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Wave Power for Desalination

JENNIFER LEIJON

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Abstract
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This doctoral thesis presents work related to wave powered desalination. Wave power for desalination could be an interesting alternative for islands or coastal regions facing freshwater shortage, and several systems have been proposed in literature. However, desalination is a process which demands a lot of energy. Studies presented in the thesis indicate that the wave energy converter designed at Uppsala University in Sweden could be used for desalination. This wave energy converter includes a floating buoy connected via a wire to a linear generator. The linear generator has magnets mounted on its movable part (the translator). Small-scale experiments have been included, indicating that intermittent renewable energy sources, such as wave power, could be used for reverse osmosis desalination. Moreover, hybrid systems, including several different renewable energy sources, could be investigated for desalination. There may be interesting minerals in the desalination brine. The thesis also includes investigations on the magnetic material inside the linear generator, as well as on control strategies for wave energy converters. An opportunity of including different types of ferrites in the linear generator has been analyzed. The thesis also presents pedagogic development projects for the electro engineering education at Uppsala University, suggesting that including a greater variability and more student-centered learning approaches could be beneficial.

Keywords: Wave power, desalination, freshwater, engineering education, linear generator, wave energy converter

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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, J.**, Boström, C., (2018) Freshwater production from the motion of ocean waves – A review, *Desalination*, 435.

II Francisco, F., **Leijon, J.**, Boström, C., Engström, J., Sundberg, J., (2018) Wave Power as Solution for Off-Grid Water Desalination Systems: Resource Characterization for Kilifi-Kenya, *Energies,* 11, 4.

III **Leijon, J.**, Salar, D., Engström, J., Leijon, M., Boström, C., (2020) Variable renewable energy sources for powering reverse osmosis desalination, with a case study of wave powered desalination for Kilifi, Kenya, *Desalination*, 494, 114669.

IV **Leijon, J.**, Forslund, J., Thomas, K., Boström, C., (2018) Marine Current Energy Converters to Power a Reverse Osmosis Desalination Plant, *Energies*, 11, 2880.

V **Leijon, J.**, Staffas, K., Boström, C., Bernhoff, H., (2020) Student-centered learning in an engineering course with project-integrated laboratory experiment, *Högre Utbildning*, 10, 1.

VI **Leijon J.**, Boström C., (2019) Lärarens arbete mot utveckling av generiska färdigheter och variation i teknikvetenskaplig utbildning genom relationsskapande åtgärder, *Högre Utbildning,* 9, 1.

VII (a)
Leijon, J., Sjölund, J., Ekergård, B., Boström, C., Eriksson, S., Dolguntseva, I., Leijon, M., (2017) Linear Generator with Different Types of Ferrite Permanent Magnets for Wave Energy Conversion, *The European Wave and Tidal Energy Conference 2017 (EWTEC)*, 27 August - 1 September, Cork, Ireland, 2017.

(b)
Leijon, J., Sjölund, J., Ekergård, B., Boström, C., Eriksson, S., Temiz, I., Leijon, M., (2018) Study of an Altered Magnetic Circuit of a Permanent Magnet Linear Generator for Wave Power, *Energies,* 11(1), 84.

VIII (a)
Leijon, J., Anttila, S., Frost, A., Kontos, S. Engström, J., Leijon, M., Boström, C., (2019) Marine Renewable Energy Sources for Desalination, Generating Freshwater and Lithium, *The International Society of Offshore and Polar Engineers (ISOPE) Conference*, Honolulu, HI, USA, June 16-21, 2019.

(b)
Leijon, J., Anttila, S., Frost, A., Kontos, S., Lindahl, O., Engström J., Leijon, M., Boström, C., (2020) Freshwater and Lithium from Desalination Powered by Marine Energy Sources, *The International Journal of Offshore and Polar Engineering (IJOPE)*, 30, 3.

IX **Leijon, J.**, Dolguntseva, I., Ekergård, B., Boström, C., (2016) Comparison of Damping Controls for a Wave Energy Converter with a Linear Generator Power Take-Off: a Case Study for the Lysekil and Wave Hub Test Sites, *The Asian Wave and Tidal Energy Conference (AWTEC)*, Singapore, 24-28 October, 2016.

X Temiz, I., **Leijon, J**., Ekergård, B., Boström, C., (2018) Economic aspects of latching control for a wave energy converter with a direct drive linear generator power take-off, *Renewable Energy*, 128.

XI **Leijon, J.**, Engström, J., Dolguntseva, I., Boström, C., (2017) Investigation of wave powered desalination for sustainable freshwater production. *The International Desalination Association World Congress*, São Paulo, Brazil, 15-20 October 2017.

XII Kontos, S., Ibrayeva, A., **Leijon, J.**, Mörée, G., Frost, A., Schönström, L., Gunnarsson, K., Svedlindh, P., Leijon, M., Eriksson, S., (2020) MnAl and other novel permanent magnets in electrical machines - a review and simulation study. Manuscript submitted to *Energies,* Status: Major Revision.

XIII Potapenko, T., Parwal, A., Kelly, J. F., **Leijon, J.**, Hjalmarsson, J., Anttila, S., Boström C., Temiz, I., (2019) Power Hardware in the Loop Real Time Modelling Using Hydrodynamic Model of a Wave Energy Converter With Linear Generator Power Take Off, *29th International Ocean and Polar Engineering Conference (ISOPE*), Honolulu, Hawaii, USA, June 16-21, 2019.

XIV Temiz, I., Parwal, A., Kelly, J., Potapenko, T., **Leijon, J.**, Anttila, S., Hjalmarsson, J., Hebert, L., Boström, C., (2019) Power Hardware-in-the-loop simulations of Grid-Integration of a Wave Power Park*, 13th European Wave and Tidal Energy Conference (EWTEC),* Napoli, Italy, September 1-6, 2019.

XV Anttila, S., Cardoso da Silva Júnior, D., Temiz, I., Goncalves de Oliviera, J., **Leijon, J.**, Parwal, A., Boström, C., (2019) Power control strategies for a smoother power output from a wave power plant, *The European Wave and Tidal Energy Conference (EWTEC)*, Napoli, Italy, September 1-6, 2019.

XVI Parwal, A., Fregelius, M., **Leijon, J.**, Chatzigiannakou, M., Svensson, O., Temiz, I., Boström, C., Oliviera, J., Leijon, M., (2018) Experimental Test of Grid Connected VSC to Improve the Power Quality in a Wave Power System, *The 5th International Conference on Electric Power and Energy Conversion Systems (EPECS 2018)*.

XVII Parwal, A., Fregelius, M., **Leijon, J.**, Chatzigiannakou, M., Svensson, O., Strömstedt, E., Temiz, I., Goncalves de Oliveira, J., Boström, C., Oliviera, J., Leijon, M., (2019) Grid Integration and a Power Quality Assessment of a Wave Energy Park. *IET Smart Grid,* 2, 4.

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Abbreviations and nomenclature

ED	Electrodialysis
FEM	Finite element method
LG	Linear generator
MCC	Marine current energy converter
MRET	Marine renewable energy technology
MVC	Mechanical vapor compression
NDP	Net driving pressure
OTS	Overtopping systems
OWC	Oscillating water columns
PBL	Problem-based learning
PM	Permanent magnet
PTO	Power take-off
REM	Rotating electrical machines
RES	Renewable energy sources
RO	Reverse osmosis
SCL	Student-centered learning
SDG	Sustainable development goal
TDS	Total dissolved solids
TSR	Tip speed ratio
WAB	Wave activated bodies
WEC	Wave energy converter
WEC/DES	Wave powered desalination
WIO	Western Indian Ocean
WPP	Wave power park

A	m^2	Area
A_a	m^2	Active area
$\mathbf{B}$	T	Magnetic flux density
B_r	T	Remanence
C_P	-	Power coefficient
C	ppm	Salt concentration
$\mathbf{D}$	$\mathrm{C/m^2}$	Displacement field
$\mathbf{E}$	$\mathrm{V/m}$	Electric field
E_{day}	Wh/day	Energy for one day

E_i	V	Induced voltage
E_{RO}	$\mathrm{Wh/m^3}$	Energy per cubic meter water
ϵ	$\mathrm{F/m}$	Permittivity
$\mathbf{F_b}$	N	Bouyancy force in calm water
$\mathbf{F_e}$	N	Excitation force
$\mathbf{F_h}$	N	Hydrostatic restoring force
$\mathbf{F_{PTO}}$	N	PTO force
$\mathbf{F_s}$	N	Spring force
$\mathbf{F_w}$	N	Wire force
FW_{day}	$\mathrm{m^3/day}$	Freshwater produced daily
$FW_{pers,day}$	$\mathrm{m^3/person}$	Daily personal freshwater need
g	$\mathrm{m/s^2}$	Acceleration due to gravity
γ	$\mathrm{Ns/m}$	Damping coefficient
$\mathbf{H}$	$\mathrm{A/m}$	Magnetic field
H_c	$\mathrm{A/m}$	Coercivity
H_S	m	Significant wave height
h_{pm}	m	Height of magnet
I_{pm}	A	Coil current
J	W/m	Power per wave crest length
$\mathbf{J}_\mathrm{f}$	$\mathrm{A/m^2}$	Free current density
K	-	Wave radiation force
N	-	Number of turns of a coil
N_{pers}	-	Number of people
N_{units}	-	Number of units
P	W	Power
P_{osm}	Bar	Osmotic pressure
P_{out}	W	Output power
P_t	W	Absorbed power by turbine
ρ	$\mathrm{kg/m^3}$	Density of water
ρ_f	$\mathrm{C/m^3}$	Free current density
Q	$\mathrm{m^3/hour}$	Water flow rate
Φ	Wb	Magnetic flux
$\mathcal{R}$	$\mathrm{J/mol \cdot K}$	Universal gas constant
R	%	Recovery rate
r	m	Radius
T	K	Temperature
T_E	s	Energy period
V_{sub}	$\mathrm{m^3}$	Submerged volume
v	m/s	Velocity
ω	rad/s	Angular velocity
μ	$\mathrm{Vs/Am}$	Permeability

1. Introduction and background

1.1. Introduction

More than 70 % of the surface of our Earth is covered in oceans. About 40 % of all people live within 100 km from the coasts [1]. Nonetheless, freshwater shortage is a global problem, and about 4 billion people experience water scarcity parts of the year [2]. The water-energy-food (WEF) nexus highlights a complex interconnected relation between these resources [3-4], which also relates to overall security.

Desalination is a process where salt is removed from saline water, generating drinking water. Desalination plants (DPs) are often powered by fossil fuels, but renewable energy sources (RES) have been increasingly utilized and investigated for desalination [5,6]. Most projects on RES powered DPs include wind- or solar powered desalination [7-9]. Wave power is a technology where electricity is generated from the movement of ocean waves, utilizing a wave energy converter (WEC) system. Due to the collocation of the ocean waves and the saline water to desalinate, wave power could be interesting to combine with desalination [10]. This could be utilized off-grid and in remote coastal regions or islands. Small-scale systems could also be developed for disaster resilience, where there is a need to rapidly ensure access to clean water or electricity [11].

Some regions in Sweden, such as the island Gotland, experience water shortage parts of the year, due to warm summers and a lot of tourism. Thus, two desalination plants have been built on Gotland: a plant in Herrvik which could produce up to 480 m^3 freshwater daily[1], and a plant in Kvarnåkershamn which could produce up to 7 500 m^3 freshwater daily[2]. Other Swedish cities have also discussed desalination as way to ensure water access[3].

Wave powered desalination has gained more interest over the recent years, as shown for example in the U.S. Department of Energy competition on innovative solutions for wave powered desalination: Waves to Water Prize[4].

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[1]http://www.bjorksrostfria.se/wp-content/uploads/2016/07/herrviksvv.pdf [Accessed: 2020-07-08]

[2]https://www.nyteknik.se/miljo/sa-ska-gotland-klara-vattenbristen-avsaltar-7500-kubikmeter-dricksvatten-6961828 [Accessed: 2020-07-08]

[3]https://www.nyteknik.se/samhalle/vattenbrist-da-kan-karlskronabor-fa-havsvatten-i-glaset-6997314 [Accessed: 2020-07-08]

[4]https://www.herox.com/wavestowater [Accessed: 2020-07-08]

1.2. About this thesis

This doctoral thesis presents research on wave power and desalination. The main research question is: can wave power be utilized to power desalination systems and generate freshwater? The thesis also describes pedagogic development in engineering education, in Paper V and VI. The methodology of the work includes literature review, calculations, simulations, and small-scale experiments. Full explanations and results etc. are provided in the different papers. The Agenda 2030 for Sustainable Development[5] and several (or all) of the 17 Sustainable Development Goals (SDGs) can be related to the work presented in thesis. Especially, the work relates to Goal 6: Ensure access to water and sanitation for all, and Goal 7: Ensure access to affordable, reliable, sustainable, and modern energy. The first part of the thesis (i.e. the kappa) is outlined as follows. Firstly, a background to parts of the work is provided. Then some of the theory and methods used are presented. Thereafter, some results are included along with a discussion. Some final conclusions are presented, followed by suggestions on directions for future research in the field.

Many researchers have focused on marine energy at the Division of Electricity[6], Uppsala University. About 35 doctors have defended their thesis on different aspects of wave power [12-46]. This doctoral thesis relates to their work in many ways, for example when it comes to the type of wave energy converter studied as well as on modeling and control of the system. But this is the first doctoral thesis at the division concerning desalination. The work on magnets inside the generator relates to for example the thesis of Dr. Boel Ekergård [24], of Dr. Oskar Danielsson [13] and of Dr. Sandra Eriksson [47]. This is the first thesis at the division concerning mixed types of magnets in the linear generator. The work involving marine current energy converters relates to for example the thesis of Dr. Johan Forslund [48]. The work in the doctoral thesis follows up on the licentiate thesis which was defended in November 2018 (Title: Wave Powered Desalination)[7]. I would like to highlight that parts of this text are reused from the licentiate thesis, and the overall theme of the licentiate thesis and this doctoral thesis is similar.

1.3. Wave power

There are many different WEC technologies designed. A wave power solution was first patented in 1799, and today, more than a thousand devices have been

[5]https://sustainabledevelopment.un.org/?menu=1300 [Accessed: 2020-07-09]
[6]https://elektroteknik.uu.se/elektricitetslara/ [Accessed: 2020-07-09]
[7]https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1270225&dswid=-9958 [Accessed: 2020-07-09]

patented [49]. Nonetheless, wave power is in an early state of commercialization. The wave power technologies designed at universities and companies could be slightly different from each other in designs, and the WECs can be categorized based on different properties [50,51]. Three categories of WEC systems are [52]: oscillating water columns (OWC), overtopping systems (OTS) and wave activated bodies (WAB). Figure 1 illustrates (a) OWC, (b) OTS and (c) different types of WABs (similar figure in [43,53]). The OWC structure, illustrated in Figure 1 (a), encloses a water column moving up and down with the waves, pressurizing the air above it, which in turn causes a turbine to rotate. The overtopping system in Figure 1 (b) utilizes water overtopping to a reservoir, which then passes a turbine on the outlet. The wave activated bodies (or oscillating bodies) in Figure 1 (c) vary in design, from a flapping device to floating buoys connected to power take-off (PTO) systems. WECs generally have hydraulic or electric PTO systems. Some challenges with wave power are for example the harsh and corrosive marine environment and the irregularity of the ocean waves. As described in [49], a large WEC could be designed to generate for example 1.5-2 MW, whereas smaller WECs, used in arrays, can be rated to about 5-20 kW each. The devices could be installed onshore or offshore. The WEC studied the most at the Division of Electricity, Uppsala University, (the UU-WEC) is a wave activated body. Figure 2 illustrates the UU-WEC.

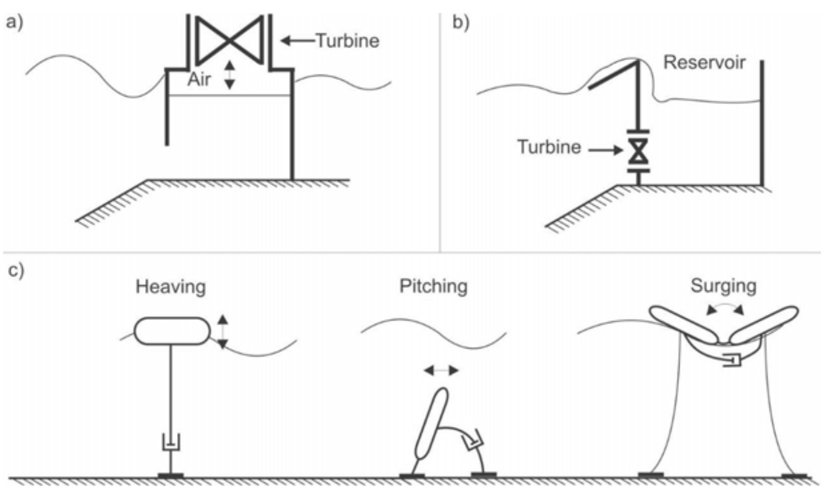

Figure 1. Different types of wave energy converters: (a) oscillating water column, (b) overtopping system, (c) various wave activating bodies [43,53].

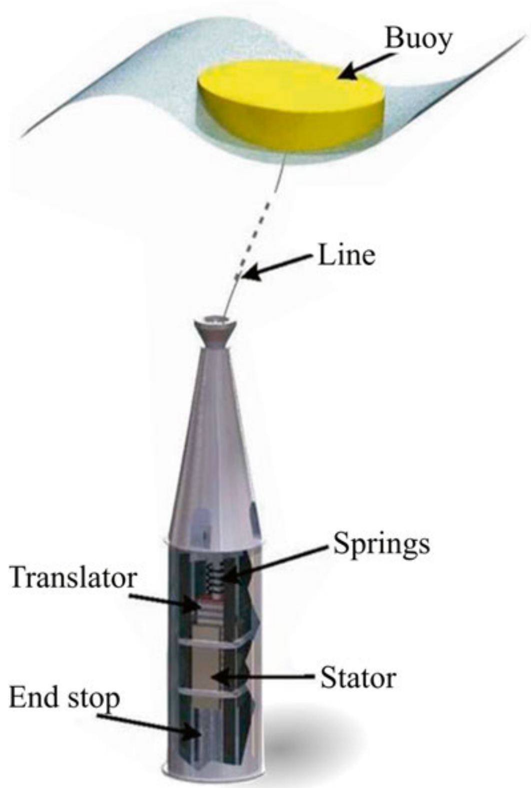

Figure 2. Sketch of the wave energy converter system designed at Uppsala University, including a floating buoy and a linear generator with stator and translator, similar figure found in for example [18].

The UU-WEC includes a floating buoy (point absorber) connected via a wire down to a linear generator (LG) power take-off (PTO) in a water-tight hull, mounted on a concrete foundation. The LG has a moveable part, the translator, and a still stator. The translator includes permanent magnets (PMs) and the stator includes windings. Current is induced in the stator windings as the translator moves up and down in relation to the stator. Research on WEC control strategies has been conducted [54]. The design goal of the UU-WEC is to be simple, robust and with only a few moving parts. Several UU-WECs could be included in a wave power park (WPP). The WECs would be connected with subsea cables via a marine substation to grid or a specific function. The UU-WEC has previously been studied with off-shore experiments in Lysekil, Sweden [55]. For implementation of WEC systems, environmental aspects should be considered [56].

1.4. Magnetic circuit of the linear generator

The magnetic circuit of the LG can be altered to, for example, improve system sustainability. Previous studies, including full-scale WEC experiments, have shown that the WECs can be built using ferrite permanent magnets instead of the rare-earth magnet $Nd_2Fe_{14}B$ [24]. In the following, investigation to further alter the magnetic circuit has been carried out, specifically on two different types of ferrite permanent magnets in the same machine. This is discussed and presented in Papers VII (a) and (b). The studies include discussions on changing parts of the magnets inside the LG from ferrites of higher grade (of type Y40) to ferrites of lower grade (of type Y30), as well as changing the shape of the machine's poleshoes. Table 1 shows the remanence and coercivity of the two different ferrites, and that one is stronger than the other.

Table 1. *Some properties of the two ferrite magnets, of type Y30 and Y40, as presented in Paper VII (a) and (b).*

	Y30	**Y40**
B_r [mT]	370 – 400	440 – 460
H_c [kA/m]	175 – 210	330 – 354

To include weaker magnets and to decrease the size of the stronger magnet could be a good option for some applications. This, for example due to limited transportations as more manufacturers manage to make smaller sizes of strong magnets, than larger sizes. The weaker or smaller magnets could be cheaper. One estimation is that the large Y40 ferrite magnets, suitable for WECs, are about six times as expensive as the Y30 magnets of same dimensions. To maintain the magnetic flux in the airgap while including weaker magnetic material, the shape of the poleshoes is changed from a rectangular shape to a T-shape.

1.5. Desalination

Desalination is the process where salt is removed from saline water. Many countries use desalination plants today. 99.8 million m^3 desalinated water each day was the cumulative contracted capacity in 2017, according to IDA [57]. The size of desalination plants varies greatly, and both large and small desalination plants exists. The desalination processes are either thermal- or membrane processes. Reverse osmosis (RO), mechanical vapor compression (MVC) and electrodialysis (ED) are shown in the sketch in Figure 3, adapted from [53]. RO in Figure 3 (a) is a pressure-driven process where semipermeable membranes separate the clean water from the salty residue. ED in Figure 3 (b) is a process where an electric field is applied to separate the salt ions from the water. MVC in Figure 3 (c) involves heating and evaporation of the feed water to separate the clean water from the salt. There are other desalination processes as well, but these three are powered by mechanical or electrical energy, which can be obtained by wave power.

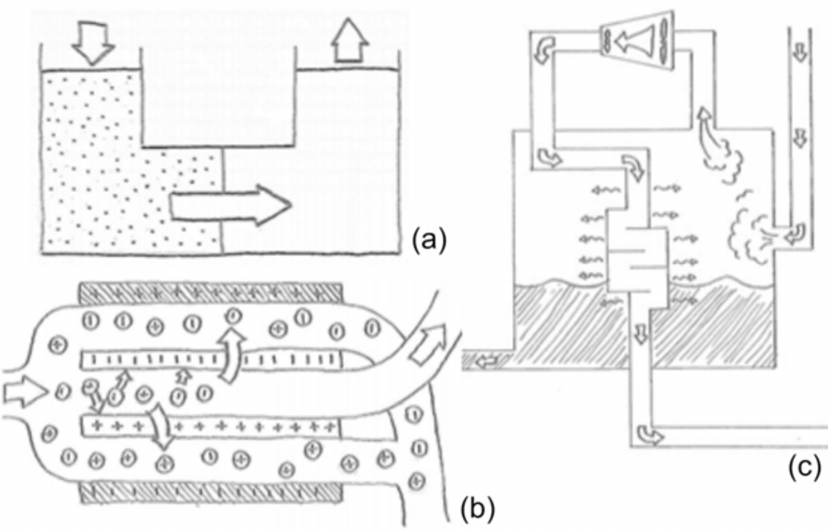

Figure 3. Desalination processes: (a) reverse osmosis, (b) electrodialysis and (c) mechanical vapor compression, a similar figure was presented in [18][53].

The most common desalination process is the membrane process RO (in 2015, about 65 % of the desalination production capacity included RO [5]). The salinity of the inlet water affects the pressure level, and thereby also power level, needed for RO for freshwater production. The RO membranes can be damaged by for example fouling, and the inlet water is often pretreated before the RO process, filtering out unwanted parts etc., as well as after treated, to ensure a high quality of the drinking water. The feed water of the desalination process can be seawater, brackish water or some other source, such as wastewater. To describe how saline the water is, the total dissolved solids (TDS) of the solute is estimated. For example, drinking water has TDS less than about 500 ppm, brackish water has TDS of 1000 to 35 000 ppm and seawater is within the TDS range 35 000 to 45 000 ppm [58]. When you separate salt from the seawater, you end up with the clean freshwater and a salty residue. Management of the hypersaline brine has to be considered [59]. In some cases, the salty brine is directly released back into the ocean. For seawater reverse osmosis (SWRO), the brine disposed is estimated to be about twice as saline as the surrounding water [59]. In Paper VIII (a) and (b), the possibility of extracting valuable minerals from the brine, such as lithium, is discussed. Two main challenges of desalination are: *(i)* the environmental issues regarding management of the salty remaining residue, and *(ii)* the energy need of the process, and the environmental issues involved with the electricity production [60]. The energy needed for desalination processes such as RO has been lowered over the years, with improved membranes and technologies, for example energy recovery systems. A review on the energy need of membrane desalination processes was recently presented in [61]. SWRO requires (at least) about 3 to 4 kWh/m^3 freshwater produced [62]. Brackish water RO (BWRO) requires around 1.5 to 2.5 kWh/m^3 freshwater [5].

1.6. Marine renewable energy sources for reverse osmosis desalination

Marine RES, such as wave- and marine current power, could be used to power a DP, as discussed in [63]. These systems could be useful in small-scale, off-grid solutions, where there is a freshwater need and unreliable electric grids. Thus, these systems could be beneficial for islands [64] or remote coastal regions. Most of the ongoing research on renewables for desalination includes solar or wind powered systems. As the variability of the marine energy sources occurs on different timescales than solar and wind [65], there are opportunities to investigate marine RES for desalination. A recent study investigates wave powered desalination for Canary Islands [66].

Desalination can be powered directly or indirectly by the ocean waves. If the wave powered desalination system acts directly, the saline water for an RO process is directly pressurized by the wave power system. If the desalination system is instead powered indirectly by wave power, the WEC will first be used to generate electricity, which is then used to power the DP. Previous projects, such as Delbuoy [69,70], have proven that the ocean waves can be utilized directly for desalination. For Delbuoy (developed in 1976), a floating buoy was connected directly to a pump on the seafloor, generating the pressurized seawater for the RO process. Another wave powered desalination project was implemented in Vizhinjam, India. It included an OWC connected to an SWRO system with the rated production of 10 000 liter freshwater daily [69]. The research on wave powered desalination has included for example the Edinburgh duck WEC [70] and a direct-driven wave powered desalination system called the AaltoRO [71]. The company Carnegie produced freshwater from wave powered desalination with their CETO system[8]. Wave powered desalination is discussed in for example [72].

The east coast of Kenya, facing the western Indian Ocean (WIO), was chosen as a case study for the work on wave powered desalination, specifically investigating the possibility of powering a desalination plant at a women training center in the area Kilifi [73] (see Paper II, III and XI). Data describing the wave climate at this location was bought from the company Fugro[9] and the

[8]https://www.carnegiece.com/project/ceto-5-perth-wave-energy-project/ [Accessed: 2020-07-10]
[9]https://www.fugro.com/ [Accessed: 2020-08-17]

wave power resource at Kilifi was analyzed for UU-WECs powering a desalination process. The project was in collaboration with Strathmore University[10] in Kenya.

The intermittency is generally lower for hydrokinetic energy sources (i.e. streaming water) than for other RES, waves included. There is a possibility to utilize marine current- or tidal energy converters to power a desalination processes, and this is a rather new and unexplored combination. The work presented in Paper IV describes a marine current energy converter (MCC) designed at Uppsala University to power an RO desalination plant. This MCC has five vertical axis blades, as shown in Figure 4. The Söderfors research site is used for experiments on the MCC [74] and the Uppsala MCC is described for example in [75]. Upper- and lower limitations on the water speed of the marine currents affects the time span where the MCC produces electricity. For this specific design and study, it is assumed that the system function with water speeds from about 1-2 m/s. The location of the case study for the investigated MCC powered DP was the South African coast, facing the Indian Ocean (see Paper IV).

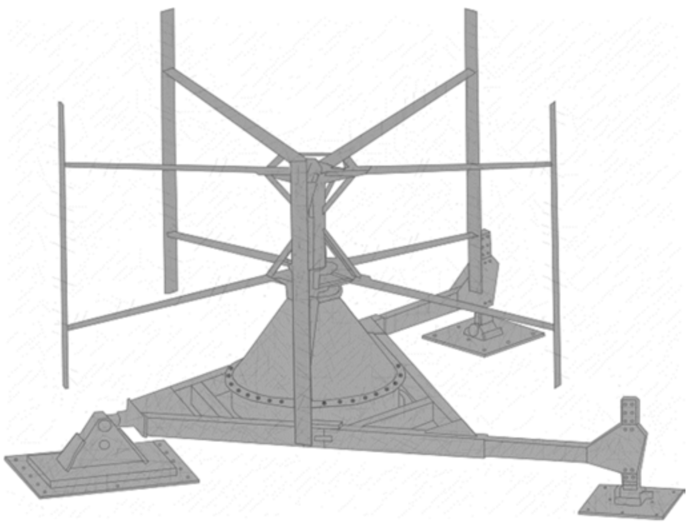

Figure 4. Marine current energy converter, designed at Uppsala University, sketch adapted from [76].

[10]https://www.strathmore.edu/ [Accessed: 2020-08-17]

2. Theory and method

2.1. Magnetic circuit of the linear generator

Maxwell's equations constitute the theoretical background to electromagnetism. Descriptions on the equations are found in for example [78-81]. Maxwell's equations are:

$$\nabla \cdot \mathbf{D} = \rho_f \qquad (1)$$

$$\nabla \cdot \mathbf{B} = 0 \qquad (2)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad (3)$$

$$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t} \qquad (4)$$

where **D** is the displacement field, ρ_f is the free current density, **B** is the magnetic flux density, **E** is the electric field, **H** is the magnetic field and $\mathbf{J}_f$ is the free current density. Equation 1 is Gauss's law for electric fields, Equation 2 is Gauss's law for magnetic fields, Equation 3 is Faraday's law of induction Equation 4 is Ampere's law.

Faraday's law of induction, Equation 3, states that the rotation of the electric field **E** is equal to the negative of a magnetic flux density **B** varying over time. That is, Faraday's law states that a time varying magnetic flux density **B** induces a rotating electric field **E**. The magnetic flux through a closed surface is denoted Φ, and can be written

$$\Phi = \int \mathbf{B} \cdot d\mathbf{a}. \qquad (5)$$

The induced voltage E_i of a coil of *N* turns, for time varying magnetic flux through the loops, is according to Faraday's law of induction

$$E_i = -N\frac{\partial \phi}{\partial t}. \qquad (6)$$

The relationship between the magnetic flux density **B** and the magnetic field **H** fields is

$$\mathbf{B} = \mu_r \mu_0 \mathbf{H} \qquad (7)$$

where μ_0 is the permeability of free space and μ_r is the relative permeability. The permeability $\mu = \mu_r\mu_0$ describes the response of a material, in terms of resulting magnetic flux density, if it is subjected to an applied magnetic field. The magnetization curves in Figure 5 are also known as the hysteresis loops or **B**-**H** curves of the materials. The remanence B_r is the magnetization of the material without an applied magnetic field and the coercivity H_c describes how high an opposite applied magnetic field should be to demagnetize the material. Therefore, the magnets inside the LG should have high remanence and high coercivity, i.e. be hard magnetic materials. On the other hand, the stator steel should have low remanence, i.e. be soft magnetic, changing magnetization direction for every magnet passing. The magnetic circuit of generators and losses etc. are described in more detail in for example [47].

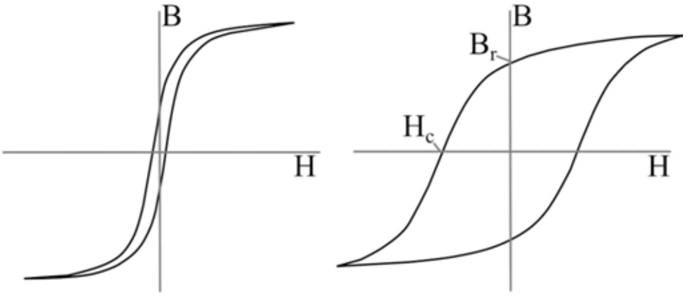

Figure 5. Magnetization curves of a (left) soft- and a (right) hard magnetic material, including the remanence and coercivity, remade from [47].

The work on the magnetic circuit, presented in Paper VII (a) and (b), included simulations in the in-house software ACE developed at ABB and Uppsala University [81]. This simulation tool solves Maxwell's equations for a two-dimensional LG segment using the finite element method (FEM). In Figure 6, an overview of the LG segment is provided. FEM simulations of the LG was previously outlined in [82]. Generated results from ACE have been compared with experiments, showing agreement [83]. Each magnet in ACE is modelled with the current sheet method, described in for example [85-87], where the magnets are modelled as current carrying coils, with current direction and coil dimension in accordance to the magnetization direction and size of the permanent magnet. For descriptions of the simulation method, see for example [13,47]. The resulting coil current to model a PM magnet is

$$I_{pm} = \frac{B_r h_{pm}}{\mu} \tag{8}$$

where the height of the magnet is h_{pm}.

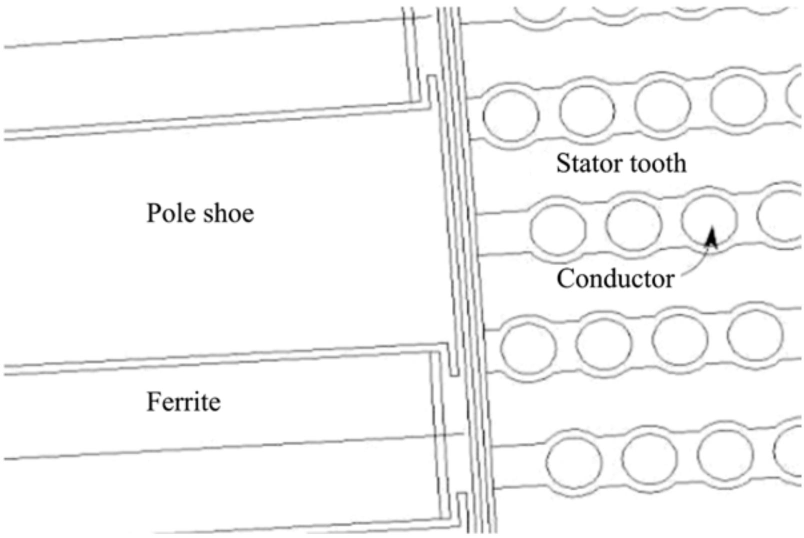

Figure 6. Overview of LG segment as modeled in ACE, including a translator with ferrite PMs between T-shaped poleshoes, near the stator with conductors [87].

2.2. Modeling and control of the wave energy converter

The power per wave crest length, J, available in the ocean waves [88], for water density, ρ, and gravitational constant, g, can be calculated as

$$J = \frac{\rho g^2}{62\pi} T_E H_s^2 \tag{9}$$

for energy period, T_E, and the significant wave height, H_s. T_E and H_s are parameters calculated from the spectral density (i.e. mathematical description) of the ocean waves. A model in Matlab[11] and WAMIT[12] was used to estimate the performance of a point absorber WEC. The input values to the model are for example design parameters of the WEC and the wave height and period. The resulting model outputs are translator velocity and power output over time etc. The accuracy of the model is limited, and theoretical background utilized for the model is provided in [89,90]. The model is based upon investigations on the forces acting on the system: on the buoy and the LG, coupled to each other via the wire force F_w. The forces acting on the different parts of the WEC are summarized in Figure 7.

[11]https://se.mathworks.com/products/matlab.html [Accessed: 2020-08-17]
[12]https://www.wamit.com/ [Accessed: 2020-08-17]

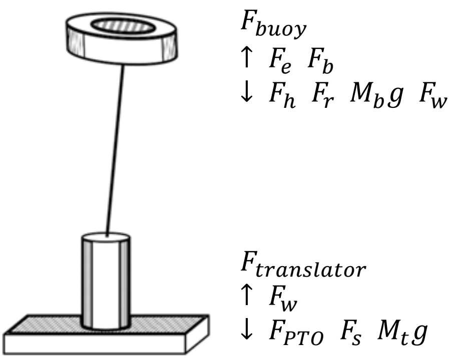

Figure 7. Sketch of wave energy converter system and the forces acting on the system, adapted from [40].

If the wire is not slack, the wire force is nonzero and calculated as

$$F_w = k_w\big(z_b(t) - z_t(t)\big) \qquad (10)$$

for a spring coefficient, k_w, and (time dependent) buoy and translator positions, z_b, and, z_t. The mass of the buoy is denoted M_b and $F_b = \rho g V_{sub}$ is the buoyancy force in calm water for a submerged volume V_{sub} and a water density ρ. The forces acting on the buoy are summarized as

$$F_{buoy}(t) = F_{hydro}(t) + F_b - M_b g - F_w \qquad (11)$$

where the hydrodynamic force F_{hydro} acting on the buoy is

$$F_{hydro}(t) = F_e(t) - F_r(t) - F_h(t) \qquad (12)$$

including the excitation force, F_e, the radiation force, F_r, and the hydrostatic restoring force, F_h. F_e is calculated as the convolution of the impulse response function of the excitation force, f_e, and the surface elevation, η,

$$F_e(t) \ = \ f_e(t) * \eta(t), \qquad (13)$$

whereas F_r is calculated as the convolution of the impulse response function of the wave radiation force K and the velocity of the buoy, $\dot{z}_b$, resulting in

$$F_r(t) = -\int_0^t K(t-\tau)\dot{z}_b(\tau)\, d\tau. \qquad (14)$$

In order to decrease calculation time of the convolution integral, a state-space method [91] was utilized and the method is described in more detail in Paper IX and X. Moreover, the hydrostatic restoring force is calculated as

$$F_h(t) = \rho g \Delta V_{sub}(t) \quad (15)$$

for a variation in submerged buoy volume, ΔV_{sub}. For a translator with mass, M_t, the forces acting on the translator are

$$F_{translator}(t) = F_w - F_{PTO} - F_s - M_t g, \quad (16)$$

where the PTO force or the damping force is, F_{PTO}, and a possible spring force acting on the system in either end stop is, F_s, (if end stop springs are available in the system). The PTO force depends on the active area, A_a, of the stator and translator (i.e. how much of the stator that is covered by the translator), the velocity of the translator, $\dot{z}_t$, and the damping coefficient, γ. This is calculated as

$$F_{PTO}(t) = \gamma(\dot{z}_t) A_a(t) \dot{z}_t(t). \quad (17)$$

The active area is calculated as

$$A_a(t) = \begin{cases} 1, & \text{if } |z_t(t)| \leq \frac{1}{2}(l_t - l_s) \\ 0, & \text{if } |z_t(t)| \geq \frac{1}{2}(l_t + l_s) \\ \frac{1}{l_s}\left(\frac{1}{2}(l_t + l_s) - |z_t(t)|\right), & \text{else} \end{cases} \quad (18)$$

Where, l_t, and, l_s, are the lengths of the translator and stator, respectively. Finally, the instantaneous power out from the WEC system model is calculated as

$$P(t) = F_{PTO}(t) \dot{z}_t(t). \quad (19)$$

More detailed descriptions on the WEC model and how the model is utilized for WEC analysis are presented in Paper IX and X.

2.3. Marine current energy converter

The power available in free-flowing water is

$$P = \frac{1}{2} A \rho v^3 \quad (19)$$

for a turbine cross sectional area, A, density of water, ρ, and the water velocity, v. The power coefficient, C_P, is the ratio of the power available in the water and the absorbed power by the MCC turbine, P_t, that is

$$C_P = \frac{P_t}{P}, \tag{20}$$

expressing the hydrodynamic efficiency of the turbine. C_P is dependent on the tip speed ratio, TSR, calculated as

$$TSR = \frac{\omega r}{v} \tag{21}$$

describing how fast the turbine blades rotate with respect to the water speed, for a turbine radius, r, and angular velocity, ω. The power coefficients of the Uppsala MCC for different tip speed rations were presented in [75].

2.4. Desalination

This section will give a brief theoretical background to RO, but more extensive background is provided in literature, such as [92-94]. As presented in for example [93, 95], the osmotic pressure, P_{osm}, of a solute is calculated as

$$P_{osm} = \mathcal{R}T \sum X_i \tag{22}$$

where $\mathcal{R}$ is the universal gas constant, T is the temperature in K and $\sum X_i$ is the sum the concentration of all constituents of the solution. For RO, the osmotic pressure of the solute is overcome by adding an additional external pressure to one side of the semipermeable membrane, as illustrated in Figure 3 (a), enhancing its chemical potential. Clean water will flow through the semipermeable membrane to restore the equilibrium. The remaining salty water is called the brine or the concentrate, whereas the produced desalinated water is called the permeate. For a feed water flow rate, Q_f, the desalination process can be written as

$$Q_f = Q_p + Q_b \tag{23}$$

for a permeate flow rate, Q_p, and a brine flow rate, Q_b. The product recovery rate, in percentage, for a system is

$$R_p = 100 \cdot \frac{Q_p}{Q_f}. \tag{24}$$

The mass and salt balance is

$$Q_f C_f = Q_p C_p + Q_b C_b \tag{25}$$

for the different salinities of the feed, C_f, the permeate, C_p, and the brine, C_b, respectively. The net driving pressure, NDP, summarizes the driving force of the RO process and the water flow, as described in for example [93, 96].

2.5. Marine renewables for reverse osmosis desalination

Simplified estimations on how much water a certain RES powered desalination system can produce, and the amount of people possibly benefitting from it, are presented. More detailed calculations on RO membrane elements, specifically under pressure variations, are provided in for example [97]. For an MCC or WEC with (here, assumed constant) power output, P_{out}, and with the number of units of the energy converter, N_{units}, the energy out from the converter system available for the RO system during one day (i.e. 24 hours), E_{day}, is

$$E_{day} = P_{out} \cdot N_{units} \cdot 24. \tag{26}$$

If the RO system utilizes a specific amount of energy, E_{RO}, per produced cubic meter freshwater (as described in for example [6]), the freshwater produced each day from the full system, FW_{day}, is estimated as

$$FW_{day} = \frac{E_{day}}{E_{RO}}. \tag{27}$$

With an estimated personal daily freshwater demand of a person, $FW_{pers,day}$, (such as at least 20 liter per day [98]), the number of people, N_{pers}, with possibility to utilize the water system for their basic freshwater demand can be calculated as

$$N_{pers} = \frac{FW_{day}}{FW_{pers,day}}. \tag{28}$$

There are limitations with this strategy. For example: in reality, personal water need differs, and the power produced from a RES varies due to intermittency etc.

2.6. Experiments on small-scale desalination system

Small-scale experiments on variability in powering of RO desalination were performed and presented in Paper III. The experiments on a commercial RO system suggested that the system could generate freshwater when powered on levels other than the rated levels in the manual. The outcomes from the experiments were used along with estimations on the wave power resource in Kilifi in Kenya. An estimation of 24 % absorption of the available waves were assumed, resulting in an assumed power output from one to three wave energy converters. The estimated power output from one WEC is shown in Figure 8. The system could also be combined in hybrid systems with solar or wind power. A photo of the experimental system is shown in Figure 9.

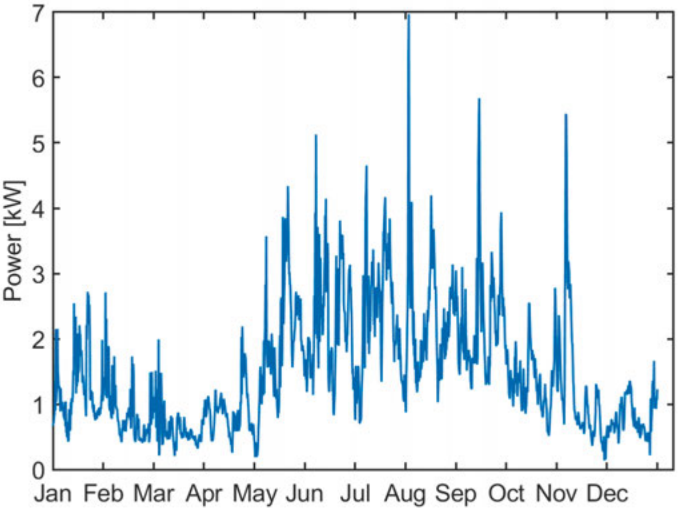

Figure 8. Production [kW] from one WEC in Kilifi, Kenya, during 2015, assuming a 24 % power absorption from the local wave resource, see Paper III.

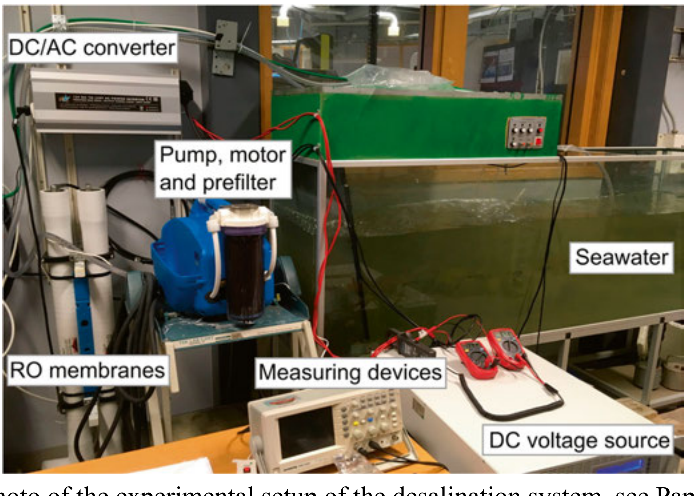

Figure 9. Photo of the experimental setup of the desalination system, see Paper III.

The small-scale, commercially available RO system is provided from Rainman [99], with some data shown in Table 2.

Table 2. *Data from manual of the Rainman RO desalination system.*

Property	**Information**
Pressure	Brackish water: 13 bar. Seawater: 55 bar, acceptable pressures: 51-58 bar.
Permeate flow	140 liter/hour.
Reverse osmosis membranes	Two 40-inch membranes.
Recommended power supply	AC, 2 kW peak, 1.6 kW continuously.

Based on experiments with the RO device, with variable power levels and resulting variable freshwater output, the amount of freshwater that could be generated from wave power in Kilifi could be estimated (see Paper III). Note that this is a very rough estimation.

3. Results

3.1. Magnetic circuit of the linear generator

This section concerns Papers VII (a) and (b). Results from the studies on the magnetic circuit are summarized in Table 3 and 4. Table 3 shows that the magnetic energy per unit stacklength [Ws/m] in the airgap decreases if parts of the magnetic material in the linear generator is changed from ferrite of type Y40 to Y30 (the poleshoe is here rectangular). The magnetic energy is higher if Y40 is closer to the stator than Y30. Based on the assumption that the Y40 magnets are about six times as expensive as Y30 magnets, the relative magnetic energy cost is calculated. It is shown that the magnetic energy increases as the shape of the poleshoe is changed from a rectangular shape to a T-shape, as shown in Table 3 and 4. If the size of the T-shaped poleshoe is about 85% of its initial size, the leakage flux decreases. Figure 10 shows the simulations in Ace for Case 2b.

Table 3. *Results from simulations, with the magnetic material is changed in steps from only Y40 to only Y30, where the * denotes the magnet closest to the stator.*

Case	Description	Magnetic energy in airgap [Ws/m]	Relative cost	Relative magnetic energy cost
1	100% Y40*	123	6	4.39
2	75% Y40 & 25% Y30*	112	4.75	3.82
2b	25% Y30 & 75% Y40*	113	4.75	3.78
3	50% Y40 & 50% Y30*	104	3.5	3.03
3b	50% Y30 & 50% Y40*	105	3.5	3.00
4	25% Y40 & 75% Y30*	96	2.25	2.11
4b	75% Y30 & 25% Y40*	97	2.25	2.09
5	100% Y30*	90	1	1

Table 4. *Results from simulations with cases presented in Table 3 combined with a T-shaped poleshoe, and when it is cut to 80-90% of full length of poleshoe.*

Case	Combination	Magnetic energy in the airgap [Ws/m]
6	3b & T	106.9
7	2b & T	115.0
8	2b & T90%	121.7
9	2b & T85%	122.4
10	2b & T80%	122.0

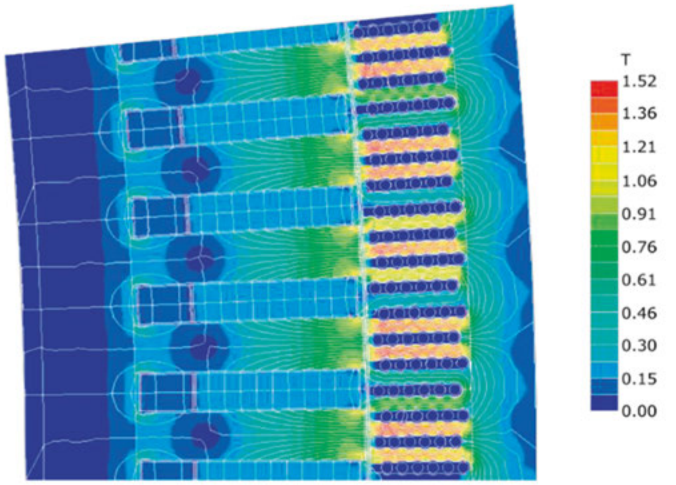

Figure 10. Simulation in Ace on LG with mixed magnets, where 75 % the magnetic material is Y40 and 25 % is Y30 (case 2b), as presented in Paper VII (a) and (b).

3.2. Control of the wave energy converter

As discussed in Paper IX, the optimal constant damping coefficient to dampen the linear generator varies with its design and the wave climate etc. For the WEC with a 10 000 kg translator, the results suggest that the optimal damping coefficient varies with different combinations of significant wave heights and energy periods, as can be seen in Figure 11. If this damping is used, the annual energy output from the WEC at the Lysekil site, Sweden, and the Wave Hub site, UK, were estimated in Paper IX. The result from Wave Hub test site is shown in Figure 12. In total four different cases of control were simulated in this study. This was further investigated in Paper X.

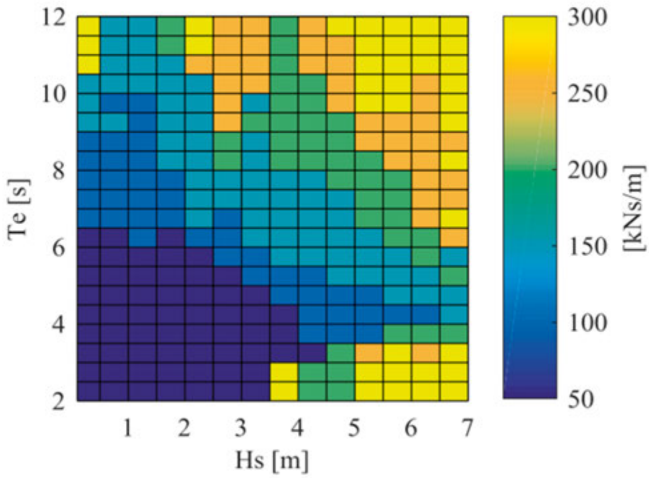

Figure 11. The optimal damping coefficient for a 10 000 kg translator of a WEC (Paper IX).

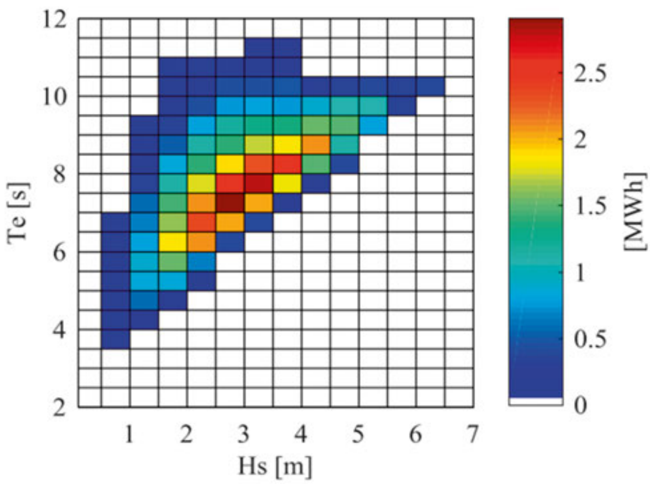

Figure 12. Estimated annual energy out from a WEC at the Wave Hub test site (Paper IX).

3.3. Wave powered desalination systems

A review on previously proposed wave powered desalination (WEC/DES) systems was presented in Paper I. There, it was highlighted that several systems had been suggested, as shown in Table 5. However, at the time of the study, only a few of the projects were ongoing or had been deployed and produced freshwater. It included suggestions on how to categorize them, showing opportunities of design of currently non-existent systems (such as wave activated bodies powering an electrodialysis desalination process). Most projects were a combination of an oscillating body and RO. A few projects resulted in freshwater production, such as the OWC powered RO plant in Kerala, India [69], and the oscillating body system designed by Carnegie[13], powering an RO process in Australia. In Paper II, the waves outside Kilifi in Kenya were analyzed. The variability of the waves over different months in Kilifi, Kenya is shown in Figure 13.

Table 5. *Different wave powered desalination projects and status, from Paper I.*

Concept	WEC/ DES	Research	Simulat-ion	Test	Deployed	Com-pany	Ongoing
3D & Surge	WAB-RO	×	×	–	–	×	–
AaltoRO	WAB-RO	×	×	–	–	–	–
Buoy array	WAB-RO	×	×	–	–	–	–
CETO	WAB-RO	×	×	×	×	×	–
Delbuoy	WAB-RO	×	×	×	×	×	–
DEIM	WAB-RO	×	×	–	–	–	–
Duck	WAB-VC	×	×	–	–	–	–
ISWEC	WAB-RO	×	×	–	–	–	–
Odyssée	WAB-RO	×	×	–	×	–	×
Oyster	WAB-RO	×	×	–	–	–	–
SAROS	WAB-RO	×	×	×	×	×	×
Uppsala	WAB-RO	×	–	–	–	–	×
Vizhinjam	OWC-RO	×	×	×	×	–	–
WaveCatcher	OWC-RO	×	–	×	–	–	–
Wind/Wave	WAB-RO	×	–	–	–	–	–

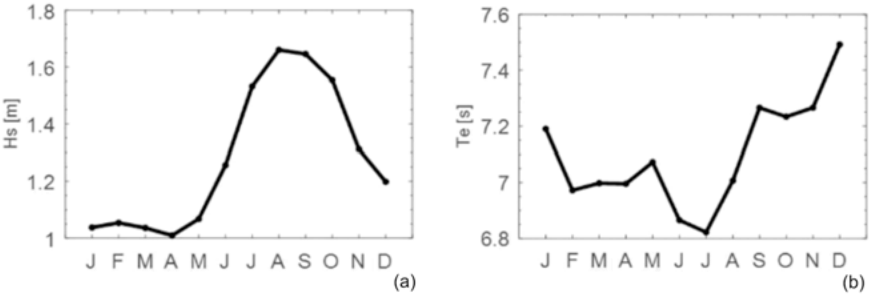

Figure 13. The (a) significant wave height [m] and (b) energy period [s] are shown over different months for Kilifi, Kenya, as presented in Paper II.

The occurrence of different seastates in Kilifi, Kenya, based on data from 1997 to 2015 and six-hour resolution, is shown in Figure 14. The number of people

[13]https://www.carnegiece.com/technology/ [Accessed: 2020-08-17]

that could fulfill a freshwater need from wave powered desalination systems was estimated (see full description in Paper II), as shown in Figure 15.

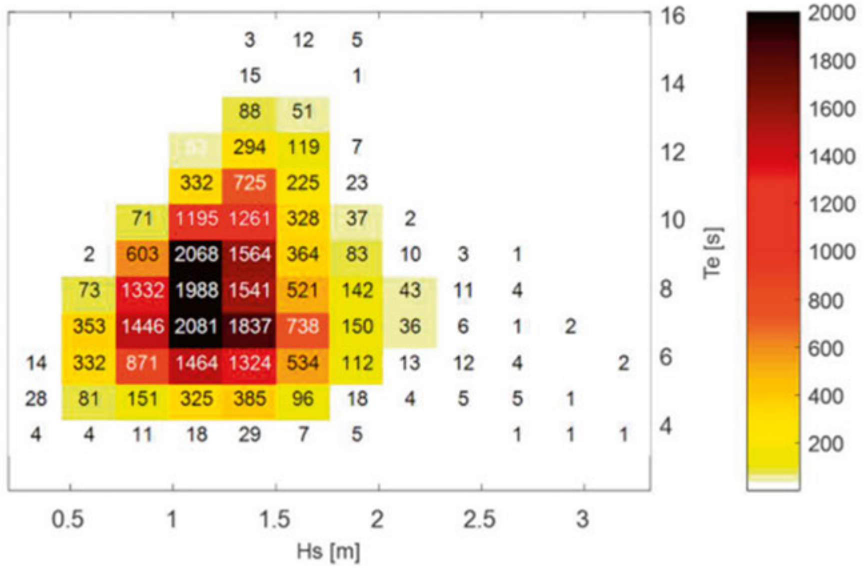

Figure 14. Occurrence of different seastates in Kilifi, Kenya (six-hour resolution), with data from 1997 to 2015, as described in Paper II.

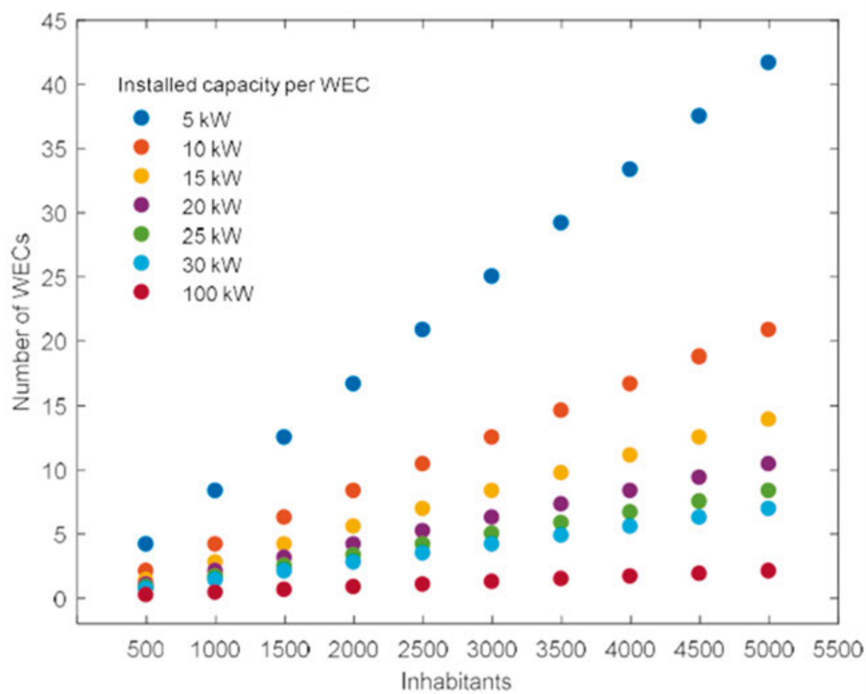

Figure 15. Number of WECs necessary, depending on their rated power values, to provide freshwater for different number of inhabitants, see Paper II.

3.4. Experiments on desalination system

Results from experiments on a small-scale desalination system, along with data on the wave resource during 2015 in Kilifi, Kenya, are presented in Paper III. Up to three WECs were estimated for powering of the desalination system. A hybrid system, including both WEC and solar PV system, was also proposed. Utilizing the system with different currents and a voltage of 12 V, experiments showed freshwater production for the different power levels, as shown in Figure 16. The estimated water output [liter/min] from one WEC in Kilifi during 2015 is shown in Figure 17.

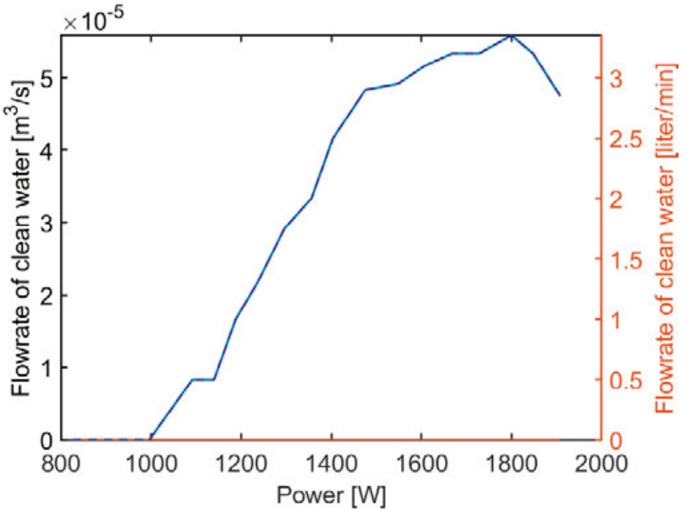

Figure 16. Rate of clean water out from the desalination system for different power levels [W], from small-scale experiments, see Paper III.

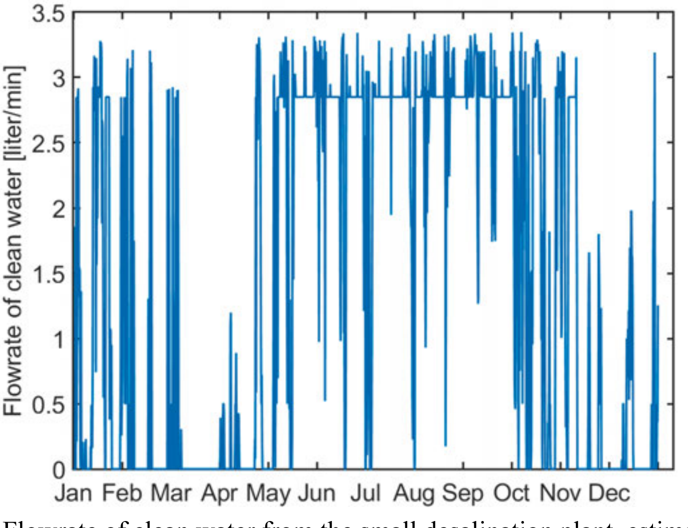

Figure 17. Flowrate of clean water from the small desalination plant, estimated for Kilifi, Kenya, during 2015, and one WEC, see Paper III.

4. Pedagogical development of electrical engineering courses

New demands have been put on the engineers in recent years, with increased focus on for example sustainability, including aspects of economy, society and environment. Also, there are other sets of skills, other than technical skills, beneficial for engineers (teamwork, communication, discussion, ethical aspects etc.) [100]. University pedagogical programs, as the one on Uppsala University, suggests that many different skillsets should be developed in the education [101]. After their studies, engineering students should be well prepared for realistic work-related situations as future engineers in industry. In the work presented in Paper VI, development of soft- or generic skills among engineering students have been discussed, in contrast to technical knowledge, or hard skills.

In the course Rotating Electrical Machines (REM) for electro engineering students at Uppsala University, with course code: 1TE670[14], several changes were implemented to better align the learning activities to the pedagogical program at the university, as described in Paper V. Also, the aim was to better prepare the students for working as engineers in the future. The inspiration was student-centered learning (SCL) and problem-based learning (PBL) [102]. One goal was to support the students in their own learning and to enhance discussions among the students. This, in contrast to a teacher who is in focus and calculates all exercises alone on the blackboard. A new type of lab was implemented, aiming to increase the students understanding of real machines in industry and questions involved when constructing these. The lab setup from Paper V is shown in Figure 18. The other teacher created online lectures which could be seen outside the classroom. The Swedish literature (compendium) was updated and improved together with a previous PhD student. Midterm evaluations, final evaluations, midterm tests and final exams all pointed towards that the implementations were successful. In the final exam in 2017, before the course development, about a quarter of the students were passing. In 2019, after the course development, about two-thirds of the students were passing the final exam, as presented in Paper V.

[14]https://www.uu.se/en/admissions/freestanding-courses/course-syllabus/?kKod=1TE670 [Accessed: 2020-08-27]

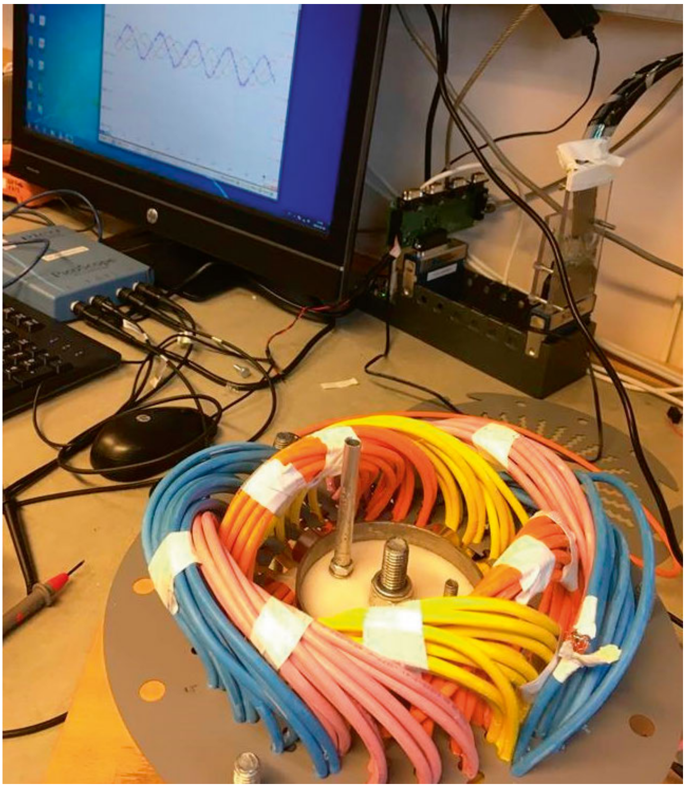

Figure 18. Student solution to the new lab implemented in the course Rotating Electrical Machines.

5. Discussion

An initial objective of this work was to investigate wave power for freshwater production. The literature, analyzed in Paper I, describes that wave power can be utilized for desalination systems and generate freshwater. The work indicates that there could be opportunities to continue investigating these areas, with for example more experimental work in wave power or marine current power for RO desalination. A photo from the experimental setup in Paper III and the author is shown in Figure 19. One of the issues with wave power is that it is still in an early stage of commercialization. Also, it seems challenging to design and construct WECs adapted to the harsh marine environment. When controlling the WECs, maximizing power output may not always be the main goal. Other values, such as keeping the WEC from structural damage or smoothen out power peaks for a stable power level, could be considered more important. Modeling and control of WECs are discussed in Paper IX and X.

Several studies indicate that there are two main challenges highlighted with sustainable solutions for desalination: the high energy demand and the need for brine management. If powering desalination with RES, the variability of the resource may cause damage to the desalination system. Also, this could result in an unreliable water production. Due to for example these issues, desalination processes are today often powered by fossil fuels. RO systems in combination with wave power could be particularly interesting for coastal regions, such as islands.

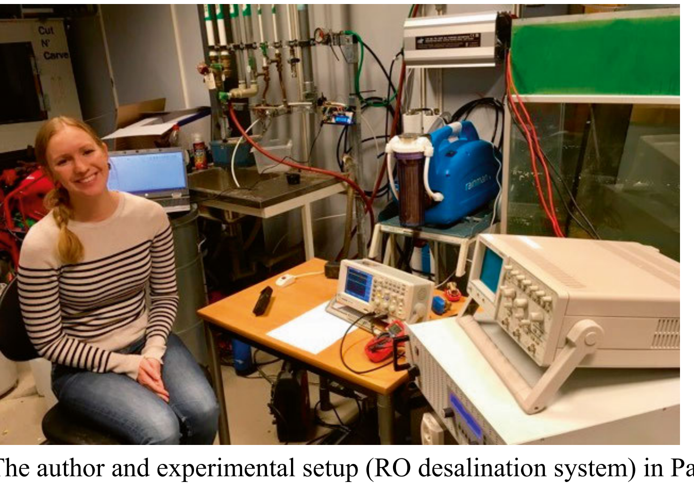

Figure 19. The author and experimental setup (RO desalination system) in Paper III.

The cost and feasibility of wave powered desalination systems greatly varies with for example locations, electricity price, other available options for water sources and transportation. When it comes to water- or energy storage, it is easier and cheaper to store water than to store electricity. There is more research done in solar or wind powered desalination than in research on any type of marine RES for desalination. In the review paper, Paper I, it is suggested that a few areas could be beneficial to study simultaneously for designing WEC/DES projects for water production: location, wave power system, desalination system, environment, cost, and overall project. In Paper II, III and XI, it is suggested that Kilifi, Kenya, could be suitable for wave powered desalination. In Paper IV, it is proposed that marine current energy converters could be interesting for desalination, in this study for South Africa. It is noted that, to the best of the author's knowledge, no desalination systems have been powered by marine current- or tidal energy converters in experiments. These results further support the idea that desalination could be powered by marine RES, and that there are several future research questions in the area.

The Papers VII (a) and (b) concerns simulations of the magnetic circuit of the linear generator. As the Y30 ferrites are estimated as cheaper than Y40, there is an opportunity to lower the system costs by altering the magnets. However, there are still uncertainties related to for example the costs and possibility to include more complicated shapes of the poleshoes. The estimations are also presented from simulations, and with no experimental work. However, this study suggests that there is an opportunity to further investigate the flexibility of the LG magnetic circuit, which could improve system sustainability (lower costs and transportations, more available manufacturers etc.). The additional complexity added to the magnetic circuit may not be beneficial for the system, as more different parts could be broken, and the manufacturing could be more costly. As such, a simple magnetic circuit could be beneficial and there is a tradeoff between cost benefits and a more complicated system. According to the contacted retailers, the price of the ferrite magnets depends on for example the grading, geometry and purchased quantity. If a full-size magnet (for the current LG design) was purchased, the magnet of grading Y40 was suggested to be six times more expensive than the same type of magnet with grading Y30. The reason to why seems to be that the manufacturing process is more complicated for the stronger and larger ferrites and that there are fewer retailers with the necessary equipment to produce these. With this study, it was shown that it could be possible to include lower graded ferrites, changing the magnets of the LG partly from Y40 to Y30. The resulting lower magnetic flux was compensated for with a different design of the poleshoes (changing the design from rectangular to a slightly shorted T-shape), directing the flux better from the translator to the stator. Enabling for a variation in the magnetic circuit could open up for cheaper LGs, a greater variety of retailers to choose from, choosing ethical working conditions and shorter transportation distances, also it was suggested that the manufacturing of the lower graded magnets of a certain size may be done in-house.

Magnetic material for generators and motors, or lithium for batteries in electric vehicles are examples of materials that could be interesting to secure locally in the future, to ensure availability for industry etc. Researchers discuss the opportunity to find lithium locally in the salty brine from desalination. The brine is a resource, or residue, from the desalination process which is mostly just poured directly back into the ocean, with possible effects on the marine environment. The opportunity of better resource management of the brine could be interesting for future research. This is the topic of the Papers VIII (a) and (b), noting that more research and development would be necessary for full-scale lithium extraction from desalination brine.

The studies are limited for several reasons, as highlighted more in the different papers. Some limitations are rough estimations in calculations, limitations due to the accuracy of the measuring devices or simulations tools, and uncertainties of how well parts of the systems could function in reality.

6. Conclusions

It is concluded that WECs can be used to power desalination systems, as this has been done in previous research projects. It is concluded that a few different types of wave power and desalination systems have been constructed over the years, proving that such systems can function and generate drinking water. This work indicates that there are more opportunities to utilize RO desalination systems in combination with wave power, marine current power or hybrid systems including both solar- and wave power for desalination. It suggests that the UU-WEC could be used for desalination. The brine produced from desalination could include valuable minerals, such as lithium, which could be economically feasible to extract. The experiments on a small-scale RO desalination system show that other power levels than the rated one can be used to produce freshwater, which suggests that the intermittent resources could be utilized. Desalination could potentially be used with ocean wave power in Western Indian Ocean by Kilifi, Kenya.

Simulations show that the magnetic circuit of the wave power linear generator can be changed from only one type of ferrites, Y40, to also include ferrites of lower grade, Y30. This, while the poleshoes are changed from a rectangular shape to a T-shape.

It was concluded that some control strategies accelerating the translator a lot during a small time period may be costly, as the resulting high translator velocity might be above the limit of what the WEC can withstand mechanically and electrically. It suggests that these control strategies may demand an over-dimensioned WEC system etc., which could be costly.

It is concluded that after many improvements were done to the course Rotating Electrical Machines, such as including an individual lab, the new students performed better on their final exam than previous students.

7. Future work

Some suggestions on directions for further research are:

- Expand the experimental work on wave powered or marine current powered desalination.
- Further develop WEC and MCC simulation models for desalination purposes.
- Design a generator for generation of both electricity and pressure (for the RO process).
- Investigate water- or energy storage for wave powered desalination.
- Propose hybrid systems for desalination, including marine RES and solar or wind power.
- Investigate disaster resilience including desalination powered by RES, with regards to the water-energy-food nexus and societal security.
- Analyze the desalination brine for lithium extraction.
- Provide analysis on water and energy related questions, such as desalination, in for example Sweden and the Nordic countries.
- Examine electric machines with different magnetic materials further. Include more experimental work on different ferrites in electric machines.
- Investigate how implementation of new pedagogical strategies, based on relevant research and pedagogical programs at universities, is supported or discouraged in engineering education.
- Continue an ongoing pedagogical project on developing a desalination lab which incorporates aspects of hard and soft skills, as well as ethical considerations, and analyze its outcomes.
- Find opportunities for innovation, development, and collaboration in water-energy systems.

Summary of papers

All papers are built upon collaboration between the authors, but the specific contribution from this thesis author has been highlighted.

Paper I

Freshwater production from the motion of ocean waves - A review.
This review paper on wave powered desalination describes different wave energy and desalination technologies. It summarizes previous designs on wave powered desalination systems and how far the projects have proceeded according to the reviewed literature. The author did most of the work and writing of the paper.

Published 2018 in *Desalination*, 435.

Paper II

Wave Power as Solution for Off-Grid Water Desalination Systems: Resource Characterization for Kilifi-Kenya.
This paper describes an analysis of the wave climate outside the Kenyan coast, by Kilifi. It discusses the variation of the waves at this site, especially with respect to wave powered desalination. The author contributed in writing of the paper, mainly regarding wave powered desalination.

Published 2017 in *Energies*, 11.4.

Paper III

Variable renewable energy sources for powering reverse osmosis desalination, with a case study of wave powered desalination for Kilifi, Kenya.
Wave powered desalination is studied with experiments on a small-scale desalination system for different power levels. Resource data from Kilifi, Kenya, together with estimations on power production from a wave energy converter are combined with results from the experiments to estimate freshwater production at the site. Hybrid systems are also discussed. The author collaborated on the experiments, did most of the calculations and wrote most of the paper.

Published 2020 in *Desalination*, 494, 114669.

Paper IV

Marine Current Energy Converters to Power a Reverse Osmosis Desalination Plant.

This paper discusses the opportunity to utilize several marine current energy converters for reverse osmosis desalination outside the South African coast. Water storage was also discussed. The author wrote most of the paper, and calculations and analysis were done in collaboration.

Published in 2018 in *Energies*, 11, 2880.

Paper V

Student-centered learning in an engineering course with project-integrated laboratory experiment

Pedagogic development of the electro engineering course Rotating Electrical Machines at Uppsala University is described here. Especially, a new laboratory assignment is presented along with the outcome of the development. The author was one of the teachers in the course and wrote most of the paper.

Published in 2020 in *Högre Utbildning*, 10, 1.

Paper VI

Lärarens arbete mot utveckling av generiska färdigheter och variation i teknikvetenskaplig utbildning genom relationsskapande åtgärder.

This text is in Swedish and discusses the opportunity to include more soft or generic values in engineering education, as a contrast to the hard or technical values which are often already well established within the education. The author did most of the work with the paper.

Published in 2019 in *Högre Utbildning*, 9, 1.

Paper VII (a)

Linear Generator with Different Types of Ferrite Permanent Magnets for Wave Energy Conversion.

This conference paper includes simulation work on the linear generator in a finite element method (FEM) tool to study different ferrites and poleshoes within the system. The author did most of the work with the paper.

Reviewed conference paper, presented in Cork, Ireland, with a poster 2017 at *The European Wave and Tidal Energy Conference 2017.*

Paper VII (b)

Study of an Altered Magnetic Circuit of a Permanent Magnet Linear Generator for Wave Power.

This paper is built upon the conference paper: Paper VII (a). The conference paper was expanded to a journal paper after the conference, due to encouragement. It discusses the magnetic circuit of the linear generator and proposes changes in the magnetic circuit, from stronger ferrites to weaker, in combination with different shapes of the poleshoes. The author did most of the work with the paper and contacted retailers.

Published in 2018 in *Energies*, 11(1), 84.

Paper VIII (a)

Marine Renewable Energy Sources for Desalination, Generating Freshwater and Lithium.

This conference paper includes an investigation on the opportunity to extract lithium from the desalination brine, if the desalination plant is powered by marine renewable energy sources. The author wrote most of the paper and presented it orally at the conference.

Reviewed conference paper, presented orally in 2019 at *The International Society of Offshore and Polar Engineers (ISOPE) Conference*, Honolulu, USA.

Paper VIII (b)

Freshwater and Lithium from Desalination Powered by Marine Energy Sources.

This paper is built upon the conference paper: Paper VIII (a). The conference paper was restructured for the journal IJOPE. The papers include investigations on lithium extraction from the desalination brine, if the system is powered by marine renewable energy sources. The author wrote most of the paper.

Published in 2020 in *The International Journal of Offshore and Polar Engineering (IJOPE)*, 30, 3.

Paper IX

Comparison of Damping Controls for a Wave Energy Converter with a Linear Generator Power Take-Off: a Case Study for the Lysekil and Wave Hub Test Sites.

This conference paper describes simulations of wave energy converters and different control strategies. It was orally presented by the author, including answering of questions from the audience. The author did most of the simulations and writing of the paper.

Reviewed conference paper. Presented orally 2016 in Singapore by the author at *The Asian Wave and Tidal Energy Conference (AWTEC)*.

Paper X

Economic aspects of latching control for a wave energy converter with a direct drive linear generator power take-off.

In this paper, control strategies of the WEC are discussed with investigations of latching and constant damping control, analyzed in terms of its potential cost. The author helped out mainly with model development and discussions.

Published in 2018 in *Renewable Energy*, 128.

Paper XI

Investigation of wave powered desalination for sustainable freshwater production.

This conference paper presents an initial rough estimation on wave powered desalination, including the Uppsala University WECs and an RO desalination process. Three regular waves acting on one specific WEC design, for a park of five WECs, were used in a Matlab and WAMIT-model, presenting a very rough estimation of the daily freshwater production. The author did most of the work related to the paper. Previously published as part of The International Desalination Association (IDA) World Congress Proceedings, São Paulo, Brazil, 2017.

Conference paper (this was not orally presented, due to illness), 2017, to *The International Desalination Association World Congress.*

Paper XII

MnAl and other novel permanent magnets in electrical machines - a review and simulation study.

This paper discusses new magnetic materials for the potential use in electrical machines. The author mainly contributed with text to the introduction and to the manuscript reviewing.

Manuscript submitted in 2020 to *Energies.* Status: Major Revision.

Paper XIII

Power Hardware in the Loop Real Time Modelling Using Hydrodynamic Model of a Wave Energy Converter With Linear Generator Power Take Off.

The author contributed mainly during the experiments in Cork, Ireland.

Reviewed conference paper. Presented orally by Tatiana Potapeno at the *29th International Ocean and Polar Engineering Conference (ISOPE*), USA, 2019.

Paper XIV

Power Hardware-in-the-loop simulations of Grid-Integration of a Wave Power Park.

The author contributed mainly during the experiments in Cork, Ireland, and with the draft of the introductory part of the paper.

Reviewed conference paper. Presented orally by Irina Temiz *13th European Wave and Tidal Energy Conference (EWTEC)* in Italy, 2019.

Paper XV

Power control strategies for a smoother power output from a wave power plant.

The author did only a very small contribution to this paper, mainly in reviewing the manuscript.

Reviewed conference paper. Presented orally by Sara Anttila at the *The European Wave and Tidal Energy Conference (EWTEC)*, in Italy, 2019.

Paper XVI

Experimental Test of Grid Connected VSC to Improve the Power Quality in a Wave Power System.,

The author did a very small contribution to this conference paper, mainly reviewing the manuscript.

Conference paper. Presented orally 2018 by Arvind Parwal at *The 5th International Conference on Electric Power and Energy Conversion Systems. (EPECS 2018)*.

Paper XVII

Grid Integration and a Power Quality Assessment of a Wave Energy Park.

The author did a very small contribution to this paper, mainly reviewing the manuscript.

Published in 2019 in *IET Smart Grid,* 2, 4.

Svensk sammanfattning

Miljontals människor saknar tillgång till rent dricksvatten. Dessutom saknar många människor tillgång till elektricitet. Den så kallade vatten-energi-mat nexusen indikerar att dessa resurser är sammanlänkande, och brist av den ena kan skapa brist av den andra. I kristider kan vatten- eller elbehov bli akut. Under den pågående corona-pandemin ser vi exempelvis ett stort behov av vatten för att hålla god handhygien och el för att driva medicinsk utrustning, såsom respiratorer. Mer än 70 % av jordens yta består av vatten och 40 % av alla människor bor inom 100 km från kusten. Därför kan det vara intressant att undersöka möjligheten att avsalta havsvatten för att säkerställa ett dricksvattenbehov. Många avsaltningsanläggningar globalt drivs av fossila bränslen, men nu undersöker man mer förnybara energikällor för att driva avsaltning, främst sol och vind. Den mest vanligt förekommande avsaltningstekniken är omvänd osmos, där det salta vattnet trycksätts och rent vatten förs igenom semipermeabla membran. Vågkraftsdriven avsaltning är förslag på ett system för att skapa rent dricksvatten med hjälp av en förnyelsebar energikälla. Det finns flera fördelar med ett sådant system: saltvattnet som ska avsaltas finns på samma plats som havsvågorna, många människor bor längs kusterna, de förnybara systemen kan ersätta fossila bränslen osv. Samtidigt finns det många utmaningar med vågkraftsdriven avsaltning som måste mötas för att systemet ska fungera och vara hållbart: vågkraften är variabel och avsaltningssystemet drivs bäst av konstant effekt, vågkraften är inte kommersialiserad fullt ännu, miljöaspekter måste tas hänsyn till och det salta avfallet bör tas omhand. Kanske finns det värdefulla mineraler såsom litium i det salta avfallet. Här i Sverige har vi oftast god tillgång till rent vatten. Fast även här har vi installerat några avsaltningsanläggningar för att tillgodose vårt vattenbehov under varma somrar med mycket turism. Ett exempel är avsaltningssystemen på Gotland.

Denna avhandling bygger på ett antal artiklar som undersöker olika aspekter av främst vågkraft och avsaltning. Vågkraftsdrivna avsaltningssystem kan drivas direkt, om vågkraftssystemet trycksätter det salta vattnet som sedan förs till ett omvänd osmos-avsaltningssystem, eller indirekt, om vågkraftssystemet först genererar el som sedan används för drift av en avsaltningsprocess. Systemen kan vara ute till havs eller inne vid land. Det finns några olika projekt som tidigare har undersökt vågkraft för att driva avsaltningssystem. Vissa projekt har dessutom lyckats implementera systemen och skapat dricksvatten, såsom Delbuoy och CETO Freshwater. Därtill finns många projekt inom vågkraftsdrivna avsaltningsanläggningar som ännu inte är fullskaliga, utan endast i forskningsstadium. En slutsats från en av forskningsartiklarna är att vid undersökningens tid så fanns inte särskilt många pågående projekt med forskning och utveckling av vågkraftsdriven avsaltning. Dock kan man säga att intresset för vågkraftsdriven avsaltning har ökats sedan denna studie, särskilt genom en tävling inom forskningsområdet utlyst av U.S. Department of Energy. Forskningen indikerar även att det kan finns möjligheter att kombinera sol- och vågkraft för att driva en avsaltningsanläggning, istället för bara använda en av energikällorna.

Det första vågkraftspatentet fanns redan 1799 och idag finns fler än tusen patent inom vågkraft, men vågkraft är fortfarande i en tidig fas vad gäller kommersialisering. Vågkraftssystemet som studeras i denna avhandling, kallat UU-WEC, är utvecklat vid Uppsala universitet och består av en flytande boj kopplad via en lina ner till en linjärgenerator. Linjärgeneratorn består av en stationär del, statorn, och en rörlig del med magneter, translatorn. Olika typer av magnetiska material kan användas i translatorn. En studie med simulering av blandade magneter i linjärgeneratorn har genomförts, med två olika typer av ferritmagneter. Vågkraftssystemet kan kontrolleras för att exempelvis påverka uteffekten från systemet eller kanske för att minska skador på vågkraftverket. I tidigare studier har detta vågkraftssystem använts inom experiment vid Lysekil.

Detta avhandlingsarbete är delvis kopplat till Kenya och särskilt kustregionen Kilifi vid västra Indiska oceanen, där man undersöker möjligheten att använda vågkraft och avsaltning för att generera mer färskvatten för jordbruk och hushåll. Inom projektet köptes vågresursdata in för området kring Kilifi. En av studierna inom denna avhandling innehåller experiment med ett litet avsaltningssystem baserat på omvänd osmos. Undersökningen handlade om att ta reda på hur systemet fungerar om det inte drivs med den effekt som föreslås av tillverkaren. Detta eftersom förnybara energikällor, såsom vågkraft, kan variera mycket i uteffekt. Det visade sig att detta avsaltningssystem kan generera vatten även för andra effekter än den föreslagna. Vi använde vågresursdata från Kilifi i Kenya och uppskattade uteffekten från ett till tre vågkraftverk där. Sedan kunde experimenten ligga till grund för en uppskattning av hur mycket dricksvatten ett vågkraftsdrivet avsaltningssystem skulle kunna generera i Kilifi.

Två studier om pedagogisk utveckling inom ingenjörsvetenskaper finns också inkluderade i denna avhandling. Den ena studien diskuterar möjligheten att inkludera mer utveckling av så kallade mjuka eller generiska värden inom utbildningen av ingenjörer, i kontrast till övning av de mer hårda, tekniska värdena som ofta redan finns väletablerat i ingenjörsundervisningen. Detta kan vara intressant då många industriföretag arbetar mer än tidigare mot hållbarhet i systemen, samarbete, diskussion, kreativitet i lösningar osv. Den andra studien inom pedagogik presenterar ett utvecklingsprojekt av kursen

Roterade elektriska maskiner, där särskilt en ny laboration inkluderas. Helheten av utvecklingsarbetet med mer studentaktiverande moment studeras. Slutsatsen av detta arbete är att studenternas ökande egna aktivitet inom kursen kan vara en av anledningarna till att många fler studenter blev godkända vid sluttentamen efter utvecklingsarbetet än före.

Sammantaget indikerar denna avhandling att det finns många möjligheter till vidare forskning inom exempelvis kopplade frågor kring förnybar elgenerering och säker tillgång till vatten.

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Slutligen vill jag rikta ett varmt tack till min älskade familj! Jag vill tacka min mamma, min pappa (avdelningschef), Boel, Olof, Olofs familj, mina syskon, mina kusiner och min släkt. Tack för att ni finns!

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