fish species. Fish species that populate the Swedish West coast and on which hearing studies have been performed include inter alia Atlantic cod (*Gadus morhua*), Atlantic herring (*Clupea harengus*), Atlantic salmon (*Salmo salar*), Haddock (*Melanogrammus aeglefinus*) and Dab (*Limanda limanda*).

1.3. Aim of this thesis

The purpose of this thesis is to study and quantify the underwater radiated noise from different operating Wave Energy Converters in the *Lysekil Wave Power Project*, in order to estimate potential effects it may have on the marine environment. Noise characteristics, propagation loss and the significance of a noise dampening feature are presented.

2. The Lysekil Wave Power Project

The *Lysekil Wave Power Project* (LWPP) began in 2002 by researchers and students at the Division of Electricity, Uppsala University. The main purpose of the project was to develop a wave power conversion concept that is simple, sturdy, effective and sustainable. The concept is based on point absorbing direct driven linear Wave Energy Converters (WECs). In 2003 a laboratory version of a WEC was finalized and in 2004 a test site where real life experimental parts of the project would take place was chosen. In March 2006 the first full-scale WEC was deployed in the *Lysekil Research Site* (LRS) [29]. In 2014 a total of nine-full scale WECs had been deployed in the LRS, and several different WEC design solutions had been tested along with two prototype substations [30, 31]. To achieve the goal of developing a sustainable concept, studies on the possible environmental impact from the WECs begun in an early stage of the LWPP. Initial environmental studies concerned topics as colonization, biofouling, artificial reef effect and effects on nearby soft bottom seabed [32-36].

2.1. The Lysekil research site

All offshore experimental testing and measuring in the LWPP is performed at the LRS which is located on in Skagerrak on the Swedish West coast (58° 11' 44.12" N, 11° 22' 22.50" E), approx. 5 Nautical Miles (NM) km south of Lysekil. The location of the LRS was chosen based on several criteria such as wave climate, proximity to port, electrical connection and research facilities, water depth and seabed conditions. To the west of the LRS is open sea (North Sea), to the north and south islets are found within a distance less than 1 NM. The seabed is soft bottom type and consists of an even surface of sand and silt, and the depth in the research area ranges between 24 and 26 meters, with the greater depth in the western part of the site [37]. In 2004 a wave measuring buoy (Datawell BV Waverider) was deployed in the LRS. Since then it has continuously provided wave measuring data. In 2008, a lattice tower equipped with a network camera was deployed on a nearby islet (Klammerskäret) [38]. The energy from the operating WECs is transmitted via a subsea power cable to a measuring station on placed on an island (Härmanö) about 3 km from the LRS.

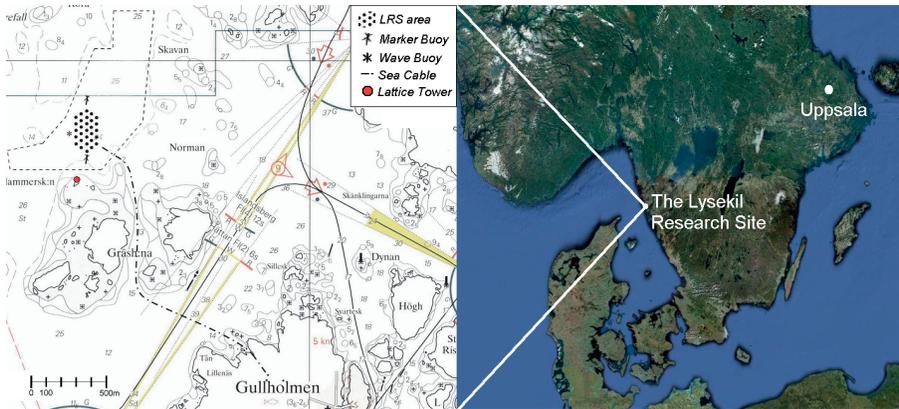


Figure. 2.1. The Lysekil Research Site: Location and sea chart of the site and its surroundings.

Until the end of 2013, the LWPP was authorized to operate up to ten WECs in the LRS together with a sea cable to land and 30 dummy units (environmental buoys) for environmental impact studies. A new authorization that extends 20 years was approved in 2014. Until the fall of 2014 a total of eleven WECs, two marine substations and 26 dummy units had been deployed. Some of these objects have been recovered and decommissioned. A detailed description of the LRS and progress within it is found in [I, VII]

2.2. The technology

The LWPP WEC concept is based on direct driven linear generators placed on the seabed [29, 39] and a point absorbing buoy on the surface. The surface buoy absorbs energy from the incoming waves which is transmitted as kinetic energy through the line when the buoy heaves. The kinetic energy in the translator is converted into electrical energy when the magnets on the translator move in relation to a fixed stator in the generator. The mechanical system in this concept is simple. However, output voltage and current of the WEC will vary in both frequency and amplitude, as the translator will move with varying speed and length. To match the electricity from the WECs to the electricity on the grid, it has to be converted. The conversion is performed in a Low Voltage Marine Substations (LVMS) [39, 40]. This technology is expected to have limited negative environmental impact during deployment, operation and decommissioning. Since the objects (WEC and LVMS) are placed on a concrete base no preparatory work such as piling is required for the deployment, thus only a minor disturbance is expected on the surrounding sediments. During operation there are no expected emissions of harmful substances such as gases, paints, heavy metals, oils etc. However there may be other significant impacts e.g. artificial reef effect, electromagnetic fields and underwater radiated noise.

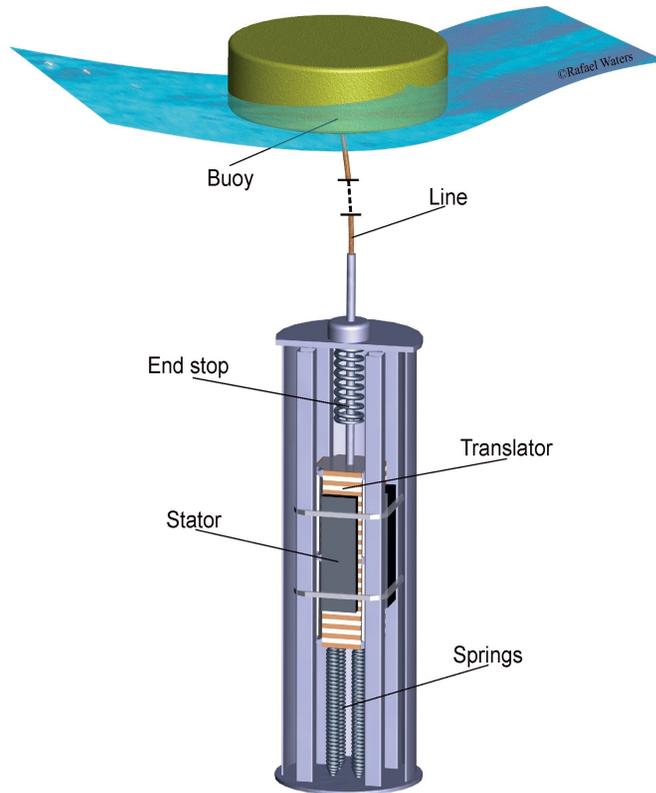


Figure 2.2. A conceptual representation of the Lysekil Wave Power Project Wave Energy Converter

2.3. Environmental impact studies in the Lysekil Wave Power Project

Environmental impacts from the WECs in the LWPP has been under consideration since the beginning of the project. The first study started in 2004; this study examined macrofaunal assemblages in the seabed around the WECs in the LRS and in a neighboring reference site were examined [29, 32]. In 2005 the first dummy units (environmental buoys) were deployed in the site. These environmental buoys were used in colonization and biofouling studies. In 2007 a total of 25 environmental buoys had been deployed in the LRS. Each unit consisted of a cylindrical concrete base with a mass of 10 metric tons (placed on the seabed) connected to a buoy on the ocean surface (Fig. 2.3). The buoys have varied in size (1-1.5m in diameter) and material (metal and/or plastic). The environmental buoys and the WECs were used to study possible

impacts that a WEC might have on the local environment including biofouling, colonization, artificial reef effect and impact on local benthic macrofauna [32-36]. On the foundations, a succession in colonization over time was demonstrated, with a higher degree of coverage on vertical surfaces. The biofouling on surface buoys was dominated by the blue mussel (*Mytilus edulis*) [35]. Colonization studies showed how low densities of mobile organisms, however the abundance of fish and crabs on the foundations was significantly higher than on the surrounding soft bottom seabed [34]. The macrofaunal composition varied greatly over the years, both within the LRS and the reference site. It has been shown earlier that macrofaunal assemblages vary greatly without being exposed to anthropogenic disturbance [40]. Results indicate that the deployment of WECs and environmental buoys may have influenced macrofaunal assemblage, but also that the deployment probably had a minor impact on the surrounding benthic community relative to the natural variation [32]. These studies have given an early insight in how the deployment of WECs may impact the local environment when considering biofouling, colonization and impact on nearby soft bottom seabed. However, long term studies are needed to see what the final impact/s will be; how long will it take before a steady state in biological succession is achieved and if the effect will be local or more widespread? These questions are difficult to answer and will be depending on more than one factor.



Figure 2.3. Deployed WEC and dummy units in the *Lysekil* research site.

3. Underwater Acoustics

The following section will shortly review the basics of sound and of sound propagation. Special emphasis will be placed on underwater sound propagation. More comprehensive theory within the area of underwater acoustics in shallow water propagation can be found in [41, 42].

3.1. Sound, the basics

Sound (acoustic waves) is a propagating vibration or a sequence of vibrations that originates from a mechanical perturbation. To disperse from the source, the acoustic waves need an elastic medium (gas, liquid or solid) in which they can propagate, hence cannot acoustic waves travel through a vacuum. Acoustic waves are longitudinal waves (compression waves) that propagate through adiabatic compression and decompression. The longitudinal waves will propagate from the source with the speed of sound (c), which is depending on the physical properties (the bulk modulus K and density ρ) of the medium in which the waves travel. K is depending on the heat capacity ratio (γ) and pressure p . In general for fluids c is proportional to the square root of the ratio of K and ρ of the medium (Newton-Laplace equation):

$$c = \sqrt{\gamma * \frac{p}{\rho}} = \sqrt{\frac{K}{\rho}} \quad (1)$$

Both K and ρ are depending on ambient conditions. In seawater K is dependent of temperature T and pressure p , and ρ is dependent of T , pressure p (dependent on depth d) and Salinity S . Hence is the speed of sound in water also depending on these conditions. An approximate calculation of the speed of sound in seawater is given by [43]:

$$c = 1412 + 3.21T + 1.19S + 0.0167d \quad (2)$$

For example, c in sea water with the same $S=35\%$ and $d=25\text{m}$, but different T :

Temperature (T)	0°C	20°C
Speed of sound (c)	1454 m/s	1518m/s

Sound is characterized by its frequency f (Hz) and its wavelength λ (m). The relationship between the speed of sound (c), frequency (f) and wavelength (λ) is described by the following equation:

$$c = \lambda f \quad (3)$$

However, if the acoustic wave is propagating in a *non-dispersive* medium the wave speed will be constant. c is in this case only dependent on the physical properties of the medium (K and ρ). All frequencies travel at the same speed and the energy transport in the sound will be constant.

If the acoustic wave is propagating in a *dispersive medium*, c will be depending on the f , through the dispersion relation. Each frequency will propagate at its own *phase velocity*, while the energy of the wave propagates at the *group velocity*. Water is a dispersive medium.

Acoustical amplitude can be expressed as acoustic intensity (sound power) or acoustic pressure (sound pressure). A sound source radiates sound power (I) which result in sound pressure (p_i). Sound power is the cause and sound pressure is the effect. I is the acoustical power per unit area (W/m^2) in the direction of propagation. Sound power level (sound intensity level SIL) is a logarithmic measure (dB) of the sound intensity, relative to a reference level. p_i is the force on a surface area perpendicular to the direction of the sound wave, due to pressure changes caused by the propagation of the sound wave, expressed in Pa or μPa . Sound pressure level (SPL) is the effective p_i of a sound relative to a reference value. The standard reference value for sound in gas is 20 μPa ; in water the reference value is 1 μPa . SPL is a logarithmic measure (dB). The logarithmic measure in both SIL and SPL are justified by the huge fluctuations I and p_i -values. Also, defined for power, the dB can be adapted to p_i , as I is proportional to the square of pressure. To calculate an absolute value of the p_i in dB, a reference value is needed. SPL and SIL are equivalent when measured in dB:

$$SIL = 10 \log \left(\frac{I_1}{I_2} \right) = 10 \log \left(\frac{p_1^2}{p_2^2} \right) = 20 \log \left(\frac{p_i}{p_{ref}} \right) = SPL \quad (4)$$

Where p_i is the measured pressure and p_{ref} is the reference value of the medium.

The reference levels used to compute SPL in water 1 μPa . The equivalent value in air is 20 μPa . When comparing SPL_{water} and SPL_{air} the difference in

reference levels and the difference in acoustical impedance (Z) between water and air (~ 3600 times higher in water) has to be considered. If converting from SPL_{water} to SPL_{air} , subtract ~ 26 dB (due to difference in reference levels) and ~ 36 dB (due to difference in acoustical impedance) from the SPL_{water} [41].

3.2 Sound propagation loss

Here follows a simplified and basic theory of underwater sound propagation loss. There are acoustic differences between deep and shallow water. Some of the main differences are stronger reverberation, attenuation and 3D effects in shallow water. Since the boundaries (ocean surface and seabed) on which underwater sound interact are closer in shallow waters, it is almost certain that the propagating sound wave will interact with them. Seabed attenuation, reflection, scattering and reverberation are more prominent in shallow water compared with deep water. 3D acoustic effects are the result of the bathymetry of the area where the sound wave propagates. In deep water, the only serious concern is the bathymetry of seamounts and islands. In shallow water, the bathymetry (e.g. slopes, shallows, reefs and canyons) can have significant 3D acoustic effects [42].

A sound wave propagating away from its source will decrease in intensity with increasing distance and since sea water is a dissipative propagation medium, two different factors are responsible for this reduction in power/pressure of the sound 1) *geometric spreading loss* and 2) *attenuation* (absorption). These two combined are called *propagation loss* or *transmission loss* (TL).

Geometric spreading loss is when the sound wave propagates away from its source, and the energy of the sound spreads over a greater surface area. The energy of the sound is constant, but spreads over a larger area with increasing distance from the source. This results in a decrease in energy per surface area, proportional to the inverse of the surface. Geometric spreading loss is independent of f . The geometric spreading loss (TL_g) can be expressed as:

$$TL_g = N \log\left(\frac{R}{R_{1m}}\right) = N \log(R) \quad (5)$$

where the reference unit (R) is the distance to the sound source in meters ($R_{1m} = 1$ m), and N is the factor of spreading loss. There are three common spreading loss factors (*spherical*, *cylindrical* and *practical*). *Spherical spreading loss* ($N=20$) is applied if the propagation of a sound occurs in an acoustic field without any boundaries (water surface, seabed) on which the sound may reflect. *Cylindrical spreading loss* ($N=10$) can be applied if the propagation occurs in a sound channel or in shallow waters where the boundaries (water surface and seabed) on which sound can reflect are close. However, a sound wave propagating in a shallow water environment will not be contained perfectly by

reflection. The sound will also experience factors such as refraction and scattering. Thus the true spreading loss of a sound is often somewhere between spherical and cylindrical spreading loss. *Practical spreading loss* ($N=15$) represents an intermediate spreading condition.

The other factor responsible for transmission loss is *attenuation* (absorption). Acoustic attenuation is an energy loss that a sound expresses when propagating in a medium. Since sea water is a dissipative medium, it will absorb a part of the transmitted energy of the sound. The viscosity of the medium will cause thermal absorption of energy. Stokes law of sound attenuation:

$$\alpha = \frac{2\eta f^2}{3\rho c^3} \quad (6)$$

where η is the dynamic viscosity coefficient of the fluid and α is the attenuation coefficient, states that different frequencies have different properties when it comes to acoustic attenuation. However, the attenuation of sound in sea water is caused not only by water viscosity but also to a minor degree by the relaxation of magnesium sulphate (MgSO_4) and boric acid (B(OH)_3). A simplified equation, based on the Francois-Garrison Model [43, 44] given by Ainslie and McColm can be used to express the attenuation in seawater as the sum of absorption from pure water and the relaxation of MgSO_4 and B(OH)_3 [45]:

$$\alpha = 0.106 \frac{f_1 f^2}{f^2 + f_1^2} e^{(pH-8)/0.56} + 0.52 \left(1 + \frac{T}{43} \right) \left(\frac{S}{35} \right) \frac{f_2 f^2}{f^2 + f_2^2} e^{-D/6} + 0.0049 f^2 e^{-(T/27+D/17)} \quad (7)$$

where α is the attenuation coefficient (dB/km), D is the depth (km), pH is the acidity, f is the frequency (kHz) considered, f_1 is the relaxation frequency (kHz) for boron (dependent on S and T) and f_2 is the relaxation frequency (kHz) for magnesium (dependent on T).

The absorption increases with increasing f and S , and decreases with increasing D . In average conditions ($T = 16^\circ\text{C}$, $S = 35\%$, $pH = 8$ and $D = 0$ km) using the Ainslie and McColm model, the decrease in sound pressure level (dB/km) at:

- 1 kHz = 0.056
- 10 kHz = 0.823
- 100 kHz = 38.137

Low frequency sounds can propagate over longer distances in deep water compared with high frequency sounds, due to lower attenuation. However, in shallow waters, or for very low frequencies ($\text{VLS} \leq 20$ Hz) the seabed can

become a part of the propagation medium instead of being a reflecting surface. In an area with soft bottom seabed, a significant part of the energy in a water-borne acoustic wave is transferred to the sediment, and there is no critical angle for this to occur. For a hard bottom seabed this loss of energy is less significant. If the sound wave hits the hard bottom with an angle less than the critical angle, the acoustic wave will be reflected off the hard bottom surface [42]. Hence is the substrate of the seabed an important factor to take in consideration when estimating propagation loss of underwater radiated sound.

Summing up geometric spreading loss and energy loss through attenuation the following equation for transmission loss is given:

$$TL = N \log \left(\frac{R}{R_{1m}} \right) + \alpha R = N \log R + \alpha R \quad (8)$$

where the reference unit (R) is distance in meters, N is the spreading loss factor and α is the absorption coefficient (dB/km).

The Source Level (SL) is the sound pressure above the reference level, at 1 meter from the source of the sound. At other distances from the sound pressure is expressed as received level (RL). RL at a specific distance can be estimated if TL in the area and SL is known:

$$RL = SL - N \log \left(\frac{R}{R_{1m}} \right) + \alpha R = SL - TL \quad (9)$$

In this thesis the measurements were performed at 1 (R_{1m}), 20 (R_{20m}) and 150 (R_{150m}) meters from the source.

In order to fully describe an underwater sound field, knowledge about both sound pressure and particle displacement or particle motion is needed. Particle displacement is the movement of a particle from its equilibrium position in a medium due to the propagation of a wave. This thesis only covers measurements on sound pressure. Particle displacement will not be discussed any further.

3.3 Measuring underwater sound

To measure underwater sound pressure levels hydrophones are used. A hydrophone is basically an underwater microphone. It is a pressure sensor based on a piezoelectric element, which generates electricity if subjected to pressure. Basically it converts pressure to voltage.

4. Underwater noise and the Environment

The purpose of this chapter is to give short insight to bioacoustics. Focus will be on sound reception in fish and marine mammals, how they utilise sound and potential adverse effects when exposed to anthropogenic noise.

4.1 Bioacoustics

The science which combines biology and acoustics is referred to as bioacoustics. It is the study of sound in animals (including humans) and includes areas such as acoustic communication, sound reception, sound production, auditory anatomy and effects of anthropogenic and environmental noise on animals.

The underwater environment is a highly acoustic environment with sounds originating from both anthropogenic (shipping, bridges, offshore drilling, renewable energy conversion, recreational activities, acoustic deterrent devices, sonars) and natural sources (wind, waves, rain, ice, seismic and biological).

Sound is as important to underwater organisms as light is to humans. Sound reception (hearing) is the alerting sense found in all vertebrates. Several species of blind fishes, reptiles, amphibians and mammals are known, but no vertebrate species completely lacking hearing have been found. In water, acoustic signals have the possibility to propagate over very large distances, thus many marine organisms use sound to extend their perception of their surroundings. Many marine species utilize sound in various ways e.g. fishes and marine mammals use sound for communication, detection of prey, predators and competitors, foraging, navigation/orientation and overall learning about their environment [17-21, 46, 47].

In this thesis the primary focus will be on hearing capabilities (sound reception) in marine fish and mammals, and possible adverse effects due to anthropogenic noise.

4.2 Fish

There are approximately 33 000³ known species of fish, and an unknown number of undiscovered fish species. Of all these species, only a small fraction has

³ Froese, R. and D. Pauly. Editors. 2014. FishBase. World Wide Web electronic publication. www.fishbase.org, version (08/2014).

been studied with respect to their acoustic mechanisms and capabilities (ability to produce and detect sound). Research on the acoustic capabilities of fish has predominantly been performed on species from the class *Actinopterygii* (bony fishes). Two systems for hearing have been discovered 1) the inner ear, which is sensitive to pressure change and 2) lateral line which is sensitive to particle displacement and pressure change. Both the lateral line and inner ear are sensory systems based on mechanoreceptors that respond to a change in an external stimulus (pressure, distortion) [48-51]. See **paper III** for a more details on the inner ear and the lateral line and fish hearing capabilities.

4.3 Marine Mammals

There are approximately 130 known species of marine mammals [52], these can be divided in to four different orders; *Cetaceans* (whales, dolphins and porpoises), *Pinnipeds* (seals, sea lions and walruses), *Sirenians* (manatees and dugongs), and marine *Fissipeds* (the polar bear, and two species of otter). Hearing capability studies have been performed on approximately 20 species [53, 54]. Marine mammals have one main organ to process sound: the inner ear. However, species in the order *Sirenians* have a sensory system similar to the lateral line in fish. *Vibrissae* distributed over the *Sirenians* body, functions as mechanoreceptors and are sensitive to hydrodynamic stimuli in frequencies between 5-150 Hz [55]. Even if the ear of all mammals (marine and terrestrial) have the same basic structure: outer (sound reception), middle (transmits and amplifies acoustic energy) and inner ear (filter and converts signal into neural impulses), there is great variation in the range of frequency in which they can perceive sound. This is due to structural adaptations that have evolved in all groups (e.g. narrow and wax filled ear canals, muscles that can close the ear canal and dense ossicles to be able to hear high frequencies better) [56]. More detailed information about the mechanisms and capabilities of marine mammals can be found in **paper III**.

4.4 Marine invertebrates

Marine invertebrates do not hear in the same sense as vertebrates do. It is believed that they sense water- or substrate-borne vibrations associated with changes in acceleration, hydrodynamic flow, and/or sound through external sensory hairs and internal statocysts (balance sensory receptor). The sensory hairs on crustaceans have been shown to be sensitive to vibrations frequencies between 20-300 Hz [57]. Studies on vibration perception associated with statocysts show a response in frequencies ranging between 30-1500 Hz (Cephalopods) [58-60] and 100-3000 Hz (Common prawn) [61].

4.5 Hearing capabilities of marine organisms

Studies on sound reception of marine mammals, fish, amphibians and invertebrates have resulted in audiograms for several species. These audiograms show the hearing threshold at specific frequencies. There is a great variation in the hearing capabilities in different species, which is coupled to the variation in anatomy and physiology [54]. The difference in sensitivity at 1 kHz for species from five different taxonomical groups (all values are in dB re 1 μ Pa):

- Goldfish (*Carassius auratus* Teleostei) \approx 65 dB [62]
- Harbor seal (*Phocoena phocoena* Cetacean) \approx 80 dB [63]
- Loggerhead turtle (*Caretta caretta* Reptilia) \approx 140 dB [64]
- Common octopus (*Octopus vulgaris* Cephalopod) \approx 150 dB [58]
- Common prawn (*Palaemon serratus* Crustacean) \approx 120 dB [61]

There is variation found between different studies on the same species. One reason for this variation is undoubtedly that the method of the studies and the acoustic conditions under which the studies were performed differ [65]. Interspecies variation have been observed, however in most hearing studies the number of subjects have been low, so the knowledge about variation in hearing capabilities within species is inadequate [54]. Most of the hearing studies only cover a few signal types and sound levels, therefore it is difficult to extrapolate the results in these studies to other sounds. When comparing broadband noise to an audiogram, the noise level must be stated in “critical band levels”, describing the acoustic power per “critical bandwidth”. Critical bandwidth is basically an auditory filter created by the cochlea in the inner ear (see **paper III**). Roughly, for a given frequency, the critical band is the smallest band of frequencies around it, which activate the same part of the basilar membrane in the cochlea. Simultaneous tones within the same critical bandwidth do not increase the perceived loudness that of the single tone, if SPL remains constant. However, since the critical bands have been identified in only a few species, a common practice (if comparing noise levels with pure tone audiograms) is to analyse the noise as 1/3rd octave bands [22]. The hearing capabilities (pure tone audiograms) of 53 species of fish and 22 species of marine mammals are summarized in [54]. Audiograms of 8 different species of fish and 2 species of marine mammals that populate the Swedish West coast is found in **Paper III**.

4.6 Environmental impact

Anthropogenic activities in the oceans have the potential to disrupt life “under the sea” through underwater radiated noise. In an environment such as the ocean or a lake, where fauna rely on hearing as a primary sense for mating,

hunting, and survival, the noise radiated from passing ships, explosions, seismic exploration, sonars, acoustic deterrent devices and industrial activities may have serious consequences. Terrestrial animals often have the option to move away from a disturbing noise, and the further away they get from the noise the more it weakens. Underwater animals are not always as fortunate, as described earlier, due to the physical properties of water, underwater sound can propagate over great distances with lower dissipation than in air. Noise from a large container ship can under the right conditions be distinguished over the ocean ambient noise at distances greater than 10 km. Also the direction of the noise could be difficult to determine, which can make it difficult to outrun or avoid the noise. There are studies which show that fish [66] and marine mammals [67] can have directional hearing (can locate a sound source). Data show that both fishes and marine mammals have a capacity of directional hearing and sound source localization. However no comprehensive theoretical explanation of the localization abilities have been found in a single species, so the sound source localization capability in these marine organisms remains to be completely understood [68, 69]. Despite the ability to hear where a noise originates from, there have been mass strandings of beaked whales, which are associated with the use of naval sonars. There is no conclusive cause-and-effect relationship between mass strandings and the use of naval sonars, but there is evidence that use of military sonar has resulted in physical damage and mass strandings of beaked whales. The whales may have been caught in the wake of naval ship sonars, suffered physical damage and in a desperate attempt to avoid the noise, mass strandings (intentionally or unintentionally) have occurred [70, 71]. However, it is not only acute noise trauma that can be dangerous to marine organisms; underwater noise have been described as “*The death of a thousand cuts. Each sound in itself may not be a matter of critical concern, but taken all together, the noise from shipping, seismic surveys, and military activity is creating a totally different environment than existed even 50 years ago. That high level of noise is bound to have a hard, sweeping impact on life in the sea.*”⁴

The degree of influence is the result of noise intensity, spectral levels, duration and repetition. The level of influence can roughly be divided into four different zones [72]:

- **Zone of audibility:** is the range and depth of which a specific sound/noise can be detected by a target species. Basically it means that the noise level of the sound is above the hearing threshold (minimum sound level of a pure tone that an average ear with normal hearing can hear with no other sound present) of the target species. The

⁴ By Sylvia Erle: Michael Jasney, Joel Reynolds, Cara Horowitz, Andrew Wetzler. Sounding the Depths II: The Rising Toll of Sonar, Shipping, and Industrial Ocean Noise on Marine Life. Executive Summary. Natural Resources Defense Council. November 2005.

spectral characteristics of the sound/noise is of importance of the audibility. If the noise frequency is outside of the target species hearing range, it basically does not matter how intense it is. In the ocean a signal must be stronger than the ambient noise to be audible. Fish and marine mammals can detect a narrowband signal in a broadband noise.

- **Zone of responsiveness:** Noise has the potential (if noise levels are high enough) to induce disruptions in both animal behaviour and cause physiological reactions. Behavioural responses have been observed due to several anthropogenic activities: boats, ships, sonars, underwater construction, offshore renewable energy conversion, air guns, etc. A number of behavioural reactions have been observed: startle and avoidance responses, changes in swimming activity (vertical distribution and schooling behaviour) and reduction in the ability to elude predators [73-77]. Studies on physiological reactions have shown: decreased egg viability and larval growth and increased levels of the stress hormone cortisol, which could disrupt, growth, maturation and reproductive success [78, 79]. Many marine mammals have shown signs that they are disturbed at noise levels around 120 dB re 1 μ Pa for continuous noise [72]. Noise might not be biologically significant if it only causes temporal changes in behavior and/or physiological reactions. But if the noise induce long term changes, then there could be a risk that activities such as foraging, mating, or nursing will be affected. This would most certain be of biological significance [80]. Long-term effects from noise, both on individuals and populations remains unknown.
- **Zone of masking:** As stated earlier fish and marine mammals use sound for a variety of purposes. If acoustic signals used in these purposes are masked, it can have serious adverse effects on an entire population in worst case. The zone of masking is the range and depth from a specific noise (e.g. ship or offshore windmill) can interfere with signals important to a target species. Underwater noise (depending on SPL and spectral levels) have the potential to interfere with all kinds of biological signals, everything from low frequency grunts (< 500 Hz) from the Atlantic cod (*Gadus morhua*) [81] to high frequency echo localization (>100 kHz) by the Bottlenose dolphin [82]. Underwater noise can mask signals critical for finding food or communication signals important to social cohesion, mating, warning, deterring predators and individual identification. Also the noise can interfere with natural sounds needed for navigation, detection prey and predators. Masking is dependent on the loudness of the signal used by the target species. The louder the signal, the less likely it is to be masked [83] The extent to which masking can affect individuals and entire

populations is not yet fully understood, however if one or more of the mentioned signals are masked to that level that the biological fitness is reduced, then the masking is considered as biologically significant [80].

- **Zone of discomfort, injury or death:** A high intensity noise has the potential to induce discomfort, hearing loss: Temporal Threshold Shift (TTS) or Permanent Threshold Shift (PTS), damage to non-auditory tissue and even death. Damage to the sensory hair cells in the inner ear leading to hearing loss (TTS or PTS) will cause a reduction in the fitness of the exposed animal. Potentially they will be unable to detect predators, locate prey, navigate and communicate acoustically (vocal species). There is little data on physiological damage on non-auditory tissues, but noise with very high SPL (explosive blast, pile driving) can potentially cause oscillations in gas filled cavities such as the swim bladder and cause them to tear or rupture [75]. Hemorrhage in the acoustic jaw fat, ears, brain, and kidneys in beaked whales have been associated with exposure to naval sonars [71]. There is additional data on the effects of high intensity noise exposure on terrestrial animals. Here effects such as hemorrhage, rupture of organs and tissues, embolism and resonance of hollow organs and have been observed. However it is very difficult to extrapolate from SPL_{air} to SPL_{water} , between different noise types and different species.

The existing knowledge of environmental impact from underwater noise is limited. Before reliable noise exposure criteria can be determined, these gaps need to be filled. Results from experiments conducted in aquariums or fish tanks are not easily applied to natural environments [84]. Both the sound and the organisms will behave differently e.g. fish are restricted in their movements when caged; the crowding could induce a different response than if it was swimming freely in the wild. There are studies (mentioned earlier in this section) showing that some sounds, under certain conditions can have various effects on some species. But sounds from different anthropogenic and natural activities have a wide range of characteristics (duration, SPL, spectral levels and repetition rate etc.), and the perception of sound can vary greatly between species. Thus extrapolation between the same sound in different conditions, different sounds and different species very difficult and unreliable [75]. To be certain if and how a specific sound/noise can affect a marine organisms, systematic studies that quantifies anthropogenic underwater noise (underwater construction, renewable energy conversion, ships, boats etc.) and studies on the effects from these noises in natural environments are required. While it is obvious that it is impossible to perform studies on all known marine organisms, studies should be performed on a wide range of taxonomically and morphologically diverse species. Also, the acoustical environment needs to be studied if an environmental impact assessment is to be done. It is important to

know the characteristics of the noise, the potential effects it can have on various species and how the noise will propagate in that specific area.

5. Results

This section presents the results from **paper I-VI**. However main focus will be on underwater radiated noise from WECs (**paper III-VI**). Only the most important results are presented. For a more in-depth understanding, see the papers corresponding to each specific section. The results from 4 different WECs are presented.

5.1 Initial results from wave climate, power output and environmental studies

Paper I provides a description of the *Lysekil Wave Power Project*, the *Lysekil research site*, the technology of the WECs, the deployment of the first full-scale WEC and initial results from studies on wave climate, power output and environmental impact.

The wave climate studies shows that the most common significant wave height (H_s) is 0.6 m, the median energy period is 5.1 s and that most of the energy was found in H_s in the interval of 1.2–2.7m (based on measurements performed in 2007). The initial power output and absorption studies show power output up to ~15 kW and power absorption from waves up to ~50%.

The first environmental studies focused on infauna and showed that there was a significantly higher species abundance in the *Lysekil research site* compared to a reference area ($p = 0.004$). Studies performed previous to the deployment of WECs showed no sign of red listed (protected) species in the *Lysekil research site*.

5.2 Sustainable or environmentally costly?

The future commercialization of wave energy conversion has raised concerns about the potential environmental impact associated with this. **Paper II** reviews general environmental aspects that may occur by wave power projects due to introduction of new substrates, electromagnetic fields, no take zones, bioacoustics etc. The conclusion is that marine ecological and environmental aspects are likely to be unavoidable. Both positive and negative effects are suggested. Negative effects can come from disturbance in form of e.g. elec-

tromagnetic fields, underwater radiated noise, loss of habitat and the introduction of non- indigenous species. Positive effects can come from the introduction of new habitat and protection from commercial fisheries. This has been shown to increase diversity, biomass and abundance. Environmental studies early stage can give an insight into possible impacts. This knowledge gives the opportunity for early design alterations to minimize or maximize effects, making wave energy conversion and more suitable for the marine environment. This paper has set the focus on topics that needs to be investigated, not in the Lysekil research site but also in wave power sites around the world.

5.3 WEC noise characteristics, first results

Paper III presents the first measurements performed on the underwater radiated noise from a WEC in the LWPP. The measurements were performed in Apr-May 2011. The results in this paper are limited to noise levels in a significant wave height (H_s) of 0.5m, due to an assembly error in the WEC (L8). The main finding in these measurements was that the main operational radiated noise from this WEC from was a repetitive transient with short duration ($\sim 0.2-0.3$ s). The noise originates from when the translator hits the end stop springs (End Stop Hit ESH) in the top or bottom of the WEC. Every ESH resulted in two transients, one when the spring was compressed and one when the spring was elongated (fig 5.1). The noise ranged over the measured spectrum (10 Hz – 22 kHz) and had the bulk of its energy in frequencies < 1 kHz.

Spectral analysis (FFT) was performed on single transient/pulse (SP) noise and double transient/pulse (DP) noise. SP and DP spectral levels were compared statistically (Wilcoxon Signed Rank test, $N=30$) at five peak frequencies (118, 145, 310, 412 and 447 Hz). A significant in difference noise level was found at 412 Hz ($p=0,001$), with slightly higher SPL in SP. A comparison between SP and DP spectral levels are seen if fig. 5.2a. A comparison between SP and ambient noise spectral levels are found in fig. 5.2b.

The SPL_{rms} was calculated for every SP, DP and ambient noise that was used in the spectral analysis. The measured noise levels from WEC L8 represent are received level at a distance of 20m (RL_{20m}) from the WEC. Source levels (RL_{1m}) were estimated by using the equation for practical spreading loss ($15 \cdot \log(R)$). Max and mean RL_{1m} and RL_{20m} values are found in tab. 1.

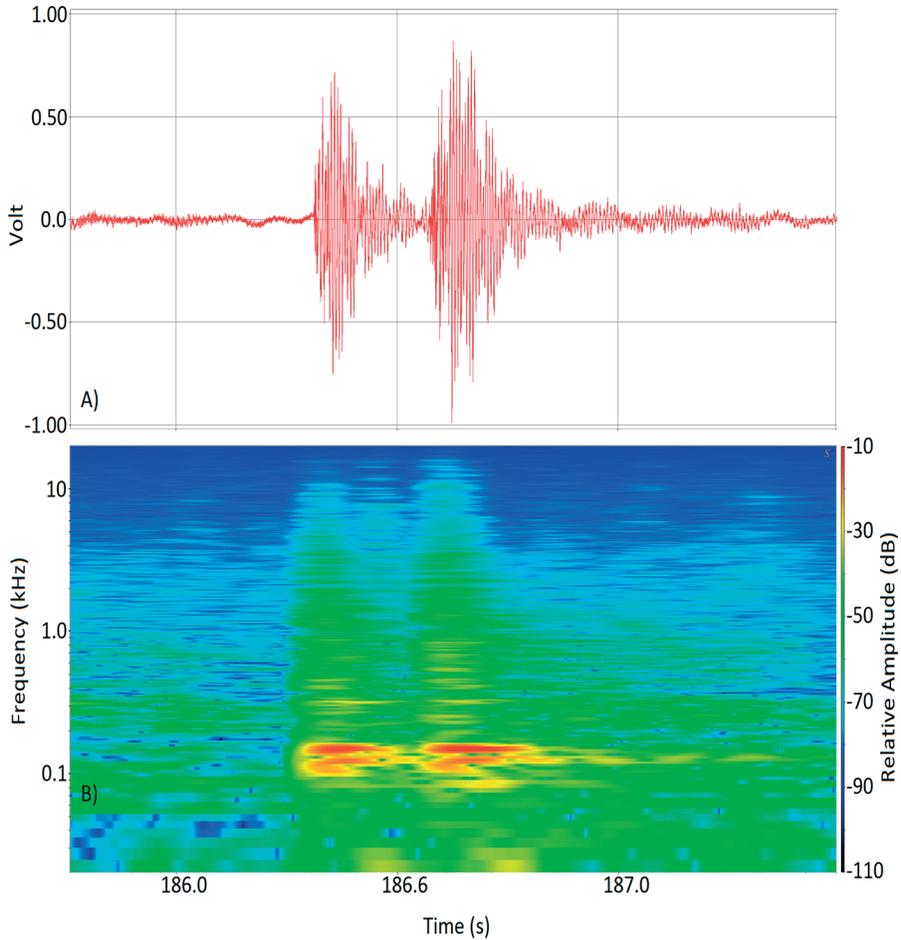


Figure 5.1. A) Temporal amplitude change when the translator hits an end stop spring. The first transient is when the spring is decompressed, the second when it elongates. Time on the x-axis and relative amplitude (141 dB re 1 V) on the y-axis. *B)* Spectrogram of the two occurrences. Time on the x-axis and frequency on the y-axis.

Table 1. A summary of WEC (L8) and ambient noise levels. Noise type, number of samples (N), noise duration, received level at 20m (RL_{20m}) and calculated source level (RL_{1m}) are shown. All noise levels are root mean square (rms) values.

Noise type	N	Duration (s)	RL_{20m}	RL_{1m}
			(dB re 1 μ Pa) Max / Mean	(dB re 1 μ Pa) Max / Mean
Single Pulse	50	0.2 - 0.3	133/129	153/149
Double Pulse	30	0.5 - 0.6	131/129	151/149
Ambient	50	0.3	91/78	--/ --

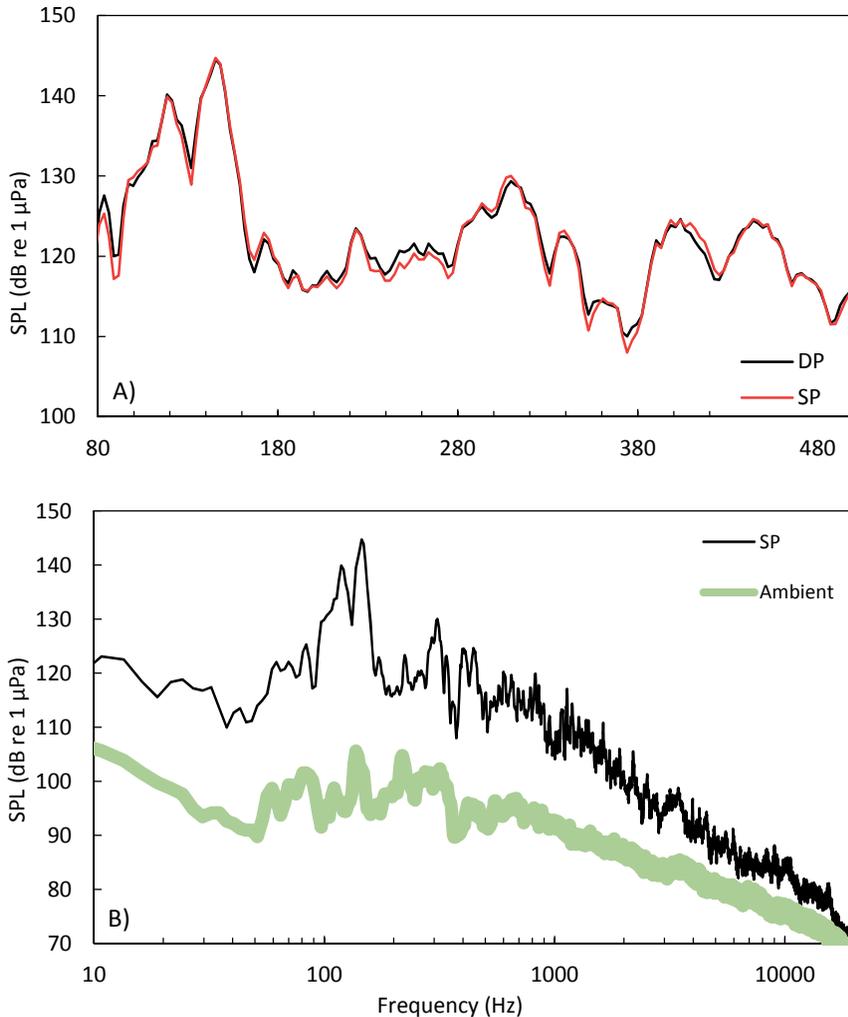


Figure 5.2. A) Comparison of the spectral levels of Single Pulse (SP) and Double Pulse noise in Hs 0.5m. The spectral line represents the average line of $n=50$ (SP) and $n=30$ (DP) B) Comparison of the spectral levels of Single Pulse (SP) noise of L8 and ambient noise. The spectral line represents the average line of $n=50$ (SP) and $n=30$ (ambient). Frequency on the x-axis and sound pressure level on the y-axis.

5.4 Comparison in radiated noise from WESA and L12a

Paper IV shows the preliminary results from measurements on one WEC (WESA) in *project WESA* and one WEC (L12a) in the *Lysekil wave power project*. *Project WESA* was a joint effort (Uppsala University, Ålands Teknikkluster r.f. and University of Turku) to conduct various tests with a WEC in the Baltic. The project ran from August 2011 until the end of 2013.

The operational noise was compared between the two point absorbing linear WECs that were of different design. The measurements are at source level distance (1m). These studies identified a second operational noise, originating from vibrations caused by the vertical motion of the translator (MT). The End Stop Hit (ESH) noise and the Moving Translator (MT) noise are both transient noises, but differs in duration and spectral levels. The MT noise is also more frequent than the ESH noise, since it is only dependent of the vertical motion of the translator, which occurs when there are waves passing the surface buoy, virtually independent of wave height. The ESH noise only occurs if the wave height is greater than the full stroke length of the translator (2.0m in WESA and L12a). Spectral levels and SPL_{rms} were calculated for one MT noise and one ESH noise in two different wave heights. This was performed both for WESA and L12a. Spectral levels ($1/3^{rd}$ octave bands) of MT and ESH noise in $H_s \sim 1.5m$ from can be seen in fig. 5.3. Duration and SPL_{rms} of the different noises from the different WECs are found in tab. 2.

Table 2. WEC and ambient noise measurements in $H_s \sim 1.5m$. Noise type: Moving Translator (MT) and End Stop Hit (ESH), noise duration, source level (RL_{1m}), ambient noise level (AL) and estimated range for the noise to reach ambient noise levels are shown. Range estimations are based on *practical spreading loss* ($15 \cdot \log(R)$). All sound pressure levels are root mean square (rms) values.

WEC	Noise Type	Duration (s)	RL_{1m} (dB re 1 μPa)	AL (dB re 1 μPa)	Estimated Range (m)
L12a	MT	1.3	155	101	4000
WESA	MT	1.5	118	104	10
L12a	ESH	0.2	160	101	8600
WESA	ESH	0.3	149	104	1000

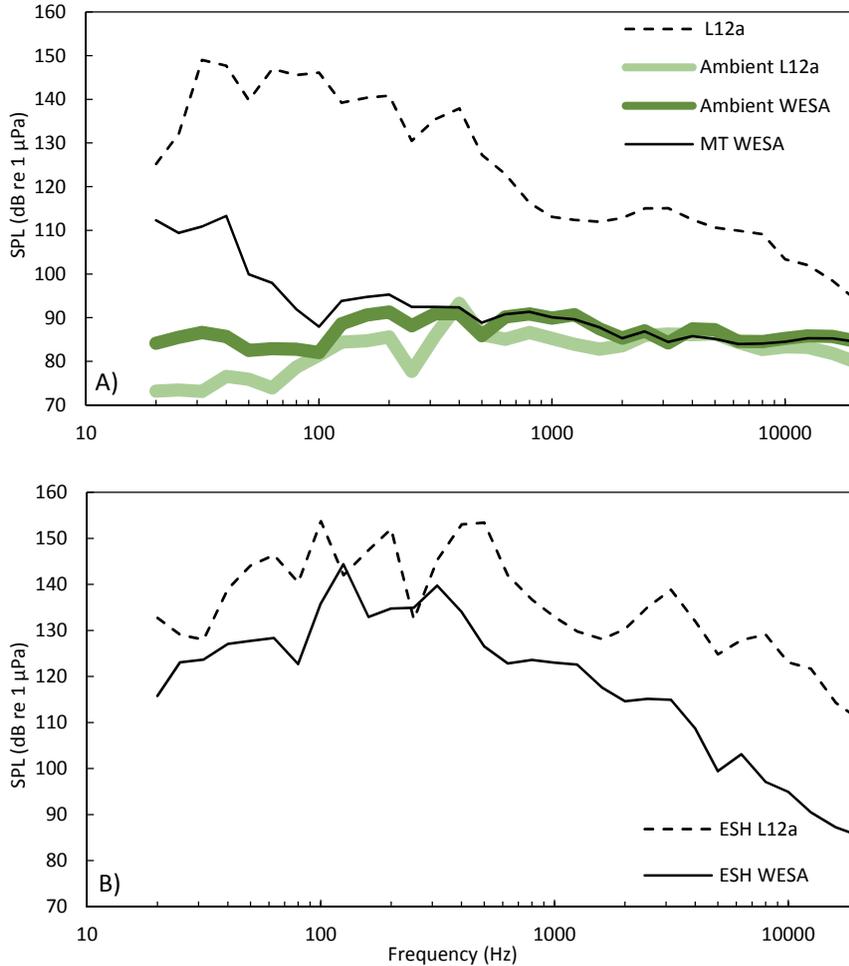


Figure 5.3. A) Comparison of the spectral levels of one MT noise event from L12a respective WESA, and ambient noise (1/3rd octave bands) in Hs 1.5m. *B)* Comparison of the spectral levels of one ESH noise event from L12a respective WESA in Hs 1.5m. Frequency on the x-axis and sound pressure level on the y-axis.

5.5 Radiated noise levels in relation to significant wave height and long term noise level estimations

In **Paper V** the measurements of the noise levels radiated from 2 different WECs (L12a and L12d) are presented. The design of the two WECs was the same with the exception of rubber dampers on the translator (noise dampers) and in the surface buoy (snatch load dampers) installed in L12d. Measurements were performed at two distances 1m (R_{1m}) and 150m (R_{150m}) from the WECs. Hs ranged between 0.1 – 2.84m during the measurements.

SPL_{rms} (of 300s measurements) at R_{1m} in relation to H_s and wave steepness (α_2) are shown in fig. 5.4. The results show a strong ($R^2=0.97$) correlation between logarithmic increase in SPL with increasing H_s, and a weak correlation linear increase in SPL with increasing α_2 . H_s was found to be a good indicator for radiated noise levels and α_2 was found to be a poor indicator for radiated noise levels

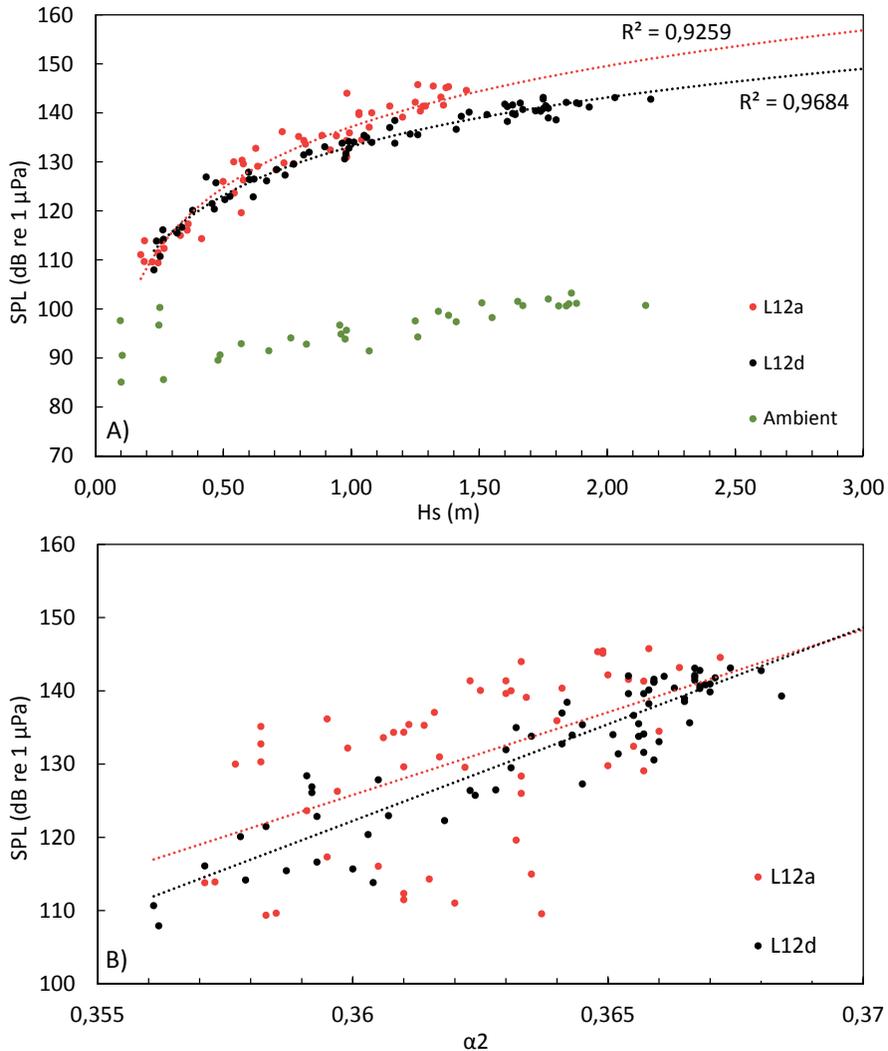


Figure 5.4. A) WEC (L12a and L12d) noise levels and ambient noise levels at R_{1m} in different H_s. Dashed lines show regression models between sound pressure level and significant wave height (H_s). H_s on the x-axis and Sound Pressure Level on the y-axis
B) WEC noise levels at R_{1m} in relation to α_2 . Dashed lines show linear regression models for the correlation between SPL and wave steepness (α_2). α_2 on the x-axis and sound pressure level on the y-axis.

The noise levels from the WECs, in different wave states, were compared statistically (independent samples t-test). Significant difference was found in Hs 0.6-1.0m and Hs 1.1-1.5m respectively, with significantly higher noise levels in L12a in both wave states. The significant difference in noise levels in Hs 1.1-1.5m is believed to be the result of the rubber dampers on the translator and in the buoy.

Based on the logarithmic regression model for L12d (fig 5.4a), measured propagation loss in the LRS, wave measuring data from 2009 (wave data for one entire year) and the eight year average annual occurrence of different Hs in the LRS [85], long term noise levels from a WEC operating in the LRS was estimated at R_{1m} and R_{150m} (tab. 3).

Table 3. Estimations of long term noise levels in the *Lysekil Research Site* in different significant wave heights (Hs) at 1m (R_{1m}) and 150m (R_{150m}) from the WEC. All Sound Pressure values are root mean square (rms) values.

Hs (m)	Estimated SPL	Estimated SPL	Time (% / year)
	R_{1m} (dB re 1 μ Pa)	R_{150m} (dB re 1 μ Pa)	
0.0-0.5	~112	90	37,4
0.6-1.0	~129	101	33,6
1.1-1.5	~137	106	16,9
1.6-2.0	~141	108	8,0
>2.0	>145	>111	4,1

5.6 Spectral levels, Sound Pressure levels and noise duration for MT and ESH

Paper VI presents the variation in measured broadband SPL, spectral levels, noise duration and propagation loss of specific operational noise events (moving translator MT and end stop hit ESH) radiated from two WECs. A fraction of the same measurements mentioned used in **paper V** (section 5.5) was further analysed with emphasis on spectral (1/3rd octave bands) and sound pressure levels (rms and peak) and noise duration of individual noise events.

Both the MT and ESH noise from both WEC have similar trends in spectral levels: the bulk of the energy in frequencies <1 kHz, and declining intensity with increasing frequency. However, they differ in peak frequencies (fig. 5.6), broadband SPL (fig. 5.5), noise duration, and repetition rate (tab. 4).

L12d expressed higher levels in frequencies >500 Hz in both MT and ESH noise, and the lower levels in frequencies <500Hz in the ESH noise, compared to L12a. This is believed to be associated with the rubbers dampers in L12d (section 5.5). The higher frequencies are associated with the compression of the rubber (mostly in the buoy), and the lower values associated with the low frequency vibration dampening properties of the rubber.

Table 4. Duration and repetition rate for MT and ESH noise. MT duration is the average of n=20. ESH duration is the average of n=15 (L12a) and 6 (L12d). Repetition rate is the number of times the noise was repeated during 300s.

	L12a MT1.0	L12d MT1.0	L12a MT1.5	L12d MT1.5	L12a ESH1.5	L12d ESH1.5
Duration (s)	1.75	1.36	1.53	1.50	0.21	0.13
Rep. rate (n/300s)	98	66	90	101	15	6

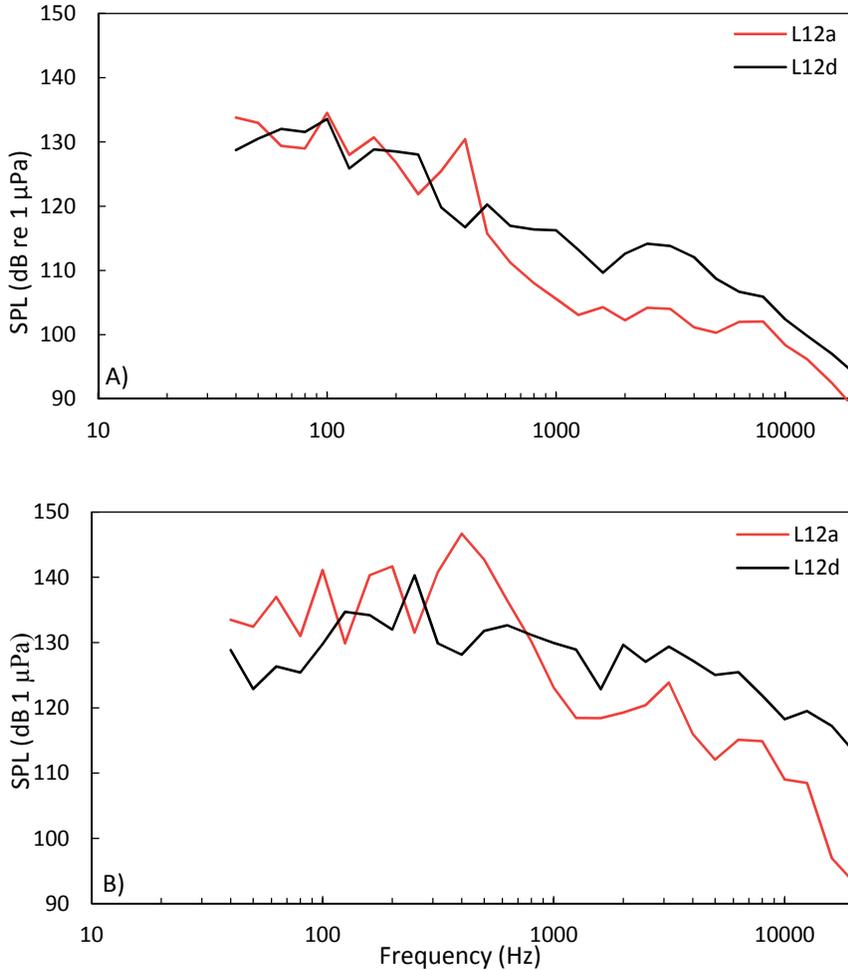


Figure 5.5. A) Comparison of the spectral levels of MT noise from L12a and L12d in Hs 1.5m. Each spectral line represents the average line of n=20. *B)* Comparison of the spectral levels of ESH noise from L12a and L12d in Hs 1.5m. The spectral line represents the average line of n=15 (L12a) and n=6 (L12d). Frequency the x-axis and sound pressure level on the y-axis.

No significant difference in SPL (rms or peak) was found when statistically comparing (t-test) MT and ESH noise levels (respectively) between the WECs in the same Hs (1.0m respective 1.5m). When comparing SPL between different Hs, significant difference was found in all cases (MT and ESH respectively). The variation in MT and ESH noise levels (rms and peak) are seen in fig. 5.6.

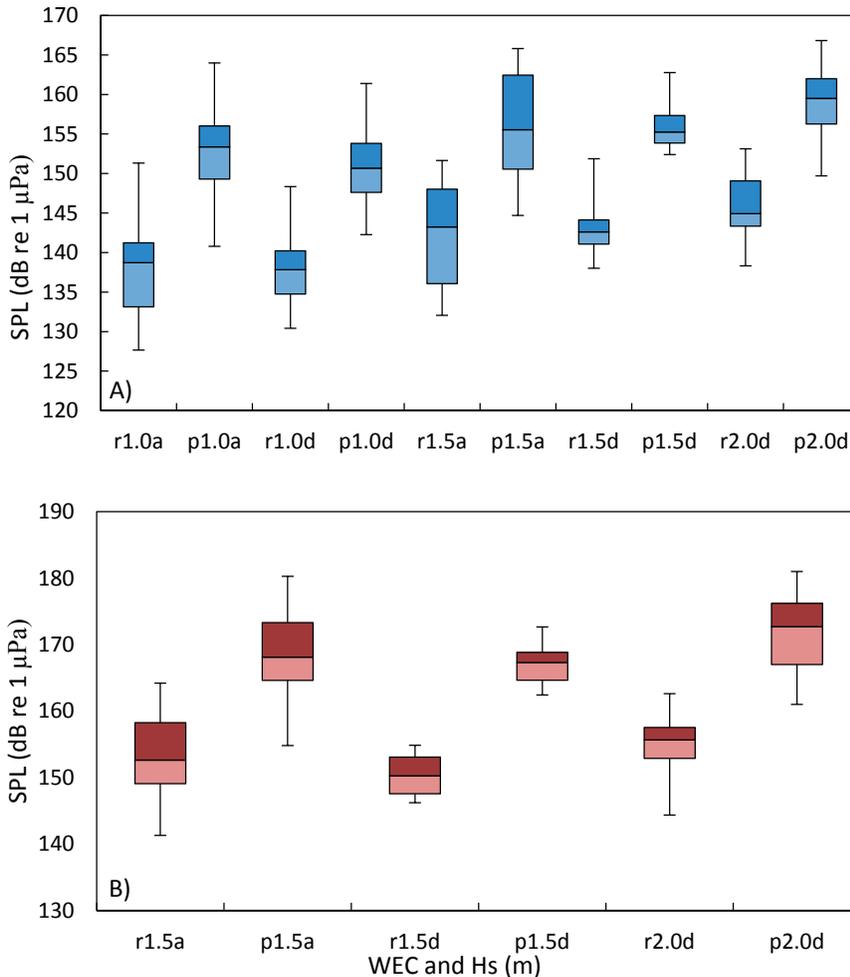


Figure 5.6. **A)** Measured MT sound pressure levels, rms (r) and peak (p) values from L12(a) and L12(d) in Hs 1.0, 1.5 and 2.0. n=20 for respective WEC and Hs. **B)** Measured ESH sound pressure levels, rms (r) and peak (p) values from L12(a) and L12(d) in Hs 1.5 and 2.0. n=15 (L12a) and & (L12d) Hs 1.5m and n=20 for L12d in Hs 2.0. Boxplots show median value (horizontal line between boxes), 25th (lower box) and 75th (upper box) percentile, min and max values (whiskers). WEC and significant wave height (Hs) on the x-axis and sound pressure level on the y-axis.

The propagation loss on spectral level in the *Lysekil research site* was studied by comparing spectral levels (1/3rd octave bands) of ESH noise recorded simultaneously at 1m and 150m in Hs 2.0m. Generally frequencies ≤ 200 Hz experienced considerably more loss in energy compared to frequencies >200 Hz (fig. 5.7). Also the SPL_{peak} of ESH noise at 1m and 150m was compared. Showing an average propagation loss of ~ 37 dB re 1 μ Pa, corresponding to a spreading loss factor (N) of ~ 18 , giving a propagation loss of $TL=18\log(R)$ on the broadband SPL in the *Lysekil Research Site*.

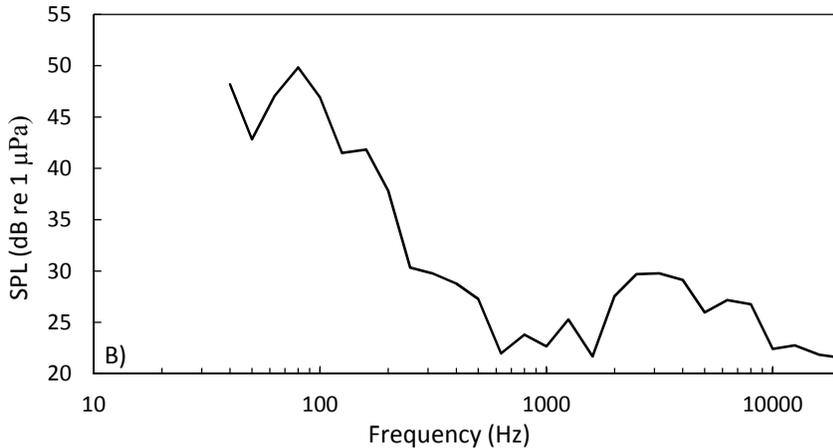


Figure 5.7. Propagation loss on spectral level, based on the average ($n=20$) difference in ESH noise spectral levels measured simultaneously at 1m respective 150m from the WEC. Frequency the x-axis and sound pressure level on the y-axis.

Impact estimations on three species of fish (Atlantic salmon, Atlantic cod and Atlantic herring) and two species of marine mammals (Harbour seal and Harbour porpoise) were made. The zone of audibility was estimated by using audiograms, measured MT and ESH peak spectral levels (1/3rd octave bands) and calculated propagation loss on spectral level. Atlantic salmon is estimated to be able to perceive the ESH noise up to 1km from the WEC, while Atlantic cod and herring may be able to perceive the noise up to a distance of 10km. Harbour porpoise and Harbour seal may be able to perceive the noise up to a distance of 15 km from the WEC (fig. 5.8). The zones of responsiveness and injuries were estimated using the maximum ESH SPL_{peak} measured in Hs 2.0m and the propagation loss of $17.7 \cdot \log(R)$. The results were compared with noise studies performed on fish and marine mammals by other researchers. In Hs 2.0 at distances >150 m from the WECs is behavioural reactions is only expected from Harbour porpoise.

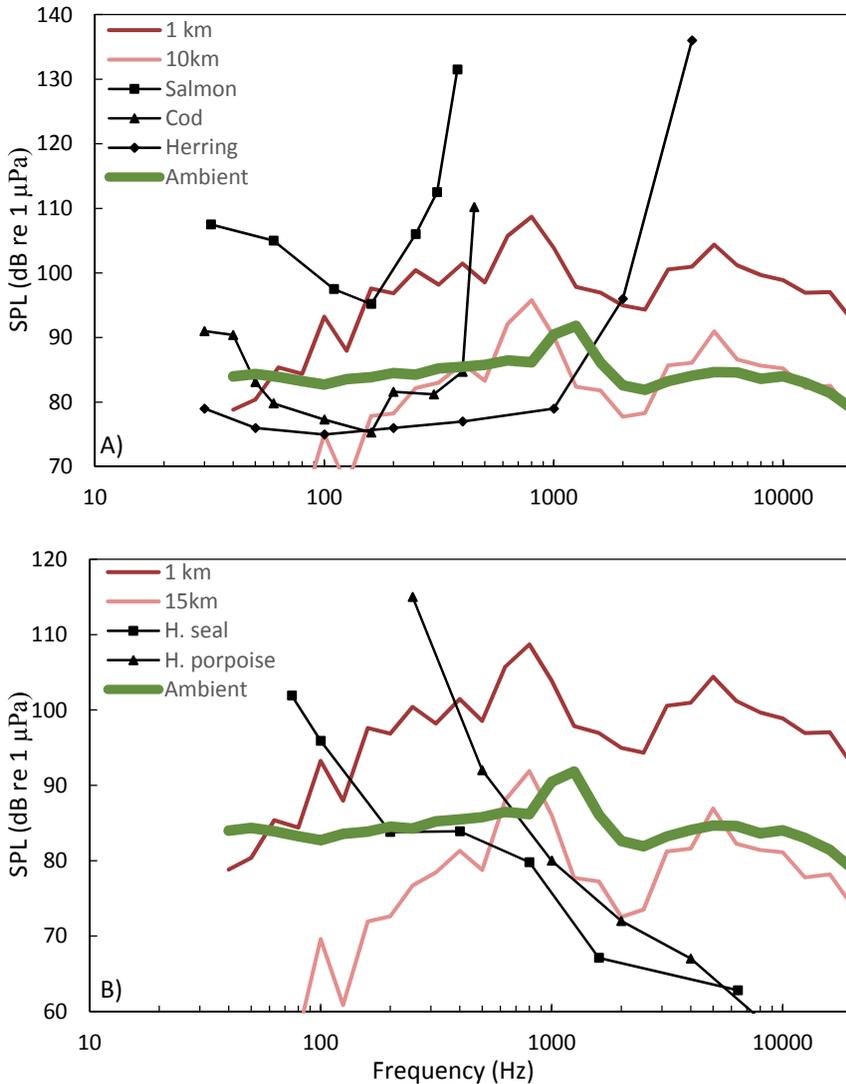


Figure 5.8. **A)** Comparison of audiograms of Atlantic salmon [86], Atlantic herring [25], Atlantic cod [26], ambient noise and the peak spectral levels of the ESH noise from L12d in Hs 2.0m at 1km and 10km from the WEC. **B)** Comparison of audiograms of Harbour seal [46], Harbour porpoise [63], ambient noise and the peak spectral levels of ESH noise from L12d in Hs 2.0m at 1km and 15km from the WEC. Frequency on the x-axis and sound pressure level on the y-axis.

6. Discussion

Underwater radiated noise from point absorbing wave energy converters is recognised as one potential source of impact on the marine environment [II].

The noise from a total of four different Wave Energy Converters (WECs) was measured. All WECs had the same basic technology (point absorbing linear generators) [I], but differed in some design details. In WEC L8 (**paper III**) and WESA (**paper IV**) the stator was mounted on an internal skeleton (which had no direct contact with the outer shell of the WEC) and the end stop springs were plate springs. In WEC L12a (**paper IV, V and VI**) and L12d (**paper V and VI**) the stator was mounted directly on the outer shell and the end stop springs were coil (helical) springs. Additionally L12d was equipped with rubber dampers in the surface buoy and on the translator.

Two events were identified as the sources of main operational noise 1) the vertical motion (MT) and 2) when translator hits end stop springs (ESH). Both noise types are transients that have the bulk of the energy in $f < 1000$ Hz.

The MT noise levels peaked in $f \leq 100$ Hz, and declined with increasing f . The most prominent difference in spectral levels between the WECs, was found in the WEC in project WESA, where the spectral levels only surpassed ambient noise levels in $f < 100$ Hz. The spectral levels of L12a and L12d were above ambient noise levels over the entire measured spectrum (20 Hz – 20 kHz). The spectral levels of L12d were higher than the spectral levels of L12a in $f > 500$ Hz, this is associated to the compression of the rubber dampers in the surface buoy of L12d. Also, a considerable difference in the broadband SPL of the MT noise was found. With considerably lower SPL_{rms} radiated from WESA (118 dB re 1 μ Pa) compared to L12a and L12d (~150 dB re 1 μ Pa) in Hs 1.5m. In the noise measurements of L8 the MT noise was not even discovered since the ESH noise dominated the measurements. This difference is directly linked to the internal design of the WECs; if the stator is mounted directly on the outer shell of the WEC, the intensity of the radiated MT noise will be higher. The duration of the MT noise duration was similar in all WECs (~1-2s).

In all WECs, the ESH noise levels peaked in $f \leq 400$ Hz, and declined with increasing f . L8 and WESA had very similar spectral levels with peak f between 125-160 Hz. L12a and L12d peaked at 400 respective 250 Hz. L12d expressed higher levels in $f > 800$ Hz, this is believed to be associated with the compression of the rubber dampers on the translator. The broadband SPL_{rms} of the ESH noise in Hs 1.5m was similar in all WECs (~150-155 dB re 1 Pa). However, the noise duration differed significantly, with considerably

shorter duration in L12d (~0.13s) compared to the other WECs (~0.2-0.3s) in Hs 1.5m

Paper V shows that the radiated noise from the WEC (L12d) at source level increases logarithmically with increasing Hs. Long-term estimations of the radiated noise levels from L12d indicate that the SPL_{rms} will not exceed 140 dB re 1 μ Pa and 110 dB re 1 μ Pa at 1m respective 150m from the WEC more than 4% / year (in the *Lysekil research site*). And that $SPL_{rms} > 150$ dB re 1 μ Pa is unlikely to occur at all. Based on propagation loss found in this study, noise $SPL_{rms} > 100$ dB re 1 μ Pa unlikely occur at all at a distance of 2 km from the WECs.

The results in **paper VI** show great variation in the SPL (rms and peak) levels of MT and ESH noise, not only in different Hs but also in the same Hs. This is because ocean waves are non-linear and vary in wave height even in short periods of time. There also a great variation between species in audibility of the WEC noise. While the peak ESH noise at Hs 2.0m will be inaudible to Atlantic salmon at distances greater than 1km from the WEC, Harbour porpoise and Harbour seal may be able to perceive the noise up to 15 km from the WEC.

However, being audible is not the same as having an impact. When estimating if a noise is disturbing or not, broadband SPL must also be taken in consideration. Studies on the effects from pile driving noise (similar to ESH noise, transient with most energy in $f < 1000$ Hz) on Trout (*Salmo trutta*) show no evidence of behavioural reactions from SPL_{peak} of 134 dB re 1 μ Pa [87] and physical injury from SPL_{peak} up to 208 dB re 1 μ Pa [88, 89]. It is important to note that the behaviour of the fish in this study might have been different if the fish was not in cages. Another study on the effects of pile driving noise, on Atlantic cod (*Gadus morhua*) and Dab (*Limanda limanda*) did show behavioural reactions to noise levels between 141-165 dB re 1 μ Pa. This indicates that SPL_{peak} of both MT and ESH noise in Hs 2.0m may induce behavioural reactions from fish in the close vicinity (<150m) to the operating WEC. However, the noise from the WECs does not increase from zero to full intensity in a few seconds, or even minutes. Gradually the noise will increase with increasing wave height, giving organisms time to leave the area if disturbed. Physical injuries due to WEC noise, even at close range are very unlikely.

Studies on the hearing capabilities of marine mammals show that they are more sensitive to sound in high frequencies. Harbour seal and Harbour porpoise have rather poor hearing in the frequencies where the noises from the WECs have their peak energy ≤ 400 Hz [III, VI]. However, the noise levels are, at 1m from the WEC, well above the hearing threshold of both Harbour seal and Harbour porpoise in these f . Generally, marine mammals have shown first signs of being disturbed at noise levels around 120 dB re 1 μ Pa for continuous noise [72]. Noise level thresholds (SPL_{peak}) for minor behavioral disturbance for Harbor seal is 160 dB re 1 μ Pa, and can be as low as 90 dB re 1 μ Pa for Harbour porpoise [73]. This indicates that Harbour seal can express behavioural disturbance if in the immediate vicinity of the WEC, but already

at a distance of 15m away (in the *Lysekil research site*) is any behavioural response improbable. However, the Harbour porpoise, being much more sensitive, is likely to express disturbance in greater distances. However no major disturbance is expected at distances >150m from the WECs [VI]. In general for marine mammals, no disturbance is expected at 2km from the WECs.

Masking effects are difficult to predict, however most teleost fishes produce sound that have most of its energy in $f < 1$ kHz [90]. Which indicates that there is a risk of masking effects on fish vocalizations if close enough to the WEC. The sound production of Harbour porpoise ranges in f between 120 to 130 kHz with SPL up to 180 dB re 1 μ Pa [91] and the sound production of Harbour seal is in f considerably lower than that of the Harbour porpoise. Much of their vocalization is in f between ~ 15 and 1000Hz, but may range up to 5 kHz. This indicates that the noise from the WECs will not mask the vocalization of harbour porpoise but it may mask the vocalizations of the Harbour seal.

7. Conclusion

As suggested in **paper II**, marine renewable energy conversion (e.g. wave, tidal and current) may induce environmental impacts not normally associated with fossil fuels and nuclear power. Instead of pollutants in form of hazardous substances, negative impact can come in the form of e.g. alteration of the habitat, electromagnetic fields and underwater noise pollution. But also positive effects are possible; commercial fishing will probably be prohibited in an area with marine renewable energy converters. This will induce a “no take zone” or *marine protected area* (MPA). This will not only benefit fished species but it will also remove the pressure from towed bottom fishing gear, giving benthic fauna the possibility to recover. MPAs and artificial reefs have been found to increase biomass, diversity and size of individuals compared to surrounding areas [16]. There is an increasing body of evidence that marine renewable energy conversion may have a positive impact on the marine environment. Both positive and negative impacts need to be studied in detail to be able to maximize respective minimize these impacts on the environment.

Paper III-VI in thesis are the first studies on the characteristics of the noise radiated from point absorbing linear WECs in the *Lysekil wave power project*. They show that marine organisms may experience disturbance due to underwater radiated noise from operating WECs, but that this disturbance is will probably only occur locally and be transitory. The studies also showed different characteristics of the radiated noise, depending on noise source and WEC design. The impact estimations are based on the peak ESH noise levels from the L12d. However the dominant noise source in this design is the vertical motion of the translator (MT), having lower SPL than ESH noise, but occurring more frequently. A reduction in this noise would make a significant difference. The design of L8 and WESA (stator on an internal skeleton), did not express similar MT noise levels as L12a and L12d. The MT noise from this design would probably not have been measurable in distances >50m from the WEC, regardless of wave height. If the L12 design could be altered so that the vibrations of the moving translator did not radiate directly into the water, then the SPL_{rms} would be reduced significantly. An alteration in the stroke length of the WECs would reduce the frequency of the high intensity ESH noise. This design change has been implemented in commercial WECs. There have been other efforts to reduce the end stop hit noise (rubber dampers), but the only significant difference found was a reduction in noise duration. This reduction could lower SPL when measuring longer periods of over time, but the question

is if an organism is less disturbed by high intensity noise that is 0.1s compared to one that is 0.2s?

Nothing is known about cumulative effects from repeated exposure of MT or ESH noises. To minimize the risk of such adverse impacts the WECs should endeavor a design that radiates as little noise as possible.

Studies of this kind are needed, not only for future marine renewable energy converters, but for all anthropogenic activities that might radiate underwater noise. Studies that examine the effect on marine organisms are equally important. Will the noise have induce a behavioural and/or physical response, have masking effects or in worst case cause physical damage or even death?

The ranges of audibility, behavioural reactions and masking in this thesis are based on peak ESH noise that occur in wave heights occurring only about 4% / year, and not even in these wave heights does these noise levels occur with every passing wave, rather with peak waves. These peak noise events, being short in duration and not very frequent can be compared with ship noise; which can be equal or even exceed in noise intensity, but is continuous in duration [92]. Thus exposing marine life to a much higher degree of noise compared to a WEC, even in high waves. Based on the results in this thesis the potential negative environmental impacts from radiated noise are believed to be outweighed by the positive effects from artificial reef effect and MPA. However, the noise must be taken under consideration when planning a wave power park. Even if the impacts might only be local and temporal, they can have serious adverse effects if affecting an area especially important for mating, foraging and/or migration.

These studies indicate that the noise levels from the WECs have limited effects on the marine environment. However, they also show that the noise can be lowered considerably. If eliminating the MT noise (in a similar way as in the L8 and WESA) and the ESH noise (by making the WEC longer, and maybe installing thicker rubber dampers) then it may be possible that the radiated noise from point absorbing wave energy converters will have no adverse effects at all on the marine environment.

8. Future Work

- Future work includes noise measurements on multiple operating WECs and a marine substation in the *Lysekil wave power project* and the *Sotenäs project* where commercial WECs will be operating. In the *Sotenäs project* will deployment and maintenance noise also be measured.
- Measurements at several distances and locations. This will be performed in order to study propagation loss properties in the areas around the *Lysekil Research Site* and the *Sotenäs site*.
- Behavioural studies in natural conditions will be performed. These studies will include optical and active acoustic surveillance of behavioural response from marine organisms due to the noise radiated from operating WECs.

9. Summary of Papers

The chapter presents short summaries of each paper in this licence thesis.

Paper I

Wave Energy from the North Sea: Experiences from the Lysekil Research Site.

This paper provides a description of the development of the Lysekil project run by Centre for Renewable Electric Energy Conversion at Uppsala University together with some previously published results. The activity within most of the research areas are described briefly. Results from buoy line force, absorbed power and preliminary environmental studies are presented.

The author has participated in several parts in the paper such as performing practical offshore work, planning and performing dive operations, planning and deploying the environmental buoys and contributing to environmental studies.

Published in Survey of Geophysics, 29:221–240, 2008

Paper II

Wave power—Sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters

This paper reviews environmental issues concerning wave power conversion, with focus on linear Wave Energy Converters used in the *Lysekil project*. Areas such as colonisation patterns, biofouling, artificial reef effect, seabed alterations, electromagnetic fields and underwater noise are discussed.

The author is responsible for literature review and writing about artificial reefs.

Published in Renewable and Sustainable Energy Reviews, 14(4):1329–1335, 2010.

Paper III

Characteristics of the operational noise from full scale Wave Energy Converters in the Lysekil Project: Estimation of potential environmental Impacts.

This paper presents the first field measurements of underwater noise emitted from a full scale Wave Energy Converter in the Lysekil wave power project. The WEC was operating in *the Lysekil Research Site*. The noise measurements were performed in May 2011. The results describe spectrum levels, sound duration, repetition rate and sound pressure levels in 0.5m significant wave height. It also includes a review of hearing mechanisms and capabilities in fish and marine mammals.

The author did all work in this the paper.

Published in Energies Energies, 6(5): 2562-2582.

Paper IV

Hydroacoustic measurements of the noise radiated from wave energy converters in the Lysekil project and project WESA.

This paper presents the preliminary results of field measurements on two Wave Energy Converters (WECs) in the *Lysekil Wave Power Project* at Uppsala University and the *Project WESA* (joint effort between Uppsala University, Ålands Teknikkluster r.f. and University of Turku). Both WECs are a full scale point absorber with a directly driven linear generator, but have design differences in the mounting of the. The radiated noise from the two WEC is presented and compared as sound pressure levels and spectral levels.

The author did all the work in this paper.

Presented at the 1st international conference and exhibition on Underwater Acoustics, UA2013, Corfu, Greece, 23rd - 28th June 2013

Paper V

Underwater radiated noise from direct driven Wave Energy Converters: Sound Pressure Levels in relation to Significant Wave Height and Wave Steepness.

This paper presents the field measurements on two different wave energy converters in the *Lysekil Wave Power Project* at Uppsala University. The measurements were performed in Apr-May and Jul-Aug 2013. Measurements are performed simultaneously at two distances from the wave energy converters. Results are presented as measured sound pressure levels at different distances and in different significant wave height, the significance of a noise dampening feature and long term noise exposure estimations.

The author did all the work in this paper.

(Submitted paper).

Paper VI

Underwater radiated noise from direct driven Wave Energy Converters: Comparison between Sound Pressure Levels, Spectral levels and Noise Duration of Specific Operational Noises

This paper presents the field measurements on two different wave energy converters in the *Lysekil Wave Power Project* at Uppsala University. The measurements were performed in Apr-May and Jul-Aug 2013. Measurements are performed simultaneously at two distances from the wave energy converters. Results are presented as spectral levels of the different operational noises and spectral propagation loss.

The author did all the work in this paper.
(*Submitted paper*).

Paper not included in this thesis

Paper VII

Lysekil Research Site, Sweden: Status Update.

The paper presents experimental results and a review of the *Lysekil project* from the start up to the summer 2011. It also gives an insight in upcoming activities in the project.

The author have mainly contributed to issues concerning environmental studies.

Presented by Erik Lejerskog at Proceedings of the 9th European Wave and Tidal Energy Conference, Southampton, UK, 5-9 September 2011.

Paper VIII

Sound measurements on full scale Wave Energy Converters in the Lysekil project.

This paper presents preliminary results of the first field measurements of underwater radiated noise from a full scale point absorbing linear wave energy converter in the *Lysekil Wave Power Project*. The measurements were performed in May 2011. The results are average spectral levels over 300 s periods.

The author did all the work in this paper.

Presented at European Conference on Underwater Acoustics 2012: Edinburgh UK, 2nd - 6th July, 2012.

10. Svensk sammanfattning

Den 19 augusti 2014 var datumet för ”Earth Overshoot Day”, som markerar det datum då mänskligheten har tömt naturens budget för årets konsumtion av världens resurser. Resten av året kommer vi leva på ”lån” från kommande år. Världens behov av energi ökar och mellan åren 2000 och 2013 ökade den totala energiförbrukningen i världen med 40 %. Fossila bränslen som kol, naturgas och olja stod för 87 % av den globalt primära energiförbrukningen 2012. Dessa energikällor är förknippade med negativa miljöeffekter som luftföroreningar, oljeutsläpp, och surt regn, och ämnet ”peak oil” debatteras i hela världen, kommer oljan att ta slut? Förnybara energikällor kan hittas i hela världen (sol, vind, hav, vattenkraft, biomassa och jordvärme) och mängderna av förnybar energi på vår jord är stor och kan i teorin möta världens energibehov flerfaldigt.

Vågkraft, eller vågenergiomvandling, har potential att bli en ren och hållbar form av energiomvandling. Den kommer oundvikligen att ha en påverkan på den marina miljön, men inte i form av utsläpp av farliga ämnen (gaser, oljor och kemikalier). En våkraftsgenerator kommer att införa hårt substrat, eventuellt i en miljö där det tidigare inte fanns. Detta substrat kommer att koloniseras av marina organismer. Detta är ett känt fenomen som kallas för reveffekt och har observerats på bl.a. på sänkta fartyg. Andra miljöfrågor som är förknippade med vågkraft inkluderar bl. a. elektromagnetiska fält, förändringar i sedimentering samt undervattensbuller.

Undervattensbuller har potential att färdas över långa avstånd och har därmed potential att störa marina organismer på stora avstånd från bullerkällan. Det finns en stor variation i förmågan att uppfatta ljud mellan marina organismer, ett ljud som är tydligt hörbar för en art kan vara helt ohörbart till en annan. Således, för att kunna bestämma potentiell miljöpåverkan associerat med undervattensbuller från våkraftsgeneratorer, måste bullrets egenskaper vara kända. Denna avhandling presenterar resultat från studier på undervattensbuller från fyra olika våkraftsgeneratorer (fullskaliga i storlek) i Lysekilsprojektet.

Hydrofoner användes för att mäta bullret från våkraftsgeneratorerna. Huvudsyftet var att studera driftljuden från generatorerna med tonvikt på egenskaper som spektrumnivåer, ljudnivå, varaktighet och upprepningsfrekvens. Detta för att kunna uppskatta eventuell miljöpåverkan samt kunna fastställa källan till ljuden, och om möjligt, göra ändringar i konstruktionen för att minska ljudnivåerna. Resultaten identifierade två huvudsakliga driftljud, båda

är transienter med huvuddelen av energin i frekvenser under 1 kHz. Resultaten visar att designen är avgörande för utstrålade ljudnivåer.

Resultaten visar att det ljudet från vågkraftsgeneratorer i drift kommer att vara hörbart för flera marina organismer (fisk och däggdjur) upp till 10 km bort. Beteendereaktioner kan uppstå från både fisk och marina däggdjur i omedelbar närhet (<150 m) av generatorerna. Ljuden tros inte uppnå sådana nivåer att fysiska skador uppstår.

Med målet att ha så liten inverkan som möjligt på miljön, är studier av denna typ viktiga. På detta sätt kan designen av generatorerna ändras i ett tidigt skede i utvecklingen och på så sätt bidra med ren och hållbar energiomvandling. Baserat på resultaten i denna avhandling tros de potentiella negativa miljöeffekterna från undervattensbuller vägas upp av de positiva effekterna från re-veffekt och från att området blir skyddat från kommersiellt fiske. Dock måste bullret tas under övervägande när man planerar en vågkraftspark. Även om effekterna endast verkar vara lokala och kortvariga kan det få allvarliga konsekvenser om påverkar ett område särskilt viktigt för parning, födosök och/eller migration.

Dessa studier indikerar att bullernivåerna från denna typ av vågkraftsgeneratorer har begränsade effekter på den marina miljön, de visar även att bullernivåerna kan sänkas avsevärt. Designen går att ändra så att de dominerande oljuden minimeras, då är det möjligt att det utstrålade ljudet inte kommer att ha några negativa effekter alls på den marina miljön.

11. Acknowledgements

Först av all så vill jag börja med att tacka min handledare Jan Sundberg som för ca: 10 år sedan gav mig möjligheten att nästla mig in (från bojmålare till doktorand) i detta nu massiva och spännande projekt. Tack för att du låter mig jobba väldigt fritt samtidigt som du alltid finns tillgänglig då jag behöver feedback och/eller inspiration.

Mats Leijon, min biträdande handledare och projektledare som var vis nog att tänka på miljöeffekter i ett tidigt skede av detta projekt. Din drivkraft är utan dess like. Inget är omöjligt (utom chins när man har en jacka på sig).

I would like to give thanks to all the financial support, especially from Statkraft AS, Fortum OY, The Swedish Energy Agency, StandUP and Ångpanneföreningen's foundation for Research and Development, which made this research possible.

Jens Engström, tack för oräkneliga roliga stunder både i och utanför kontoret "tie tölv!?".

Rickard, Erland och Andrej, tack för att ni bjuder till skratt och lättar upp stämningen när det behövs, samt för att ni tar emot mina pranks utan några som helst tankar på att ge igen, det uppskattas!

Would like to express gratitude to everyone in the wave power research group. Thanks to your work this project moves forward, and I have something to measure on.

Gunnel Ivarsson, Maria Nordengren, Anna Wiström och Ingrid Ringård, ett stort tack för all hjälp med fakturor, resor, beställningar, rekvisitioner reseräkningar och allt annat pappersarbete som jag har noll koll på, var vore jag utan er?

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