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Offshore deployments of marine energy converters

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Abstract

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The depletion warning of non-renewable resources, such as gas, coal and oil, and the imminent effects of climate change turned the attention to clean and fossil fuel-free generated electricity. University research groups worldwide are studying solar, wind, geothermal, biomass and ocean energy harvesting. The focus of this thesis is the wave and marine current energy researched at the division of Electricity at Uppsala University (UU).

The main drawbacks that hinder the commercialization of marine energy converter devices is a high installation, operation, maintenance and decommissioning cost. Furthermore, these processes are highly weather dependent and thus, can be time consuming beyond planning. In this thesis, an evaluation of the cost, time and safety efficiency of the devices' offshore deployment (both wave and marine current), and a comparative evaluation regarding the safety in the use of divers and remotely operated vehicles (ROVs) are conducted. Moreover, a risk analysis study for a common deployment barge while installing an UU wave energy converter (WEC) is presented with the aim to investigate the failure of the crane hoisting system.

The UU wave energy project have been initiated in 2001, and since then 14 WECs of various designs have been developed and deployed offshore, at the Lysekil research site (LRS), on the Swedish west coast and in Åland, Finland. The UU device is a point absorber with a linear generator power take off. It is secured on the seabed by a concrete gravity foundation. The absorbed wave energy is transmitted to shore through the marine substation (MS) where all the generators are interconnected. In 2008 an UU spin-off company, Seabased AB (SAB), was established and so far has developed and installed several WECs and two MSs, after the UU devices main principle. SAB deployments were conducted in Sotenäs, Sweden, at the Maren test site (MTS) in Norway; and in Ada Foah, Ghana. The active participation and the thorough study of the above deployments led to a cost, time and safety evaluation of the methods followed. Four main methods were identified and the most suitable one can be chosen depending on the deployment type, for example, for single or mass device deployment.

The first UU full scale marine current energy converter (MCEC) was constructed in 2007 at the Ångström Laboratory and deployed at Söderfors, in the river Dalälven in March 2013. The UU turbine is of a vertical axis type and is connected to a directly driven permanent magnet synchronous generator of a low-speed. With this deployment as an example, four MCEC installation methods were proposed and evaluated in terms of cost and time efficiency.

A comparative study on the use of divers and ROVs for the deployment and maintenance of WECs at the LRS has been carried out, showing the potential time and costs saved when using ROVs instead of divers in underwater operations. The main restrictions when using divers and ROVs were presented. Most importantly, the modelling introduced is generalized for most types of wave energy technologies, since it does not depend on the structure size or type.

Finally, a table of safe launch operation of a WEC is presented. In this table the safe, restrictive and prohibitive sea states are found for a single WEC deployment, using a barge and a crane placed on it. The table can be utilized as a guidance for offshore operations safety and can be extended for a variety of device types and vessels.

Keywords: offshore deployments, risk assessment, wave energy converter installation, marine current energy converter installation, economic efficiency, time efficiency, offshore operations, point absorber, hydrodynamic analysis, slack sling criterion, hoisting system failure.

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To my family

List of Papers

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

I **Chatzigiannakou, M.A.**, Dolguntseva, I., Leijon, M. (2017) Offshore deployments of Wave Energy Converters by Seabased Industry AB. *Journal of Marine Sciences and Engineering*, 5(2), 15; doi:10.3390/jmse5020015.

II **Chatzigiannakou, M.A.**, Ulvgård, L., Temiz, I., Leijon, M. (2018) Offshore deployments of Wave Energy Converters by Uppsala University, Sweden. Submitted to the *Journal of Marine Systems and Ocean Technology*.

III **Chatzigiannakou, M.A.**, and Temiz, I. (2019) Marine Current Energy Converters deployments modelling. Submitted to the *Journal of Cleaner Production*.

IV Rémouit, F., **Chatzigiannakou, M.A.**, Bender, A., Temiz, I., Sundberg, J., and Engström, J. (2018) Deployment and Maintenance of Wave Energy Converters at the Lysekil Research Site: A Comparative Study on the Use of Divers and Remotely-Operated Vehicles. *Journal of Marine Sciences and Engineering*, 6(2), 39; https://doi.org/10.3390/jmse6020039.

V **Chatzigiannakou, M.A.**, Potapenko T., Ekergård, B., and Temiz, I. (2019) Risk assessment of deployment of an Uppsala University wave energy converter from a barge in different sea states. Submitted to *Reliability Engineering & System Safety journal*.

VI **Chatzigiannnakou, M.A.**, Dolguntseva, I., Leijon, M. (2014) Offshore deployment of point absorbing Wave Energy Converters with a direct driven linear generator power take-off at the Lysekil test site. *The 33rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE, San Francisco, California*.

VII **Chatzigiannnakou, M.A.**, Dolguntseva, I., Leijon, M. (2015) Offshore Deployment of Marine Substation in the Lysekil Research Site. *The 25th International Ocean and Polar Engineering Conference, ISOPE, Hawaii, USA*.

VIII Parwal, A., Remouit, F., Hong, Y., Francisco, F., Castellucci, V., Hai, L., Ulvgård, L., Li, W., Lejerskog, E., Baudoin, A., Nasir, M., **Chatzigiannakou, M.**, Haikonen, K., Ekström, R., Boström, C., Göteman, M., Waters, R., Svensson , O., Sundberg, J., Rahm, M., Engström, J., Savin, A., and Leijon, M. (2015) Wave Energy Research at Uppsala University and the Lysekil Research Site, Sweden: A Status Update. *The 11th European Wave and Tidal Energy Conference, EWTEC, Nantes, France*.

IX(a) Parwal, A., Fregelius, M., Leijon, J., **Chatzigiannakou, M.**, Svensson, O., Temiz, I., Boström, C., G. de Oliveira, J., Leijon, M. (2017) 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; DOI: 10.1109/EPECS.2018.8443488*.

IX(b) Parwal, A., Fregelius, M., Leijon, J., **Chatzigiannakou, M.**, Svensson, O., Strömstedt, E., Temiz, I., Goncalves de Oliveira, J., Boström, C., Leijon, M. (2018) Grid Integration and a Power Quality Assessment of a Wave Energy Park. Under review at *IET Smart Grids*.

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Contents

Abbreviations

Abbreviation	Description
ADCP	Acoustic Doppler Current Profilers
DP	Dynamic Positioning
LRS	Lysekil Research Site
MCEC	Marine Current Energy Converter
MS	Marine Substation
MTS	Maren Test Site
MPOV	Multi-purpose Offshore Vessel
MV	Motor Vessel
MW	Marine Works
RAO	Response Amplitude Operator
ROV	Remotely Operated Vehicle
RRSV	Robotic Riverbed Survey Vessel
SAB	Seabased AB
SIAB	Seabased Industry AB
UU	Uppsala University
WEC	Wave Energy Converter
WESA	Wave Energy for a Sustainable Archipelago

1. Introduction

1.1 Renewable energy

The continuously rising worldwide demand for energy is met by 80% from fossil fuels, resulting in climate change [1]. The adverse consequences of the global climate change [2], [3] and the finite nature of the pollutant fossil fuels are increasing the need for inexhaustible and clean energy. According to BP statistical review of world energy [4], the predicted years left of the three fossil fuels, as of 2016, are: 50.7 years of coal use, 52.8 of natural gas and 114 years of coal exploitation. Renewable energies such as geothermal, hydropower, modern biomass, solar, tidal, wave, onshore and offshore wind [5], [6] have minimal environmental impact compared to fossil fuels. The focus of this thesis is marine energy.

Although about 70% of the earth surface consists of water, the boundless energy it contains is largely unexploited. Moreover, the water density is about 800 times higher than air, meaning that for the same given speed, the higher the density [7], the larger the generated power. To this day, wave energy converters (WECs) [8]–[14] and marine current energy converters (MCECs) [14]–[17] have been developed and tested globally to take advantage of the kinetic energy found in the water waves and currents, respectively.

The high installation, operation, maintenance and decommissioning costs [14], [18]–[21] are hindering these technologies from going beyond the experimental phase [22]–[26]. Strategies to lower the installation costs include, precise planning and careful choice of an offshore deployment method [27], [28] and use of ROVs to automate specific tasks [29].

Extracting energy from marine energy sources is challenging because of high forces involved, while the WECs operation in energetic waters brings additional obstacles to the installation procedure. Offshore deployments are associated with high dependency on operational weather windows, and risks. Safety issues that come up during offshore installation of marine energy devices can be mitigated by conducting a safety evaluation of the permitted operational sea states for the hired vessel.

1.2 Marine energy technologies

1.2.1 Wave energy technologies

Over 1000 wave energy conversion technologies have been patented globally [14]. They are categorized depending on their location, type and wave energy utilization mode of operation [8], [9]. The classification according to their location is shoreline, nearshore or offshore converters. The device type is listed as attenuator, point absorber, or terminator [30]. Regarding the wave energy utilization mode of operation the converters are classified as oscillating water columns, oscillating body systems, and overtopping devices.

1.2.2 UU wave energy converter and marine substation concepts

The UU WECs (*Figure 1* (a)) have been developed and manufactured since 2002. The first full scale device was deployed in 2006 at the Lysekil research site (LRS). This device is an offshore point absorber, operating in heave with a direct driven linear generator power take off (PTO). A watertight pressurized hull encloses the generator that is comprised by the stator and the translator. The translator consists of permanent ferrite or neodymium magnets, while the stator is comprised of windings. The buoy is directly connected via a steel wire to the translator. As the buoy moves with the wave motion the generator transforms this kinetic energy into electricity. This device is intended to operate in depths of 20 to 100 meters where is kept on the seabed by a concrete gravity foundation. During the WEC submersion into the water, is being pressurized with 0.1 bar of nitrogen gas for every meter of submersion, to prevent it from oxidizing and achieve even pressure inside and outside of the device [27], [29], [31]. The UU WEC has a robust and simple construction containing minimum moving parts, so it has a simple mechanical system and can withstand the harsh underwater environment [32], [33]. This device is also scalable.

A single WEC delivers limited power, thus a cluster of devices is needed to increase the power production and provide a required installed capacity [34]. This cluster is interconnected to a marine substation (MS) (*Figure 1* (b)) that gathers the generated electricity before it is transmitted to shore [35]. Besides that, the MS maximizes the electrical efficiency of the devices and the system (WECs and MS) reliability, reduces the sea cable expenses, improves the transmission efficiency of the WECs and assists their individual control. Lastly, it rectifies currents of each WEC and subsequently converts it to AC currents suitable for grid connection [36], [37].

The UU WEC concept has been commercialized by Seabased AB (SAB), a Swedish UU spin-off company.

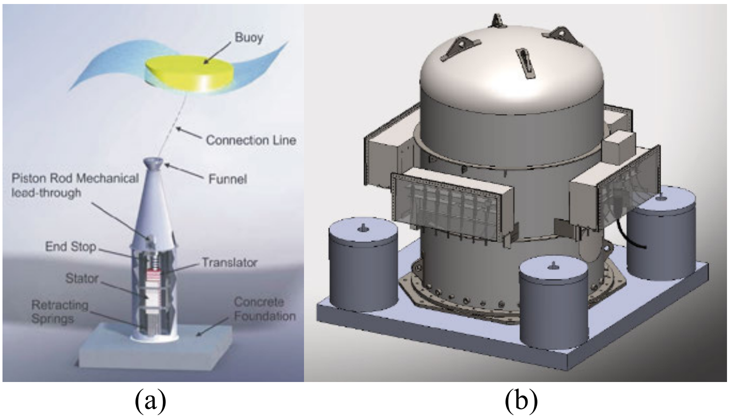
1.2.3 Marine current energy technologies

MCECs are converting the marine current kinetic energy to electricity [38]. The tidal current turbines are classified as: horizontal axis turbines, vertical axis turbines, oscillating hydrofoils, tidal kites and ducted turbines [7], [21], [38], [39] with regards to their interaction with the water. Moreover, they are distinguished between direct drive (with permanent magnet generator) or induction generators [40], and can be either directly grid connected or through fully or partially rated power electronics [41], [42]. The converters are mounted on support structures that are distinguished as: gravity-based foundation, monopole, floating, or tripod constructions [7].

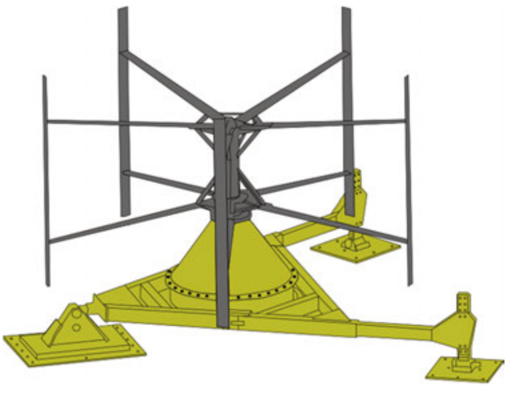
1.2.4 UU marine current energy converter concept

The marine current energy group at UU, taking into consideration the high predictability of tidal energy of 98% [43], the fact that it can be harvested from rivers and shallow waters [44], and the significant output power that can be extracted even in low water velocities, has developed the UU MCEC (*Figure 1* (c) [45]). Similar to WECs, UU MCECs are built in a robust manner to operate underwater during a long time period.

The UU MCEC is an omnidirectional vertical axis current turbine connected to a direct-driven permanent magnet synchronous generator, constructed at the Ångström Laboratory in 2007. This device is designed for low current velocities [46] with 7.5 kW power rating for 1.4 m/s water velocity [47] and lowest operational speed of 1 m/s, resulting in 1.7 kW rated power [48]. Its operational depth is 7 m minimum. The turbine has a 3 m radius, and 5 straight blades each 3.5 m high, and projected cross-sectional area of 2 m^2 [48], [49]. The MCECs is 5 m high, weights 12 tons, and is placed on a steel tripod gravity foundation.



(a) (b)



(c)

Figure 1. The UU WEC (a), MS (b), and MCEC (c)

1.3 Deployment locations

The areas of the deployments and their specifications according to the project are as follows.

a) UU Lysekil project

14 UU WECs and two marine substations have been deployed in the Lysekil research site (LRS) that is located 100 km north of Gothenburg and 2 km from the island Härmanö, at the Swedish west coast (*Figure 2* (b)). The area selection was due to the smooth seabed that consists mostly of sandy silts, and its medium depth of 25 m. [35], [50]

b) WESA (Wave Energy for a Sustainable Archipelago) project

This single-WEC deployment with its buoy and a wave measurement buoy took place on Åland, Finland (*Figure 2* (c)). The project was financed by the EU and was a collaboration between UU, Ålands Teknikkluster r.f. and the University of Turku. [51], [52], [53], [54]

c) SAB wave energy projects

i) Sweden: this project is based in Sotenäs (*Figure 2* (d)), located northwest of Smögen, on the Swedish west coast. The depth at the site is approximately 50 m.

ii) Norway: 2 WECs and a substation were installed at the Maren Test Site (MTS), located 400 meters off the Island of Runde (*Figure 2* (e)). The installation spot is 15 km from the shore, with a depth of about 50 m. This deployment project was a cooperation between Runde Environmental Centre (REC) ltd, Vattenfall AB and the Norwegian electricity producer and distributor Tussa Kraft AS. [55]

iii) Ghana: 6 WECs were deployed by a SAB customer approximately 3 km offshore, in the sea outside the estuary of the Volta River, near Ada Foah, in the Greater Accra Region of Ghana (*Figure 2* (f)). The site's depth is 16m. [56]

d) UU Söderfors project

The UU MCEC was deployed in March 2013 in Söderfors area (*Figure 2* (a)) in Dalälven River, located approximately 78 km from Uppsala. The advantages of the site are the low depth of about 7 m, the absence of vessel traffic in the area, a bridge located over the test site and Vattenfall AB hydro power plant established 800 m upstream of the site. The bridge is facilitating the MCEC's deployment while having a hydro power plant in close proximity gives the possibility to control the water flow during deployment. In the area, the current is almost at all times less than 1.5 m/s and the slowest usual current observed is 0.2 m/s. [46], [49],[50]

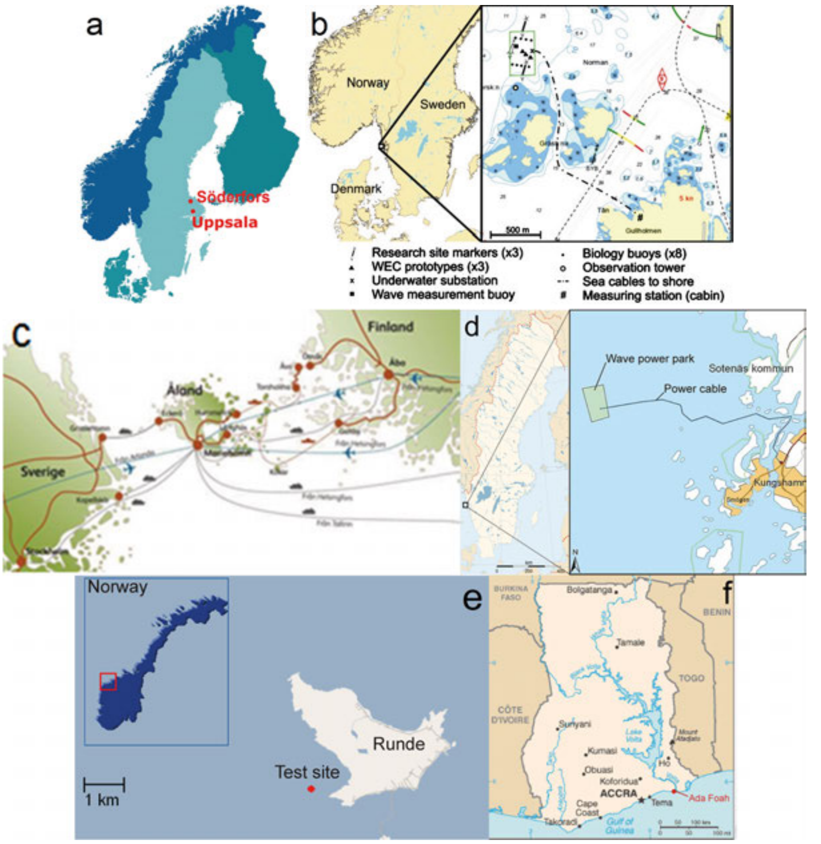


Figure 2. Söderfors deployment area (a), Lysekil research site (b), Åland (c), Sotenäs (d), Maren test site (e), Ada Foah (f)

1.4 Previous research in UU

From 2006 to this day, the following doctoral theses have been produced from the wave energy and marine current groups of Electricity division, UU:

“Wave Energy Conversion, Linear Synchronous Permanent Magnet Generator”, Oskar Danielsson 2006
“Electric Energy Conversion Systems: Wave Energy and Hydropower”, Karin Thorburn 2006
“Modelling and Experimental Verification of Direct Drive Wave Energy Conversion. Buoy-Generator Dynamics”, Mikael Eriksson 2007
“Low Speed Energy Conversion from Marine Currents”, Karin Thomas 2008
“Energy from Ocean Waves. Full Scale Experimental Verification of a Wave Energy Converter”, Rafael Waters 2008
“Wave energy conversion and the marine environment: Colonization patterns and habitat dynamics”, Olivia Langhamer 2009
“Ocean Wave Energy: Underwater Substation System for Wave Energy Converters”, Magnus Rahm 2010
“Electrical systems for wave energy conversion”, Cecilia Boström 2011
“Hydrodynamic Modelling for a Point Absorbing Wave Energy Converter”, Jens Engström 2011
“Buoy and Generator Interaction with Ocean Waves”, Simon Lindroth 2011
“Fluid mechanics of vertical axis turbines – Simulations and model development”, Anders Goude 2012
“Experimental measurement of lateral force in a submerged single heaving buoy wave energy converter”, Andrej Savin 2012
“Submerged Transmission in Wave Energy Converters: Full Scale In-Situ Experimental Measurements”, Erland Strömstedt 2012
“Experimental results from the Lysekil wave power research site”, Olle Svensson 2012
“System perspectives on hydro-kinetic energy conversion”, Katarina Yuen 2012
“Full scale applications of permanent magnet electromagnetic energy converters”, Boel Ekergård 2013
“Hydro-kinetic energy conversion: resource and technology”, Mårten Grabbe 2013
“Hydrokinetic Resource Assessment: Measurements and Models”, Emilia Lalander 2013
“Offshore marine substation for grid-connection of wave power farms - An experimental approach”, Rickard Ekström 2014
“Buoy geometry, size and hydrodynamics for power take off device for point absorber linear wave energy converter”, Halvar Gravråkmo 2014
“Underwater radiated noise from point absorbing wave energy converters: Noise characteristics and possible environmental effects”, Kalle Haikonen 2014
“Grid connected three-level converters: studies for wave energy conversion”, Remya Krishna 2014
“Modelling wave power by equivalent circuit theory”, Ling Hai 2015
“Grid connection of permanent magnet generator based renewable energy systems”, Senad Apelfröjd 2016

“Sea Level Compensation System for Wave Energy Converters”, Valeria Castellucci 2016

“Numerical Modelling and Mechanical Studies on a Point Absorber Type Wave Energy Converter”, Yue Hong 2016

“Theoretical and experimental analysis of operational wave energy converters”, Erik Lejerskog 2016

“Numerical Modelling and Statistical Analysis of Ocean Wave Energy Converters and Wave climates” Wei Li 2016

“Marine Current Energy Conversion”, Staffan Lundin 2016

“Demagnetization and Fault Simulations of Permanent Magnet Generators”, Stefan Sjökvist 2016

“Cooling Strategies for Wave Power Conversion Systems”, Antoine Baudoin 2017

“Resource characterization and variability studies for marine current power”, Nicole Carpman 2017

“Multilevel Power Converters with Smart Control for Wave Energy Conversion”, Deepak Elamalayil Soman 2017

“Automated Production Technologies and Measurement Systems for Ferrite Magnetized Linear Generators”, Tobias Kamf 2017

“Wave Loads and Peak Forces on Moored Wave Energy Devices in Tsunamis and Extreme Waves”, Linnea Sjökvist 2017

“Wave Energy Converters: An experimental approach to onshore testing, deployments and offshore monitoring”, Liselotte Ulvgård 2017

“Modelling and advanced control of fully coupled wave energy converters subject to constraints: the wave-to-wire approach”, LiGuo Wang 2017

“Studies of a Vertical Axis Turbine for Marine Current Energy Conversion: Electrical system and turbine performance”, Johan Forslund 2018

“Robotized Production Methods for Special Electric Machines”, Erik Hultman 2018

“Automation of underwater operations on wave energy converters using remotely operated vehicles”, Flore Rémouit 2018

“Adapting sonar systems for monitoring ocean technologies”, Francisco Francisco 2019

2. Aim of the thesis

The aim of this thesis is to address a topic that has not been researched before at the division of Electricity at UU, the optimization of offshore installations of WECs, MSs and MCECs. It is important to draw attention to this matter and share newly obtained understanding with the scientific community to help maximizing the cost, time and safety efficiency of these operations with the ultimate goal to commercialize offshore technologies.

The following research questions have been addressed in the thesis:

(1) How WEC, MS and MCEC deployments have been performed so far, evaluating them in terms of economical, time and safety efficiency
(2) How different MCEC deployment strategies can be adopted, depending on the operation type, to result in an inexpensive and time-efficient installation
(3) What are the advantages and disadvantages of using divers and/ or ROVs in offshore installation operations from a safety, cost and time perspective
(4) How to quantify the risk of failure in the hoisting system during a WEC deployment from a barge

This thesis is arranged as follows. The theory is presented in Chapter 3, followed by the background in Chapter 4. Chapter 5 is comprised of the research methods, while Chapter 6 presents the results of this study. Chapters 7 and 8 introduce the discussion and conclusions, respectively. The future work suggestions are presented in Chapter 9.

3. Theory

3.1 Kinetic power in marine currents

The kinetic power available in marine currents is represented by the formula:

$$P = \frac{1}{2}\rho A V^3 \tag{1}$$

where ρ is the fluid density, A is the cross-sectional area of the turbine and V is the fluid velocity [57].

3.2 Wave-structure interaction

The linear potential flow theory represents the external flows that surround bodies, where the fluid is assumed to be incompressible, irrotational, and inviscid. The viscous effects occurring in the thin, boundary layer next to the body can be neglected [58].

We define the potential function, φ, as a function of displacement x, y, z and time, t, to represent the fluid velocity field, that must fulfill the equations of conservation of mass and momentum. Taking into account the velocity potential φ, the equations of conservation of mass and momentum given the stated assumptions are reduced to the Laplace equation [59]:

$$\nabla^2\varphi = \frac{d\varphi^2}{dx^2} + \frac{d\varphi^2}{dy^2} + \frac{d\varphi^2}{dz^2} = 0 \tag{2}$$

Expressing the total velocity potential as a superposition of contributions of incident wave and disturbances of floating body presence and motion we derive:

$$\varphi = \varphi_R + \varphi_D + \varphi_I \tag{3}$$

where φ_R is the radiation potential, φ_D is the diffraction potential, and φ_I is the incident wave potential.

The radiation, excitation and hydrostatic restoring forces are the hydrodynamic forces acting on the body. These forces are calculated by integrating the hydrodynamic pressure on the surface of the body, and they depend on the body form and the frequency and amplitude of the incoming waves. Response amplitude operator (RAO) determines the behavior of a floating body in interaction with a fluid in the frequency domain. For six degrees of freedom, RAOs are represented by the equation of motion (4):

$$[-\omega^2 \cdot \left(M + A(\omega)\right) + i\omega \cdot B(\omega) + C] \cdot X(\omega) = F(\omega) \tag{4}$$

where M is the body mass, $A(\omega)$ is the added mass, $B(\omega)$ is the hydrodynamic damping, C is the restoring force coefficient, $X(\omega)$ is the body displacement, and $F(\omega)$ is the excitation force. RAOs are calculated as:

$$RAO(\omega) = \frac{F(\omega)}{-\omega^2 \cdot (M + A(\omega)) + i\omega \cdot B(\omega) + C} \tag{5}$$

The RAO's amplitude defines the motion amplitude per incident wave amplitude, and its phase specifies the phase shift between the body motion and the waves [60].

3.3 Risks of failure in hoisting system

The conditions of failure of the hoisting system during installing a UU WEC from a barge are depending on the limiting lifting capacity of the crane, slings, shackles and crane hook, the crane tip velocity, the steel wire safety load factor, the minimum breaking load, the fulfillment of static strength and the slack sling criterion [61], [62]. The formulas follow.

3.3.1 Steel wire safety

The steel wire safety load factor, S_F, is taken from:

$$S_F = 2.3\psi \tag{6}$$

where ψ is the dynamic load factor for the crane, and the safety factor is taken as:

$$S_F = \frac{10^4}{0.885\,SWL + 1910} \tag{7}$$

where SWL is the safe working load as defined by the manufacturer.

3.3.2 Minimum breaking load

The minimum breaking load, B, of steel wire ropes cannot be less than:

$$B = S_F S \tag{8}$$

where S is the maximum load in the rope resulting from the effect of the working load and loads due to any applicable dead weights.

3.3.3 Static strength

Fulfilling (9) is proof of static strength:

$$F_{Sd,s} \leq F_{Rd,s} \tag{9}$$

where $F_{Sd,s}$ is the design rope force and $F_{Rd,s}$ is the limit design rope force.

The design rope force in vertical hoisting is taken as:

$$F_{Sd,s} = \frac{m_{Hr}g}{n_f}\varphi f_{s1} f_{s2} f_{s3} \gamma_p \gamma_n \tag{10}$$

where m_{Hr} is the mass of the hoist load or that part of the mass of the hoist load that is acting on the rope falls under consideration, g is the gravity constant, n_f is the number of falls carrying m_{Hr}, φ is the dynamic factor for inertial and gravity effects, for example the dynamic load factor for the crane, f_{s1} is the rope reeving efficiency factor, f_{s2} is the rope force increasing factor due to non-parallel falls, f_{s3} is the rope force increasing factor due to horizontal forces on the hoist load, γ_p is the partial safety factor that is taken as 1.34 for regular loads, 1.22 for occasional loads and 1.1 for exceptional loads, γ_n is the risk coefficient. The limit design rope force is taken from:

$$F_{Rd,s} = \frac{F_u}{\gamma_{rb}} \tag{11}$$

where F_u is the minimum breaking force of the rope as specified by the manufacturer, and γ_{rb} is the minimum rope resistance factor, which is dependent on the geometry of the reeving system and is calculated as:

$$\gamma_{rb} = 1.34 + \frac{5}{\left(\frac{D}{d}\right)^{0.8} - 4} \tag{12}$$

where D is the minimum relevant diameter, and d is the rope diameter.

The hoisting line can snap if the capacity of the hoisting system is lower than the load.

3.3.4 Slack sling criterion

The slack sling threshold is defined by

$$F_{hyd} \leq 0.9F_{static} \tag{13}$$

and it should be fulfilled to secure that snap loads are avoided in the hoist line and the slings.

3.3.5 Hydrodynamic and static forces for slack sling criterion

The forces calculations that follow are in accordance to the simplified method for lifting through wave zone [61], [60]. Using this method one can calculate the forces acting on a body, or a multi-body system, in this case the WEC, and decide if the hoisting system capacity is sufficient to carry out the installation successfully. We assume the following: the horizontal extent of the WEC is insignificant compared to the wave length, the WEC and water vertical motion dominates, disregarding any other motions, the WEC vertical motion equals the crane tip vertical motion, the calculations include the zero crossing periods [63], the lowering operation through the wave zone of the WEC takes up to 30 min, i.e. the sea state remains the same during the offshore installation. The forces formulas [61] are as presented below.

The total and static forces are defined by:

$$F_{total} = F_{static} + F_{hyd} \tag{14}$$

$$F_{static} = Mg - \rho Vg \tag{15}$$

where M is the mass of the body in air, g is the gravitational acceleration, ρ is the density of sea water, and V is the volume of displaced water by the structure during different stages when passing through the water surface. The hydrodynamic and drag forces, are calculated as:

$$F_{hyd} = \sqrt{(F_D + F_{slam})^2 + {F_M}^2} \tag{16}$$

$$F_D = 0.5\, \rho C_D A_P {V_r}^2 \tag{17}$$

where, C_D is the drag coefficient in oscillatory flow of the submerged part of object [64], [65], [66] , A_P is the area of the submerged part of object item projected on a horizontal plane, and V_r is characteristic vertical relative velocity between the object and water particles, taken as:

$$V_r = V_c + \sqrt{{V_{ct}}^2 + {V_w}^2} \tag{18}$$

where, V_c is the hook lowering velocity, and V_{ct} is the characteristic single amplitude vertical velocity of the crane tip, calculated from:

$$V_{ct} = 2\pi \sqrt{\left(\frac{\eta_3}{T_3}\right)^2 + \left(\frac{b \sin \eta_4}{T_4}\right)^2 + \left(\frac{l \sin \eta_5}{T_5}\right)^2} \tag{19}$$

where η_3 is the characteristic single amplitude heave motion of vessel, η_4 is the characteristic single amplitude roll angle of vessel, η_5 is the characteristic single amplitude pitch angle of vessel, T_3 is the heave natural period, T_4 is the roll natural period, T_5 is the pitch natural period, b is the horizontal distance from the vessel center line to the crane tip, and l is the horizontal distance from midship to crane tip, V_w is the characteristic vertical water particle velocity, defined from:

$$V_w = 0.30\sqrt{\pi g H_s}\, e^{-\frac{0.35d}{H_s}} \tag{20}$$

where d is the distance from water plane to the center of gravity of the submerged part of the object. The hydrodynamic mass formula is taken as:

$$F_M = \sqrt{[(M + A_{33})a_{ct}]^2 + [(\rho V + A_{33})a_w]^2} \tag{21}$$

where A_{33}, is the heave added mass of the WEC, a_{ct}, is the characteristic single amplitude vertical acceleration of crane tip, calculated in (22), and a_w is the characteristic vertical water particle acceleration, calculated from (23).

$$a_{ct} = 4\pi^2 \sqrt{\left(\frac{\eta_3}{{T_3}^2}\right)^2 + \left(\frac{b \sin \eta_4}{{T_4}^2}\right)^2 + \left(\frac{l \sin \eta_5}{{T_5}^2}\right)^2} \tag{22}$$

$$a_w = 0.10\pi g e^{-\frac{0.35d}{H_s}} \tag{23}$$

$$F_{slam} = 0.5\, \rho C_s A_{ref} {V_s}^2 \tag{24}$$

where C_s is the slamming coefficient [67]–[69], A_{ref} the reference area, and $V_s = V_r$.

4. Background

4.1 Preparation of offshore devices for deployment

The offshore installation procedures of MCECs, WECs and MSs are costly, time consuming and complicated. Moreover they are highly weather-dependent and can be hazardous. The buoys and cables installation makes the process additionally complex. All steps of the process should be planned ahead carefully taking into consideration the budget, hiring an experienced crew, choice of the operational weather windows, specific information on the deployment area, transportation duration, and the meticulous choice of equipment.

The planning for a device (MCEC, WEC and/ or MS) installation should start from the preparation of the device itself. The common preparation and installation steps, for an UU marine energy device, as observed for this thesis are presented in *Figure 3*.

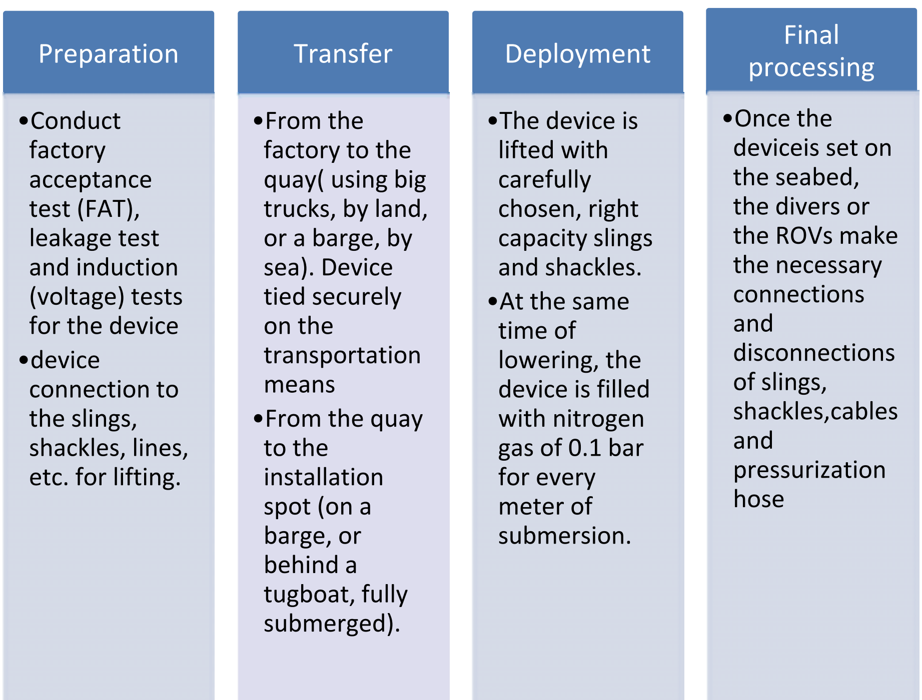


Figure 3. Preparation and installation steps of an UU device

4.2 Background on divers and ROVs work

4.2.1 Safety in diving

In the case of hiring divers for underwater tasks extra precaution measures should be taken, and all safety standards should be followed, such as [70]. The key criterion in diving that determines both safety and cost is the depth. For example, and referring to Swedish rules and regulations, for working in over 30 m depth, an advanced diving certificate is needed. When the depth reaches 40 m, extra safety measures should be taken, with either using a decompression chamber or with decompression time over 31 min. The chamber is either required onboard or should be in-reach within 30 min after the dive. The diving time is dependent on diving depth, the number of completed dives, and the number and duration of the surface breaks between the dives. From the UU installations and maintenance operations review at the LRS (at about 25 m depth) a diving team of four, can conduct up to 7 dives/day with maximum total time in the water of 3.5 h/day and mean diving time about 25 min/ dive. In conclusion, the deeper the operation waters, the more costly and hazardous it becomes to use divers.

4.2.2 General information on ROVs

To use ROVs for underwater tasks effectively, an updated knowledge regarding underwater vehicles capabilities is required. These vehicles are distinguished between manned and unmanned [71], while the latter between ROVs and autonomous underwater vehicles (AUVs) [72]. ROVs possess a tether supplying it with power and for communication purposes, and can perform a variety of tasks, in contrast to the limited uses of AUVs, that mostly are observatory. For this research ROVs are studied. ROVs are of three categories, a) observation, usually being small, show good maneuverability and are not supplied with power while underwater, b) medium ROVs with limited tooling for small tasks, and c) working class ROVs that are large, slow, designed for heavy work and are provided with high power supply and good tooling /equipment. Indicative ROVs are shown in *Figure 4*. A crew of two people (observation ROVs) to five (working class) is needed to operate the ROVs. In this thesis, calculations are made for a medium-class ROV.

(a)

(b) (c)

Figure 4. Observation ROVs Videoray Pro 4 and Ocean Modules V8 Sii (a, b) and working-class ROV ZEUS (c)

5. Methods

5.1 Offshore deployments of marine energy devices

5.1.1 Offshore deployments of WECs and MSs

Papers (I) and (II) present and evaluate offshore installations of WECs carried out by SIAB and UU respectively, while (VI) and (VII) describe the offshore installations of three UU WECs and the substation. These papers are based on active participation at a number of the deployments described, analysis of the available literature [51] and [66], and information obtained from interviews with Robert Leandersson, Boel Ekergård, Daniel Käller, Jan Sundeberg, Rafael Waters, Andrej Savin, Erland Strömstedt, Bjorn Bolund and Mats Leijon who were actively involved in previous UU installations. Ten years of installation costs are analyzed in Paper (II), converted to their net present value (NPV) of 2016 taking into account the annual interest rate as presented at Swedish Riksbank. The expenses conversion to USD, was done with exchange rate of 0.1182 on the 01-01-20161. Papers (VI) and (VII) are based on the involvement of the author in the deployments of the aforementioned devices.

5.1.2 Offshore deployments of MCECs

Paper (III) is proposing and evaluating four installation methods, for MCECs of UU type and evaluating them in terms of cost and time. This study was conducted for Norway, taking into consideration its length of coasts, where the actual prices were obtained from. The time input of this study was acquired from the author's participation in the UU MCEC deployment. For the calculation of the installation times a MatLab implementation of Monte Carlo method [73], [74] is used. The operation time is sampled, about a given average time within a given time range for number of samples $n = 10^6$. The MatLab function used is **ureal**. Deployment time and cost mathematical models are used, while the sampled time extend is utilized to derive the mean, minimum, maximum, 10%- and 90%-quantiles, of the operational times and costs.

The formulas used for the time and cost calculations for each method follow in Section 5.1.2.1.

5.1.2.1 Time and cost calculations of four offshore installation methods for MCECs

Method I uses a medium truck to transport the device to the port from the storage facility, a tugboat transferring a 90 x 27 m barge, a 50 to 55 ton capacity crane to install the MCEC and ROVs for the underwater tasks. The crane capacity was decided according to the MCEC weight (12 tons) and a maximum crane arm extension of 10 m[1]. The barge is able to carry up to 10 devices per route, while the truck carries one per route and can transfer up to 10 per day. The time needed for the positioning and mooring of the barge is taken into consideration in the T_{barge} estimation. Throughout this study the preparation time of the device includes the loading time on the vessel or transportation truck. The company closing the roads is paid once. The time calculation for Method I is:

$$T_I = T_{prep}\, n + T_{truck,1} n + T_{barge} \left\lceil \frac{n}{10} \right\rceil + T_{depl} n + T_{ROV} n \tag{25}$$

where n, is the number of MCECs to be deployed.

Method I costs are derived from:

$$C_I = C_{barge} m + C_{crane} m + C_{ROVs} m + C_{truck,1} m \; + C_{comp} \tag{26}$$

where m is the number of 12-hour deployment days.

Method II employs a 90x30 m DP specialized vessel that includes in its rental price a high capacity crane and ROVs and can carry 10 devices per trip. The ROVs provided are usually of large work class type, equipped with the necessary tooling to carry out a variety of tasks. This vessel can operate at up to 5 m significant wave height and in rivers of minimum 15 m depth, and the accuracy of its DP system is ±10 cm. It also contains a "fly-by" policy meaning no mobilization fee is payed when there is a flexibility on the schedule. The installation completion time with method 2 is calculated as:

$$T_{II} = T_{prep}\, n + T_{truck,1} n + T_{vessel} \left\lceil \frac{n}{10} \right\rceil + T_{depl} n + T_{ROV} n \tag{27}$$

And the cost as:

$$C_{II} = C_{vessel} m + C_{truck,1} m + C_{comp} \tag{28}$$

The large truck hired for methods III and IV carries 2 MCECs per transport and 20 devices in a working day. The overall time and costs for method III are calculated from:

$$T_{III} = T_{prep}\, n + T_{truck,2} \left\lceil \frac{n}{2} \right\rceil + T_{barge} \left\lceil \frac{n}{10} \right\rceil + T_{depl} n + T_{ROV} n \tag{29}$$

$$C_{III} = C_{barge} m + C_{crane} m + C_{ROVs} m + C_{truck,2} m + C_{comp} \tag{30}$$

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[1] https://nckynningsrud.com

Time and expenses for method IV are calculated as:

$$T_{IV} = T_{prep}\, n + T_{truck,2} \left\lceil \frac{n}{2} \right\rceil + T_{vessel} \left\lceil \frac{n}{10} \right\rceil + \ T_{depl} n + T_{ROV} n \tag{31}$$

$$C_{IV} = C_{vessel} m + C_{truck,2} m + C_{comp} \tag{32}$$

5.2 Employment of divers vs ROVs in offshore operations

Paper (IV) is presenting a comparative study in the use of ROVs versus divers in the offshore deployment and maintenance of UU WECs at the LRS. For this purpose three deployment and maintenance methodologies are evaluated. The time and expenses figures provided in the paper are actual, acquired from experience in past deployment and maintenance procedures. The costs are converted in euros, €, with equivalence for 6 March 2018, as 1 € = 1.24110 USD. Diving specifications for Sweden were obtained from personal communication with Martin Häggström, MW diver.

To evaluate the efficiency in offshore operations conducted by divers and ROVs, the parameters taken into consideration for the divers is safety and time, while for ROVs is the complexity of the task and time. These are the most prioritized factors indicating, which procedure needs to be changed or optimized. The following Tables 1 and 2 (Paper IV) present this evaluation.

Table 1. Scale for evaluation of personal safety for divers- and operation complexity for ROV-conducted operations.

Scale	Operational Time	Personal Safety	Complexity of Operation
1	< 5 min	Entirely safe	Very simple procedure, repetitive and simple task
2	> 5 min and < 15 min	Very low chances of injury	Mono-action operation with very low chances of sudden troubleshooting
3	> 15 min and < 30 min	Minor chances of injury	Mono-action operation with minor chances of sudden troubleshooting
4	> 30 min and < 1 h	Not safe	Complex operation involving multiple actions or high thrust and high accuracy
5	> 1 h	Life threatening	Very complex operation requiring high thrust, high accuracy, and multiple actions

Table 2. Evaluation of different deployment and monitoring tasks for divers and ROVs. Scaling is taken from Table 1. The multiplication of the operational time by the personal safety, or the task complexity, gives the priority level result. Level 1 to 4: the task is efficient as it is, Level 5 to 12: The task could be improved with special additional tooling/under certain circumstances; and Level 13 to 25: The task needs to be automated or improved.

Phase	Task	Divers			ROVs		
		Operational time	**Personal Safety**	**Priority level**	**Operational time**	**Task Complexity**	**Priority Level**
WEC deployment	Monitoring of the submersion process	2	4	8	2	1	2
	Pressurization hose disconnection	1	3	3	1	2	2
	Disconnecting the slings and the shackles	2	2	4	4	4	16
Cable connection	Drag the cable to the MS	5	3	15	1	1	1
	Filling the air in the connector pocket / chamber	2	2	4	1	2	2
	Underwater cable connection	1	3	3	1	3	3
Buoy deployment	Lifting the translator	3	4	12	3	5	15
	Attaching the buoy	3	4	12	4	5	20

5.3 Risk assessment in deployment operations

In Paper (V), a risk assessment in deployment operations is conducted. Specifically the failure of the crane hoisting system was investigated, while it deploys a UU WEC from a standard barge. For this study the DNV standards DNV-RP-H103, DNV-RP-N103, DNVGL-RP-G107 and [60] are followed. The analytical method is explained below.

5.3.1 Input

5.3.1.1. General Input

The input for the above calculations is presented in Table 3.

Table 3. Coefficients and distances

Parameter	**Value**
Horizontal distance from the vessel center line to the crane tip, b	12.65 m
Horizontal distance from midship to crane tip, l	0 m
Vessel speed	0 knots
Crane placement	8.5 m from the center line of the vessel 32.28 m from the vessel's aft
Hook lowering velocity, V_c	0.1 m/s
Drag coefficient, C_D	$C_{Dfundament} = 1.5$ $C_{Dgenerator} = 0.82$
Distance from water plane to center of gravity of submerged part of the object, d	1.24 m initially and it reduces by 0.25 m to each 0.25 m of submersion.
Slamming coefficient, C_s	$C_s = 5.15$ at the moment the fundament entered the water $C_s = \pi$ while the WEC is submerged $C_s = 0.8$ for fully submerged WEC

We assume the barge to be fixed and that the hydrodynamic impact by the submersing WEC is insignificant.

5.3.1.2 Barge input

A Svitzer Arc type barge (*Figure 5*) is used for the hydrodynamic response calculations, since this vessel has deployed UU WECs in numerous occasions. The parameters of the barge are presented in Table 4.

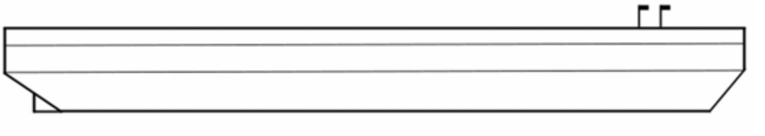


Figure 5. Side view sketch of the barge

Table 4. Dimensions of the "Svitzer Arc" barge

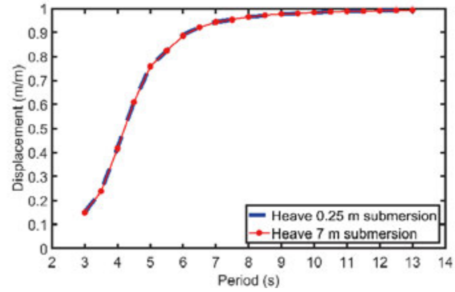
Upper length	64.56 m
Bottom length	50.96 m
Width	17 m
Height	4.05 m
Draft	0.9 m

5.3.1.3 Hydrodynamic modelling of vessel response

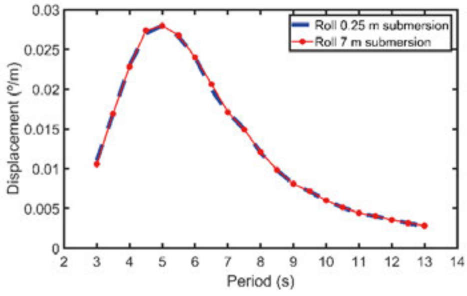
According to:

$$8.9\sqrt{\frac{Hs}{g}} \leq Tz \leq 13 \quad (33)$$

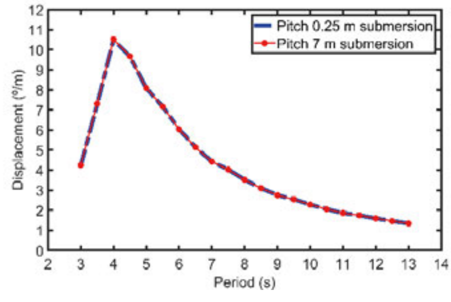
the calculations were conducted for 3 to 13 s zero crossing period. In *Figure 6* the heave (a), roll (b) and pitch (c) RAOs for the vessel for 0.25 m and 7 m of the WEC's submersions are presented. The fact that the RAOs in each figure are absolutely overlapping indicates the negligible influence of the WEC submersion on the barge.



(a)



(b)



(c)

Figure 6. The heave (a) and roll (b) and pitch (c) RAOs for the vessel for 0.25m and 7 m of the WEC's submersion

5.3.1.4 WEC description and placement

The WEC used in the simulations and consecutive calculations was a UU device and its sketch is illustrated in *Figure 7*, while its dimensions are presented in Table 5.

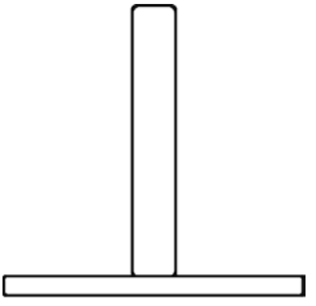


Figure 7. WEC simplified sketch for ANSYS AQWA simulations.

Table 5. WEC dimensions

Fundament diameter	6.3 m
Fundament height	0.5 m
Generator height	6 m
Generator diameter	1.20 m
Total mass	55.000 kg

The barge-WEC-crane system and the angle of attack of the incoming wave, relative to the global coordinates are illustrated in *Figure 8*.

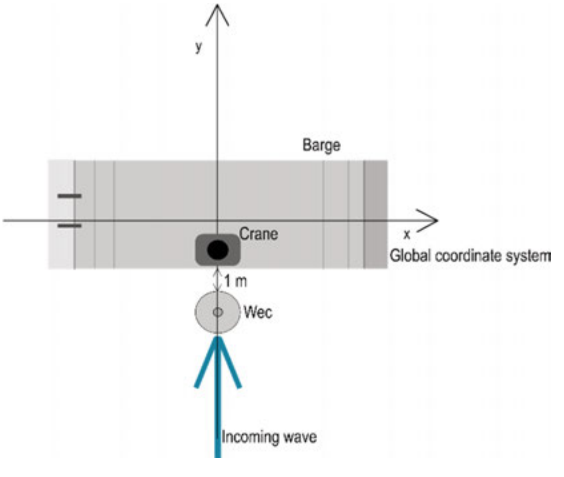


Figure 8. Barge-WEC-crane system and incoming wave direction given in the global coordinates

The barge-WEC system is simulated in ANSYS AQWA. Subsequently, the hydrodynamic and hydrostatic forces are found in AQWA for zero crossing periods from 3 to 13 s and WEC's submersion from 0 m to 7 m with a step of 0.25 m.

6. Results

The results presented below are found in Papers (I), (II), (III), (IV), (V), (VI), and (VII).

6.1 Offshore deployments of WECs and MSs

6.1.1 UU and SIAB WEC deployment methods

From the offshore installations of WECs conducted by UU and SIAB four main deployment strategies derived. Those methods differentiation was due to and dependent on: a) the deployment location, b) the sea depth that varied from 16 to 50 m, c) the operation being experimental or commercial, d) the dimensions and number of devices, and e) the vessels and equipment used. The four methods are shown in *Figure 10*. Details on each operation, such as cost, time, equipment, crew, advantages and disadvantages are presented in Tables 7 and 8.

The installation method is dependent on the following parameters:

Vessel employed	Placement of the device on the vessel	Submerging method of the generator
• Barge i) With a high capacity crane mounted on it ii) With a special structure fitted on the aft • Tugboat • Specialized offshore operation vessel	• On the vessel • Hanging from the special structure on the barge • Towed submerged/semi-submerged from the aft of the tugboat	• Lowered onto the seabed by the high capacity crane from the vessel • Lowered onto the sea bottom by the tugboat's winch system • Lowered from the wires of the special structure attached to the barge

Figure 9. Parameters that determine the installation method of a WEC

According to the above, the four offshore deployment methods for WECs and MSs are: a) the barge-special structure method, b) the barge-crane method, c) the tugboat, and, d) the specialized vessel approach (*Figure 10*).

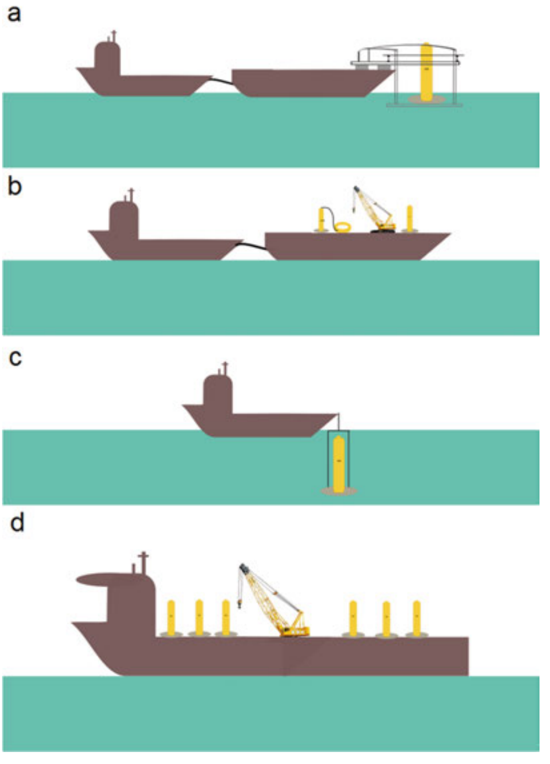


Figure 10. The four deployment methods: barge–special structure (a), barge–crane (b), tugboat (c), specialized vessel (d)

6.1.1.1 The barge-special structure method

The barge-special structure method, *Figure 10* (a), involves a barge, a tugboat that transports it, and a special structure mounted on the barge that transfers and deploys the device. This strategy was followed to deploy L1, the first WEC manufactured by UU, and 10 WECs and one MS from SIAB.

The WEC, its buoy and a 100 m power cable, *Figure 11* (a), were installed using a specialized structure comprised of steel beams and hydraulic wire jacks that were welded on the barge aft. The device was held semi-submerged through its transportation to the deployment spot, and was released for submersion by the hydraulic wire jacks of the structure. The special structure with the wire jacks that was removed from the barge after the operation was completed, consisted from four metallic beams, and was constructed and welded on the barge by Tunga Lyft company. [75]–[78]

While installing the first 10 generators of the SIAB Sotenäs project, Samson vessel, *Figure 11* (b), was hired, a fixed A-frame crane barge. During transportation to the installation spot, two generators were hanging from wires, held in the crane hooks, and ROVs were used for the underwater tasks. Ten people consisted the crew, working 12-hour shifts.

The SIAB MS was deployed in a similar manner, where it was transferred, submerged in the water to weigh less (it weighs 20 tons in water and 115 tons in the air), hanging from the cranes' winches steel wires. "Pharaoh" barge was employed, *Figure 11* (c), onto which the SIAB employees built an 80-ton capacity crane. Six SIAB employees worked on the barge. The attempt to deploy WECs with this structure did not work.

The barge–special structure method is considered inefficient, because it can carry only one or two devices at a time, and has a very slow lowering pace during submersion. Although this can be a crane-less method it still consumes time in mounting and demounting the extra structure from the barge. Moreover, this structure lowers the vessels maneuverability.

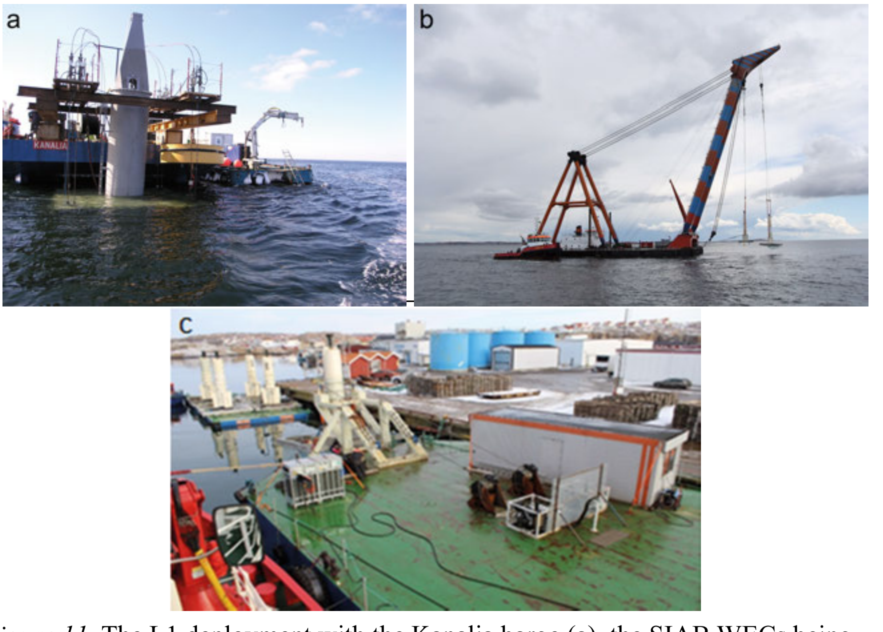


Figure 11. The L1 deployment with the Kanalia barge (a), the SIAB WECs being transported with the Samson barge (b) and the SIAB MS on the Pharaoh barge (c)

6.1.1.2 The barge-crane method

The barge-crane installation method, *Figure 10* (b), is the most frequently used so far by UU. This strategy employs: a tugboat transferring the barge which carries the device, a high capacity crane mounted on the barge and a crew of divers or ROVs. For the operations conducted at the LRS and Sotenäs, the large capacity crane from Lysekil quay was employed for the placement of the devices on the barge. Most of the times the diver's crew of 4 were hired from Marine Works company, except for the Norway and the WESA project deployments. In crew usually included the employees from the tugboat, the barge, UU, SIAB and the crane drivers.

So far, the following WECs installed using this method: L2 and L3 (*Figure 12* (a)); two SIAB WECs of the L2 type with their buoys and a MS at the MTS (*Figure 12* (b)); L9 (*Figure 12* (c)); L4, L5, L7, L8 (*Figure 12* (d)); the WESA project WEC with its buoy and a wave measurement buoy (*Figure 12* (e)); L12B (*Figure 12* (f)); L6, L9, L12A and a MS (*Figure 12* (g)). Details on UU deployments using this strategy are presented in Table 8, while the procedure description of the MTS installation follows.

The first SIAB operation installed two WECs with their buoys while the underwater cable was laid on the sea bottom, at the MTS, Norway. For the deployment a tugboat towed a large barge provided by Ulstein, and Nautilus Maxi from Seloy were hired. The barge had a high capacity mobile crane mounted on it and carried the two WECs attached to their buoys and the electrical cables. The cables coming from the WECs were rolled up on cable drums next to them. The MS, the electrical cable and the electrical cable drum, and the four divers were transported by Nautilus Maxi that was equipped with a cable winch and high capacity deck cranes. For this procedure, a pressurized chamber for the divers welded onto the smaller boat, the electrical cable drums and custom-made slings and shackles were used.

The indicative cost in prices of 2013, of this installation method is presented in Table 6:

Table 6. WEC deployment expenses using the barge–crane method given in prices of 2013 (Paper VI)

Expense item	**Price**
Barge of 65 m length and 1120 m^2 deck area	65,000 SEK/day
To bring the barge to shore	50,000 SEK
Rent of the barge (per day)	15,000 SEK/day
Divers	80,000 SEK/day
Crane	40,000 SEK/day
Tugboat	45,500 SEK (=6,500 SEK/h. ×7 h.)
Total	**295,500 SEK/day**

Figure 12. L2 and L3 installation (a), 2 WECs deployment in the Maren test site (b), L9 during submersion (c), L4, L5, L7 and L8 WECs (d), WESA WEC installation (e), L12B generator (f), L6, L9, L12A and MS deployment (g)

6.1.1.3 The tugboat method

The tugboat installation strategy, *Figure 10* (c), is the most recently tested method by UU and utilizes a tugboat to transport and install the device on site. The WEC is transported fully submerged from the aft of the tugboat, and when on spot, the tugboat positions and lowers the device onto the sea bottom with a wire or a fiber rope. No cranes are hired, besides the quays crane that lifts the WEC and attach it at the aft of the tugboat. The crew is comprised from the five tugboat employees and four MW divers (Paper II). With this method, the L10 attempted to be installed twice, and the L12C and L12D were successfully deployed (*Figure 13* (a)).

When the L10 was to be deployed the first time, a non-rotation free wire was used to drag the generator into the water, contributing in the devices rotation and the resultant tangling of the pressurization hose, lines, slings and wires. This entanglement caused the snapping of the pressurizing hose, the device was filled with sea water and the operation was cancelled. To deploy L10 for the second time along with L12C, the same method was used with the optimizing addition of non-rotating wire and specialized equipment for protections and guidance of the pressurizing hose. Although the pressurization valve of L10 detached due to vibration, L12C was deployed successfully. The L12D generator was successfully installed at the same time with its buoy, using the tugboat method.

(a) (b)

Figure 13. L10 during deployment, April 2015 (a), Svitzer Thor tugboat (b)

6.1.1.4 The specialized vessel method

With this approach, *Figure 10* (d), 31 WECs, a MS, and connection of buoys to WECs and cables to MS have been carried out by SIAB. This method uses a specialized vessel, that usually provides high capacity cranes, experienced crew, a large deck and ROVs included in the price, although it is possible to hire divers also, depending on the underwater tasks. Specialized vessels are costly, exactly because they offer this "all inclusive" price and are specifically designed and equipped for this kind of operations. When hiring a vessel like this, the time spent on communication with different vessel, crane and ROV companies lowers, since only the specialized vessel manager needs to be contacted for arrangements.

The specialized vessels used so far from SIAB, namely Dina Star, Siem Daya 2, and M.V. Craic are shown in *Figure 14* and details on the deployments they facilitated are presented in Table 7.

Figure 14. Dina Star (a), MPOV Siem Daya 2 (b), Motor Vessel (M.V.) Craic (c)

6.1.1.5 Summary of the WEC and MS deployments carried out by UU and SIAB

The tables that follow summarize the UU and SIAB deployment projects, including equipment, crew, time and costs.

Table 7. SIAB deployment projects. The costs are presented as a percent of the overall deployment cost at Sotenäs (Paper I)

Project	WEC, date	Vessels	Advantages	Disadvantages	Crew	Time	Cost
Norway	2 WECs of L2 type with their buoys and a MS, Sep 2009	Tugboat towing large barge from Ulstein. Nautilus Maxi from Seloy	High capacity cranes Simultaneous deployments of WECs, their buoys and underwater cable. Nautilus Maxi cable winch. Pressurized chamber for divers Electrical cables' drums Custom-made slings and shackles	Depth and divers	10 p.	6 h /WEC	30%
Sotenäs		Samson June 2014	DP system ROVs Crane capacity	2 WECs at a time, very slow	10 p.	2.4 h /WEC	15%
	25 SIAB WECs	Dina Star April 2015	Vessel and crane capacity, 2 ROVs, mooring GPS, DP system, operating 24 h.	Availability Cost Pilot Positioning	31 p. 20 p. vessel crew, ROVs crew of 4 p., 7 p. from SIAB	1.92 h /WEC	50%
	MS	Pharaoh	Low cost rate	Mooring No DP system	6 p.	36 h / MS	11%
	MS, connecting buoys to WECs and cables to the MS	Siem Daya 2	Versatile Vessel and crane capacity 2 ROVs GPS, DP system mooring, operating 24 h.	Cost	20 p. 10 vessel employees and 10 for ROV and crane	4 h / MS	24%
Ghana	6 SIAB WECs	M.V. Craic April 2015	Crane capacity of 120 tons Small draft to operate in 16 m depth Two diving compressors included in the vessel's equipment.	No DP system	20 p. 2 SIAB employees, 15 from the vessel and 3 divers from Ghana	2.7 h /WEC	>20%

Table 8. Details of the UU WEC and MS installation projects

Project	**WEC and date**	**Vessels**	**Adva-ntages**	**Disad-vantages**	**Crew**	**Time**	**Cost**
Lysekil	L1 March 2006	"Belos" tugboat (Buksér og Berging) "Kanalia" barge (Sandinge Bogsering & Sjö-transport)	Safe Effi-cient	Slow Hard to ma-neuver Time loss to mount and demount structure Barge titled when deploy-ing	11 p. incl. 4 divers from Dyk & Sjötjänst i Udde-valla AB	12 h/ WEC	Up to 2,5 MSE K
Lysekil	L2, L3 Feb 2009 [79], [80]	Medium sized barge. Two tug-boats to transport the barge and keep it in position	Fixed crane of 100 tons, GPS, depth measur-ing de-vice	Boat capacity not enough in harsh weather, crane close to its limit Positioning problems	22 p.	8 h/ WEC	700 kSEK
Lysekil	L9 Dec 2009 [81], [82]	Boa Siw tugboat, Boa Barge 41 from Röda bola-get	Kynnin gsrud high ca-pacity mobile crane	Difficulty to position the barge	9 p.	12 h/ WEC	900 kSEK
Lysekil	L4, L5, L7, L8 Nov 2010	Svitzer Boss tug-boat tow-ing Svitzer Lindo barge from Norway	Havator crane of ~ 300 tons ca-paci-tyEx-cellent barge posi-tioning	Not discov-ered	14 p.	3 h/ WEC	900 kSEK
WESA Åland, Finland	Cus-tomiz ed L2 with buoy and wave meas-ure-ment buoy Jan 2012 [51], [53], [54]	Varma tugboat Barge from Åbo. Small boat from "Subsea Åland" for cable in-stallation.	300 tons ca-pacity crane secured on the barge	Anchoring problem Icy, slippery conditions could jeop-ardize safety	9 p.	4 h/ WEC	N/A

Lysekil	L12B March 2013 [83], [84],	Svitzer Boss tug-boat trans-porting the Svitzer Ark barge	High capacity “Nordic crane” se-cured on the barge	Slow	16 p.	10 h/ WEC	850 kSEK
Lysekil	L6, L9, L12A, MS July 2013	Tugboat transport-ing Svitzer Ark barge	High capacity crane	Costly	12 p.	5 h/ WEC	2,000 kSEK
Lysekil	L10, April 2015	Svitzer Thor tug-boat	Eco-nomical Effi-cient moor-ing	No rotation-free wire Deployment aborted	12 p. tugboat crew of 4, 4 di-vers and 4 from UU	N/A	270 kSEK
Lysekil	L10, L12C, Au-gust 2015	Svitzer Thor tug-boat	Cost Effi-cient moor-ing Non-ro-tating wire	L10 deploy-ment aborted	13 p. 5 from tugboat	5 h/ WEC	270 kSEK
Lysekil	L12D 2017	Svitzer Thor tug-boat	As above		10 p. 5 from tugboat	5 h/ WEC	270 kSEK

6.1.2 Offshore deployment methods of UU MS

Three approaches had been followed so far to deploy MSs: the specialized vessel method by SIAB, the barge-crane method and a small vessel and lifting buoys strategy both carried out by UU.

In this section the third strategy is studied, and the comparison of the two UU strategies is drawn in Table 9.

The third method (Paper VII) to deploy the 6.5 tons UU MS [37], is utilizing a small vessel, a small capacity crane, two lifting buoys, weights, and a divers’ crew with their boat (*Figure 15*). The MS is transported by the small vessel to the installation spot while floating with the buoys help. Moreover the buoys are reducing the drag forces. Once the MS reaches the installation spot, the buoys are detached and the weights are placed on the MS foundation and the substation is being submerged while pressurized with 3 bars of nitrogen. The pressurization was conducted in an automated manner, with the use of a pneumatic tool fastened to the hull. When the MS is on the seabed, the pressurizing cable is removed, four supplementary concrete blocks of 100 kg each are placed on its foundation to keep it stable and the cables are connected, all tasks carried out by the divers.

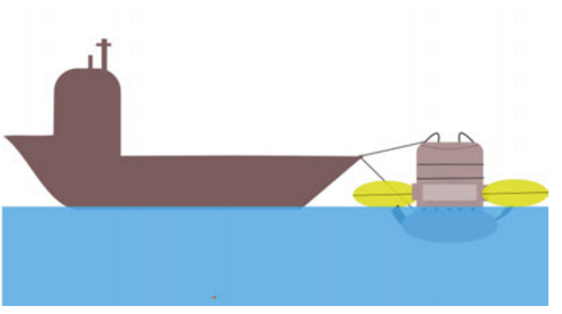


Figure 15. UU MS deployment method using a small vessel

Table 9. Comparison of the two UU offshore deployment methods for the MS

Method	Advantages	Disadvantages	Cost	Time
Barge-crane	A safe/ fairly safe procedure Suitable for multiple de-ployments	Hard to maneuver Mooring problems time-inefficient Expensive in the long term Narrow operational weather windows	73,400 USD/ day	5 h
Small boat, crane, lifting buoys, weights	Safe Fast Economic Larger operational weather window	Recommended for single de-vice deployments	8,600 USD/ day	~ 3 h

As observed in Table 9, the small vessel method is 8.5 times more economical than the barge-crane strategy and 1.7 times faster. Taking into consideration the frequent maintenance of the MS, the small vessel approach is the optimal.

6.2 MCECs installation methods

6.2.1 Case study

The case study to evaluate four installation methods of an UU MCEC was conducted for Norway, due to its long coastline, and prices and electricity consumption data were acquired accordingly. The rated power for an UU MCEC (used in methods I and II) is 7.5 kW, meaning it can supply the local electricity grid with 180 kWh/day and 65.700 kWh/ year if the device produces power 24/7. However, this is not feasible due the renewable energy technology degree of utilization [85]. The degree of utilization is the actual energy delivered to the grid within a year, in comparison to the installed power. For marine current technologies, the utilization degree is about 46%. With this in mind, the UU MCEC delivers to the grid 82.8 kWh/day and 30.222 kWh/ year. The MCEC of double the cross-sectional area, used for method III and IV, has 15 kW rated power and will supply the grid with 165.6 kWh/day and 60.444 kWh/year. The average yearly electricity consumption in Norway, for 2014, as reported by trading economics[2], was approximately 17.980 kWh/ household. Therefore, a UU MCEC supplies electricity to 1.68 households/ year, and to supply 100 households 60 such devices are needed. The scaled-up device can support 3.36 households/year, and to supply 100 households 30 devices of this type are required.

The assumptions while conducting this study were the following: a) the device placement would be at a river or fjord, with minimum depth and width of 15 m, b) the site currents should be approximately 1.03 – 2 m/s in accordance to the device design, c) no bridge and no hydropower stations are located over or upstream of the site, d) there are no technical limitations when scaling up the MCEC.

6.2.2 Preparation for a MCEC deployment

The installation preparation for a MCEC includes the following steps:

1. Site current speed assessment: for reliable data, the measurement of the area currents can be done up to two years in advance[3] of the project start, and accomplished by ADCPs, placed in a radius of 5 m upstream and downstream from the decided location of the MCEC
2. Site weather assessment: the weather forecast for the deployment day should be monitored and the site current forecasts as well as the seasonal variation details should be acquired. In Norway, an online weather monitoring is possible through seNorge[4] and the Norwegian Water Resources and Energy Directorate[5].
3. Riverbed check: the riverbed must be appropriate and smooth enough for a gravity foundation. This evaluation is usually carried out by survey vessel, sonars, Robotic Riverbed Survey Vessels (RRSVs), Acoustic Doppler Current Profilers (ADCPs) or/ and divers.
4. License and permission to operate: should be acquired from the local authorities and municipality, also when applicable, a special permit for in-water construction, and a special building license for an on-land station, should be acquired [86].
5. Project duration permission
6. Environmental impact studies
7. Decommissioning studies

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[2] www.tradingeconomics.com
[3] https://oceanservice.noaa.gov
[4] http://www.senorge.no
[5] https://www.nve.no

6.2.3 Deployment methods for MCECs

The installation methods for a UU MCEC (methods I and II) and a double installed capacity of UU MCEC (methods III and IV) developed were:

- Method I: employs a low draft barge, a crane of 50 to 55 tons capacity mounted on it, ROVs, medium transportation truck to transfer an UU MCEC per route, and a company to monitor the traffic and install warning signs around the deployment area.
- Method II: used a low draft DP specialized vessel that includes a high capacity crane and ROVs, a medium transportation truck, and a traffic monitoring company.
- Method III: as method I, with the difference of hiring a large transportation truck with a trailer to transport two large MCECs per route.
- Method IV: as method II, but instead of the medium truck, it uses the large.

Companies providing barges in Norway are BOA[6], FFS[7], J.J. Ugland Companies[8], and DOF[9]. Moreover, DOF Subsea Norway AS provides specialized vessels of low draft. A Norwegian crane supplier is Crane Norway group[10], and ROVs can be supplied from Argus Remote System AS[11], IKM subsea[12], Sperre[13], and Kystdesign[14], and the University of Bergen.

ROVs are employed in all methods because drivers cannot be hired to work at currents over 0.2 m/s, since it is prohibited from the diving regulations. The operational restriction currents for ROVs are up to 1.54 – 1.7 m/s, depending on the design, model and company. ROVs are inspecting the device landing on the riverbed and the firm placement of the cables, and disconnect the slings and shackles, thus ROV-friendly lifting points should be considered in the design of MCECs.

6.2.4 Input description

For this study the time data used are acquired from personal experience in the MCEC deployment of UU, 2013. The cost data are obtained from quotations from vessel, crane, truck, and ROV companies in Norway. The costs are considered for 12-hour operational days. The times and costs for all installation methods are in Tables 10 and 11.

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6 http://www.boa.no
7 http://ffs-as.com/marine-division
8 http://www.jjuc.no/
9 http://www.dof.no/en-GB/Contact-DOF
10 https://cranenorway.com
11 http://argus-rs.no/
12 https://www.ikm.com/ikm-subsea-norway
13 http://sperre-as.com/
14 https://kystdesign.no/contact/

Table 10. Statistical times, in minutes, simulated in MatLab for methods I, II, III and IV

Times	**Average**	**Deviation /range**
Preparation time (T_{prep})	120 min	110 – 130 min
Transportation of the MCEC to the port /quay ($T_{truck,1}$)	50 min	35 – 60 min
Transportation of the MCEC to the port/ quay with large truck with a trailer ($T_{truck,2}$)	90 min	80 – 100 min
Port-to-site transfer time with barge incl. the vessel positioning time (T_{barge})	45 min	40 – 65 min
Port-to-site transfer time with specialized vessel incl. the vessel positioning time(T_{vessel})	20 min	15 – 35 min
Lifting and submersion of the device on the riverbed (T_{depl})	30 min	25 – 45 min
ROVs inspection and disconnection of lifting equipment (T_{ROV})	45 min	40 – 50 min

Table 11. Expenses for MCEC deployment methods I, II, III and IV

Item	**Cost**
Crane of 50 to 55 tons capacity	132 €/h, at a minimum hire time of 12 hours
Crane driver	80 €/day (12-hour day)
ROV with suitable equipment	2,700 €/day
Truck transportation $C_{truck,1}$	1,250 €/day
Large truck transportation $C_{truck,2}$	3,000 €/day
Company closing the roads and place warning signs in the area	~2,500 €
Standard barge of 90 x 27 m incl. towing boat	Average daily rate ~3,500 €
DP specialized vessel of 90x30 m, including high capacity crane and ROVs	36,905 €/day

6.2.5 Time and cost plots for methods I, II, III and IV

The plots for the time and cost calculation for each of the four methods are presented in *Figures 16 – 23*. The minimum, maximum, 10%- and 90%-quantiles of the average times and cost were calculated for 1 to 100 MCECs deployment and for a number of samples $n = 10^6$.

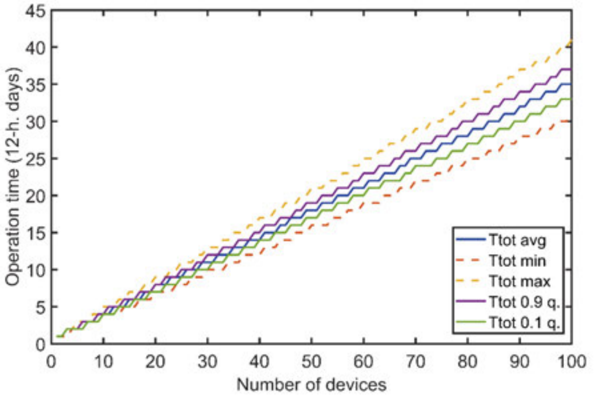


Figure 16. The installation time for 1 to 100 devices, Method I

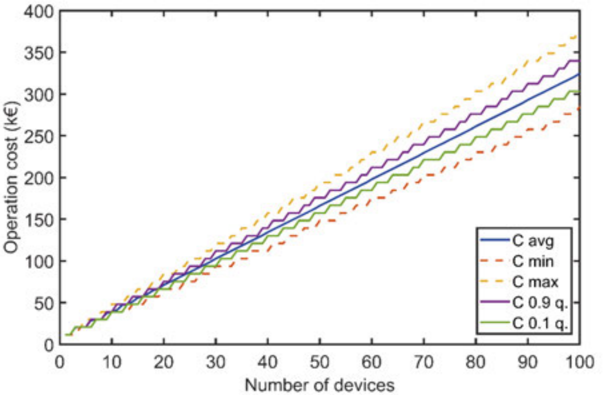


Figure 17. The installation cost for 1 to 100 devices, Method I

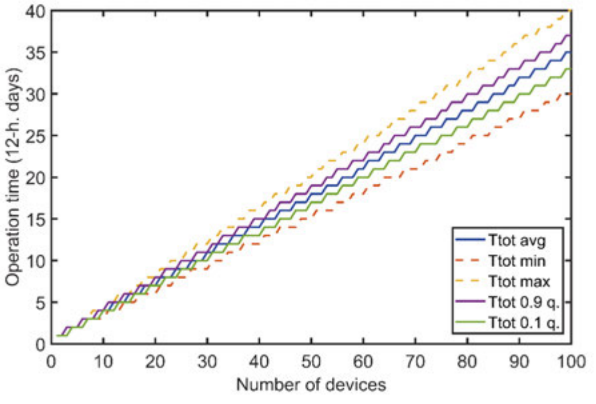


Figure 18. Installation time for 1 to 100 devices, Method II

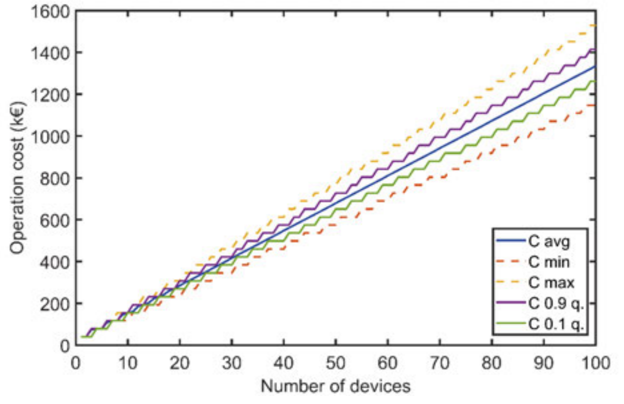


Figure 19. Installation cost for 1 to 100 devices, Method II

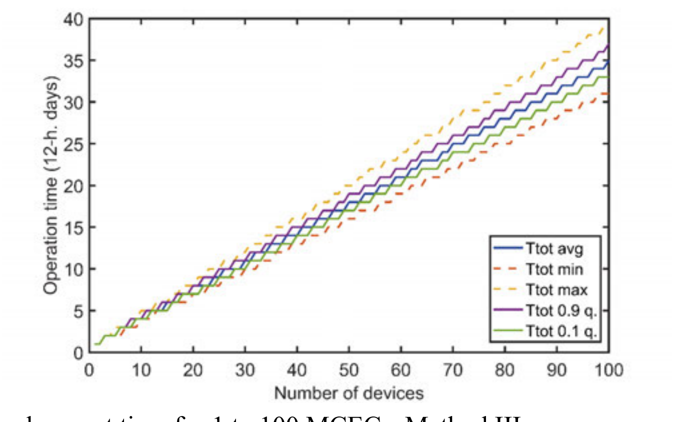


Figure 20. Deployment time for 1 to 100 MCECs, Method III

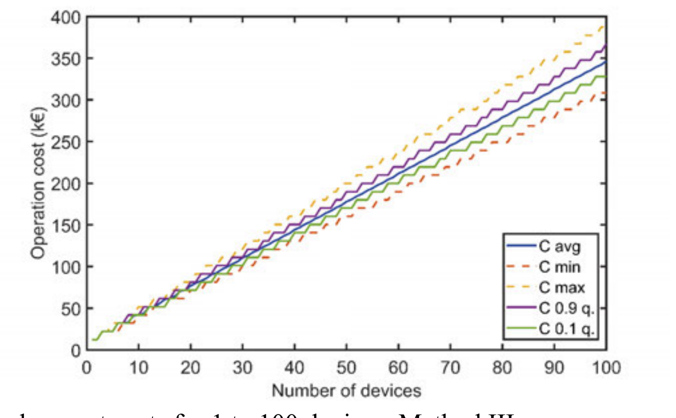


Figure 21. Deployment costs for 1 to 100 devices, Method III

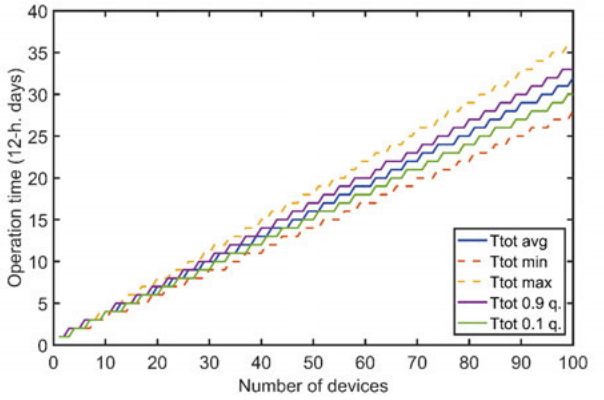


Figure 22. Installation times for 1 to 100 MCECs, Method IV

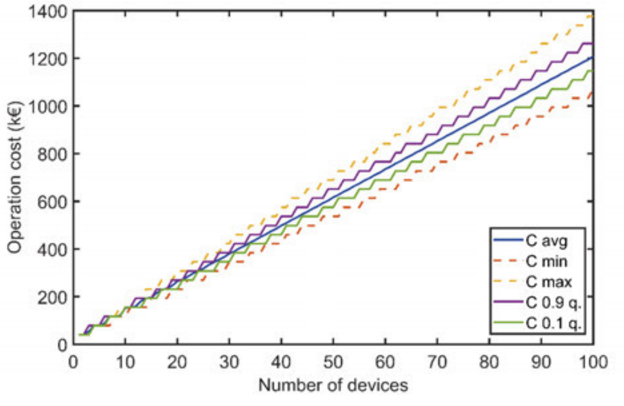


Figure 23. Deployment costs for 1 to 100 MCECs, Method IV

The average deployment cost and time for each method is presented in Table 12.

Table 12. Average installation times and costs for each method

	Time (h)				**Cost (k€)**			
	Method				**Method**			
	I	II	III	IV	I	II	III	IV
1 MCEC	4.8	4.4	5.7	4.6	12 k€	41 k€	12 k€	41 k€
100 MCECs	420	418	408	372	321 k€	1,346 k€	347 k€	1,212 k€
100 house-holds installed capacity	252	248	125	113	193 k€	811 k€	110 k€	380 k€

6.3 Efficiency in time, cost and safety in WEC deployments using ROVs vs using divers

Using divers in offshore operations can jeopardize their safety and is costly [27] and although ROVs can ensure the operational safety, they are not yet developed to their full potential. A methodology to compare the time and cost efficiency in offshore operations has been studied and developed in Paper IV. The methodology presented can be used broadly, for point absorbers and oscillating water columns, because it is not dependant on the type or size of the device. The factors this methodogy depends on are: the number of devices to install, the preparation and submersion time by divers and ROVs, the connection time of buoys and cables by divers and ROVs, divers employment costs, and ROVs rental expenses.

To evaluate the efficiency in offshore deployments of WECs three installation methods are compared: a) method 1, deployment of a WEC separately from its buoy hiring only divers, b) method 2, deployment of a WEC separately from its buoy employing divers and ROVs, and c) simultaneous installation of a WEC and its buoy using ROVs.

Method 1 is a previously tested, commonly used by UU strategy, employing divers for underwater tasks. After the WEC is submerged to the sea bottom by a crane, while being pressurized, the divers perform all underwater tasks. These tasks are the disconnection of slings and shackles, closing the pressurization valve and pulling off the pressurization hose [40]. To connect the buoy to the generator, the translator is lifted upwards with airbags. A diver attaches the safety and connection lines to the buoy. Using divers during this operation compromises their safety.

In the second method, the divers are connecting the buoy, since an ROV of the chosen size cannot lift the translator being as heavy as 1 to 10 tons [83] and provide the required task accuracy. The ROV is therefore carrying out the underwater processes that are adapted for ROVs. This is a suggested method and an intermediate step towards fully automatized operations. On the upside, it is an expensive and time consuming method due to the costs for both divers and ROVs and the time needed for their cooperative work.

What is particularly sensitive in the first two methodologies, is to lift the translator carefully and with precision so it will not hit the stator while it is moving up considering its weight and the buoy moving at the water surface.

The third method, has not been tested so far, is using exclusively ROVs that perform the same tasks as previously. To submerge the generator and connect the buoy, two cranes are used: the first is lowering the WEC onto the seabed while the second brings the buoy for connection. All lines, ropes and hoses should be sturdily fastened. This strategy requires more equipment, and accurate and longer preparation that makes it expensive.

An important input concearning LRS (25 m depth) is that diver team of four people can dive seven times with total diving time of 3.5 h within a working day.

The advantages and disadvantages of employing divers and ROVs are shown in Table 13.

Table 13. Advantages, disadvantages and cost for hiring divers and ROVs in an off-shore operation

	Advantages	**Disadvantages**	**Cost**
Divers	Can carry out detailed tasks Experience, ability to troubleshoot	Depth limitations Diving time limitations >30 m depth the expenses rise significantly Injury risks Limited operation at high waves or currents, areas with little visibility	66 – 98 € / diver/ hour
ROVs	Operational depth of several thousand m No working time limitations	Limited operation to < 3 knots currents Medium class cannot perform heavy tasks (carrying, pushing, dragging) Limited operation at high waves or currents, areas with little visibility	7,000 € / day 50 – 340 k€ for purchase

The comparative study on the time and the cost of the deployment operations is based on the assumption of ideal circumstances during deployment (no delays or unpredicted issues rising) and data from the following Tables 14 and 15, taken from Paper (IV).

Table 14. WEC deployment expenses with divers and ROV assistance.

Resource	**Cost**
Diver	90 €/h
Worker for device preparation	50 €/h
Boat (for ROV or diver)	120 €/h
Video Ray Pro 4 with cutter and gripper	7,000 €/day
Video Ray Defender	7,000 €/day
Video Ray Pro 4 alone	2,000 €/day

Table 15. Time duration in hours for each step of a WEC deployment with divers and ROV assistance

Operation	**Time per WEC using Method 1 (h)**	**Time per WEC using Method 1 (h)**	**Time per WEC using Method 1 (h)**
WEC preparation	1	1	1.5
WEC submersion	0.5	0.5	0.5
Buoy preparation	1	1	1.5
Buoy connection	3	3	-
Cable connection	0.5	1	1

The cost and time results for each deployment method, and for 5 to 100 devices, are shown in the following *Figures 24* and *25*.

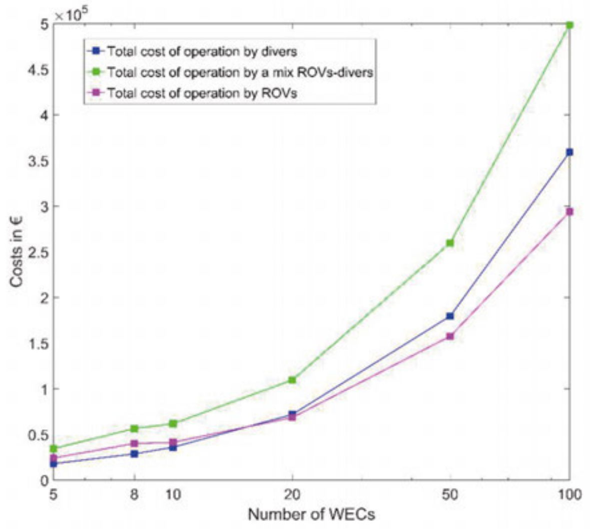


Figure 24. Comparison of the operational costs for the three deployment methods and WEC number from 5 to 100

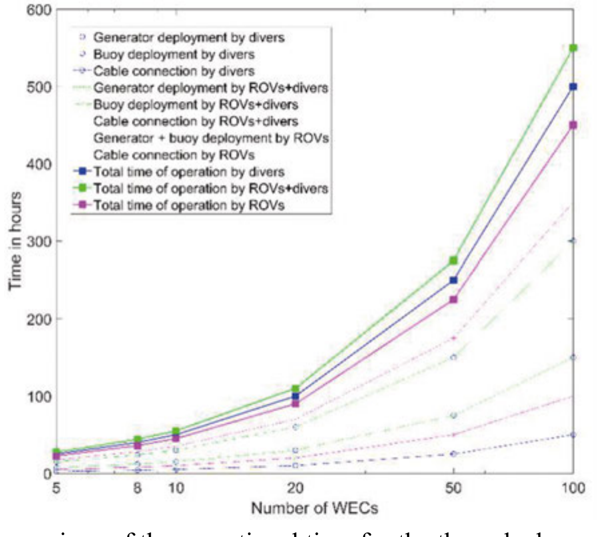


Figure 25. Comparison of the operational time for the three deployment methods and WEC number from 5 to 100

It is seen from the graph in *Figure 24* that method 2 is the most expensive making it the least advantageous, while method 1 is effective for fifteen WECs at maximum, and method 3 is preferable for larger number of WECs. For this difference between methods 1 and 3 the cable connection task is responsible. To perform the cable connection with method 1 involves a 0.5 h dive per

WEC, while with method 3, two ROVs and 0.5 h per WEC are needed. Renting ROVs has a fixed price for a full operational day, thus even if it takes less time to complete a task (e.g. ROVs require less than a day to connect the cables for one to five WECs) the cost has a fixed price. With the WEC number rise, the ROVs are used more cost effectively by performing a larger number of cable connections. With the use of presise connection tools that will require one ROV instead of two, this task expenses would be half.

The deployment time graph in *Figure 25* shows that the installation of five devices takes about the same amount of time for the three methods. Moreover, method 3 is the most time-efficient for 5 to 100 WECs, followed by method 1. Method 3 has two steps to be fullfilled by ROVs while method 1 has three steps carried out by the divers icluding the time consuming, 2 h, and demanding buoy connection task. Using method 2 increases the installation time by 9% compared to method 1, and by 23% in comparison to method 3. This is due to the diver's limitation in the amount and duration of dives. The translator lifting task is time consuming and demanding. With the development of specially designed lifting tools the operational time would lessen and become easier for divers.

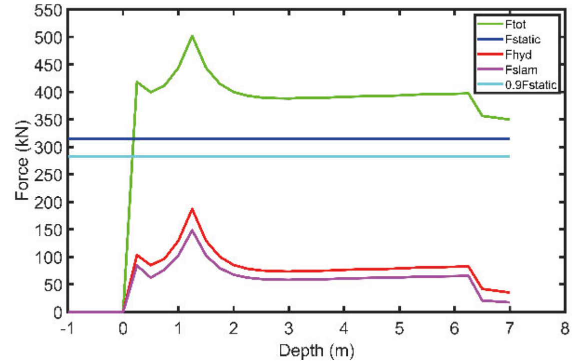
It is evident that especialy for mass installations, method 3 that includes ROVs is preferable than method 1 that employs divers, while method 2 that uses a combination of divers and ROVs is the least cost and time efficient. For maximum five devices the most inexpensive method is 1, while for increasing number of devices method 3 is recommended. All methods take about the same amount of time for the installation of five devices. For the installation of 20 devices with method 3 the cost is reduced to 1/3 in comparison to method 1. Lastly, the divers expenses can triple for depths greater than 30 m while their safety decreases.

Particular attention should be given to lowering the existing high installation costs. Moreover these costs can increase rapidly by a logistics mistake, even double, for example in the case where a vessel was not delivered on time for the operation and another one had to be hired last minute. The final costs as mainly determined by the vessel choice, the automatization level (divers or ROVs) and the transportation costs. For instance, employing a diving team in Sweden can cost from 66 € up to 98 € for one diver/hour [29]. The use of a decompression chamber can raise the diving costs three to four times since it involves a suitable vessel and extra crew.

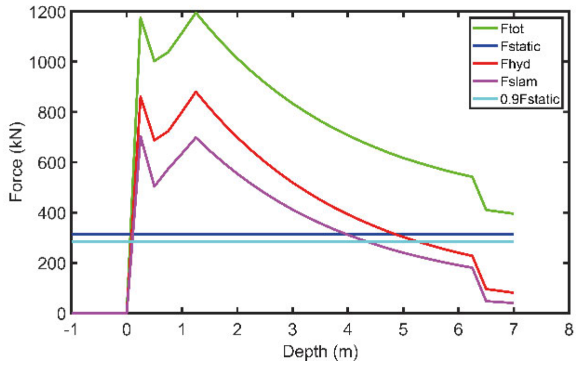
6.4 Hoisting system risk assessment results

6.4.1 Interaction between barge, WEC and waves

Figure 26 illustrates the F_{total}, F_{static}, F_{hyd}, F_{slam} and $0.9F_{static}$ amplitudes of the vessel, in regards to the WEC's submersion from 0 m to 7 m, for 8 s zero crossing period and significant wave height 0.25 m and 1.75 m, and for V_c =0.1 m/s.



(a)



(b)

Figure 26. Forces F_{total}, F_{static}, F_{hyd}, F_{slam} and $0.9F_{static}$ of the barge while installing the WEC, for 8 s zero crossing period and a significant wave height of 0.25 m (a) and 1.75 m (b)

In *Figure 26* (a), the slack sling criterion is met since the $0.9F_{static}$ line is over the F_{hyd} line, unlikely *Figure 26* (b) where the criterion is not met, the operation entails risks and therefore should not be conducted.

6.4.2 Risk assessment of deployment for a hook lowering velocity of 0.1 m/s

The permissive, restrictive and prohibitive operational sea states table for the barge-WEC system and for hook lowering velocity V_c = 0.1 m/s is shown in *Figure 27*.

Hs/Tz	3 s	3.5 s	4 s	4.5 s	5 s	5.5 s	6 s	6.5 s	7 s	7.5 s	8 s	8.5 s	9 s	9.5 s	10 s	10.5 s	11 s	11.5 s	12 s	12.5 s	13 s
0 m	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
0.25 m	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
0.5 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
0.75 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1.25 m	N/A	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1.5 m	N/A	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1.75 m	N/A	N/A	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
2 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.25 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.5 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.75 m	N/A	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
3 m	N/A	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no

Figure 27. Representation of the permitted and restrictive significant wave height amplitudes for each zero crossing period for V_c = 0.1 m/s

The installation of the WEC can be safely installed with the Svitzer Arc barge for sea states of 0 m and 0.25 m significant wave height, and 3 s to 13 s zero crossing period. The installation should be done cautiously for significant wave heights from 0.5 m and up to 2 m and respective zero crossing periods of 3 s to 13 s (warning zone). For significant wave heights 2 m to 3 m and zero crossing period of 3 s to 13 s, the operation is prohibited.

7. Discussion

7.1 Efficiency in WEC deployments

Reviewing Tables 16 and 17, the most economical strategy is the tugboat method with total expenses of 270,000 SEK per deployment day.

In terms of time efficiency, the tugboat approach is the optimal in single-device or up to two WEC deployments, taking 5 h total installation time with Svitzer Thor, including the transportation time to and from the quay. For multiple device deployments, the specialized vessel method is preferable, taking 1.92 hours per WEC installation (Dina Star).

Regarding safety efficiency, both tugboat and specialized vessel methods are the safest, providing safety gunnels and side walls around the vessel to protect the personnel.

The optimal method to follow for mass WECs installation that is also the most cost efficient is the barge-crane approach. Barges provide large decks to fit multiple devices and the crane is chosen regardless the barge, so it can be as fast and high capacity as needed. On the downside, barges operate under smaller operational windows than tugboats and specialized vessels and without careful planning or an unpredicted weather change, delays can occur to result in higher unexpected costs.

Concerning multiple device deployments without a budget restriction, the optimal strategy is hiring a specialized vessel. The large deck, high capacity cranes, the ROVs and its time efficiency is providing value for money long term. However, due to their specialization, these vessels are limited in availability.

In strictly vessel efficiency terms, e.g. being fast, safe and providing suitable equipment, from all vessels reviewed above, specialized ships are optimal (for instance Dina Star and Siem Daya 2). The advantages of these vessels are the mooring GPS, DP systems, ROVs, experienced crew, large decks and high capacity cranes they provide. Moreover, they are operating for 24 hours and under large operational windows. Some can operate in up to 5 m significant wave height and have a "fly-by" policy where mobilization fee is payed when the schedule is flexible (Paper III). However, they are of limited availability due to the high demand (especially from the offshore oil sector) and are expensive (Paper IV).

Table 16. Evaluation of all four deployment methods

Method	Advantages	Disadvantages	Accomplish-ments	Cost	Time
Barge-special structure / Hydraulic jacks	Safe	Slow Hard to maneuver Time loss to mount and demount structure Unsuitable for multiple deployments	Deployed one WEC w/ buoy in a day	2,5 MSEK	12 h/ WEC
Barge - crane	A safe/ fairly safe procedure, depending on the weather Recommended for multiple deployments	Narrow operational weather windows causing delays and increasing costs Restricted maneuverability Positioning problems due to lack of DP system Expensive long-term	Deployed ten WECs	Varying from 880,000 SEK to 1,8 MSEK	8 h/ WEC
Tugboat	Safe Most cost - efficient	Not recommended for multiple deployments Can cause vibration when transporting the WEC which can lead to snapping of the hoses	Deployed two WECs, one with its buoy	270,000 SEK/ day	5 to 6 h/ WEC
Specialized vessel	Safest method Specialized equipment Optimal for mass installations	Most expensive Limited availability	Deployed 25 WECs in 2 days	N/A	1.9-2.7 h/ WEC

Table 17. Optimization in crew number for the three UU deployment methodologies

Method	Optimal crew number employing divers	Optimal crew number using ROV/ ROVs
Barge - special structure / Hydraulic jacks	12 (4 divers, 4 people from the tugboat and 3 from the barge, 1 UU employee)	8 (4 people from the tugboat and 3 from the barge, 1 UU employee)
Barge - crane	13 (4 divers, 4 people from the tugboat, 3 from the barge, 1 crane driver and 1 UU employee)	9 (4 people from the tugboat, 3 from the barge, 1 crane driver and 1 UU employee)
Tugboat	9 (4 divers, 4 people from the tugboat and 1 UU employee)	5 (4 people from the tugboat and 1 UU employee)

7.1.1 Problems encountered during WEC offshore installations

Prominent problems faced so far in offshore deployments of WECs, MSs and MCECs were:

- Delays due to prohibitive weather that subsequently raised the overall costs
- Logistics issues, for example, the failure of delivering a vessel on time for installation
- Entanglement of hoses and wires while the device was transported underwater with a tugboat
- Mooring issues
- Snapping of the pressurizing hose of the WEC, while it was transported underwater with a tugboat. This incident almost destroyed the generator that was filled with water and caused the cancellation of the deployment.

Time efficiency can be hindered by a variety of aspects. First and foremost are the weather circumstances that can keep a barge idle for a lengthy amount of time. Poor weather forecast monitoring and planning can lead to significant time losses. The methods that are most time-inefficient are the barge-crane and the barge-specialized structure strategies. In the first methodology, the use of a barge that has no DP or adequate mooring system, is transported by other vessel (a tugboat), is hard to maneuver and operates under the least sea states than any other offshore operation vessel, causes the time losses. Adding to the above, the maneuverability lost by a specialized structure mounted on a barge, the barge-specialized structure methodology is the most time consuming. Moreover, the lowering pace of this method is the slowest amongst all vessels. Also, when the deployment strategy uses a barge extra time is needed for transportation to and from the deployment spot, positioning and anchoring. The incident of a vessel not arriving on time for the operation has caused delays and extra costs for the last minute vessel rental. Furthermore, having the right equipment beforehand is vital to mitigate the preparation time. Lastly, the simultaneous deployment of the WEC and its buoy can shorten the operational time, while the vessel choice and its mooring abilities can reduce or prolong the operation schedule.

The operational costs depend on several factors, for example crane rent, increasing the expenses the higher its capacity, the choice between hiring ROVs or a crew of divers, and a last minute vessel cancellation that can result to doubling the expenses. The most important cost consideration is the deployment method choice. The most cost-efficient method reviewed so far is the tugboat strategy with total expenses of 270,000 SEK/day in contrast to the barge-specialized structure methodology that costs 2,5 MSEK. The high price of the barge-specialized structure strategy is due to slow submersion pace of the device, and the hydraulic jacks construction that costs extra to make, mount and de-mount of the vessel. Finally, although the specialized vessel method is considered costly, the fact that includes in its price the ROVs, high capacity crane, crew and transportation, makes its price reasonable. The weather is another prominent element affecting the final operational charges as explained in the previous paragraph. The depth at the installation location affects further the deployment cost, with the deeper the area, the more time the process takes and the higher the expenses. [87], [88]

The safety of an offshore task can be jeopardized by the vessel's inefficient mooring, anchoring, and ability of maintaining its steady position, its operational weather windows, the stability of the crane in case it is mounted on the vessel, and inappropriate equipment. The vessel to most probably manifest the previous issues is a barge. Unlike tugboats and specialized vessels, a barge is lacking effective positioning and maneuverability since it is moving by a tugboat and does not have a DP system. Furthermore, a mobile crane is usually mounted on a barge to perform tasks that can further jeopardize the stabilization if not conducted properly. To solve the positioning and anchoring issue of the barge the four point mooring is suggested, meaning the vessels anchoring on each of the vessels four corners, at 200 m distance. Detailed planning and organization, including careful weather monitoring, provision of adequate capacity lifting slings and shackles, and non-rotating wire, is critical for the smooth outcome of the operation. Lastly, the lifting and submerging means should be carefully chosen, for instance, the hydraulic wire jacks are cheaper but more time consuming and complex in handling than a crane.

7.1.2 Vessel selection criteria in WEC deployments

The vessel choice depends on the following:

- The demand and consecutive availability of the vessel
- Its proximity to the operational area
- The budget of the operation
- The installation type (WEC and buoy simultaneous installation, for instance) the dimensions and number of devices to be deployed
- The location sea states, depth, and distance from shore.

In past deployments, vessel choices that were taken with the low cost criterion, were proven expensive in the long-term, more time consuming and complicated in handling than expected. For example, Samson expenses were higher than expected, while Pharaoh and Kanalia barges demanded extra fitting work. Furthermore, in many instances a barge solution resulted in higher-than-expected expenses due to weather-dependent idle days.

7.1.3 Cost- and time-efficiency comparison between the barge-crane and the tugboat methods

A cost and time efficiency comparison was conducted between the barge-crane and the tugboat methodologies for 1 to 10 WECs (Paper II). Since the barge-hydraulic jacks strategy is too time consuming and expensive it was excluded from the comparison. For being disproportionately costly, the specialized vessel method was also excluded.

The time and cost comparison was conducted for a best case scenario, where no delays occurred, to have a clear net view of the operational time and consecutive costs. The expenses calculation for each method follow in Table 18.

Table 18. Cost distribution for the barge-crane and the tugboat methods

Method	Cost distribution
Barge-crane	Tugboat, barge, crane, crew = 600,000 SEK/ day
	Barge rent for preparation = 100,000 SEK/ day
	Divers = 80,000 SEK/day
	Total = 780,000 SEK/ day
Tugboat	Tugboat = 180,000 SEK/day
	Divers = 80,000 SEK/day
	Harbor crane = 10,000 SEK/WEC
	Total = 270,000 SEK / day (1 WEC)

The results are shown in *Figure 28*.

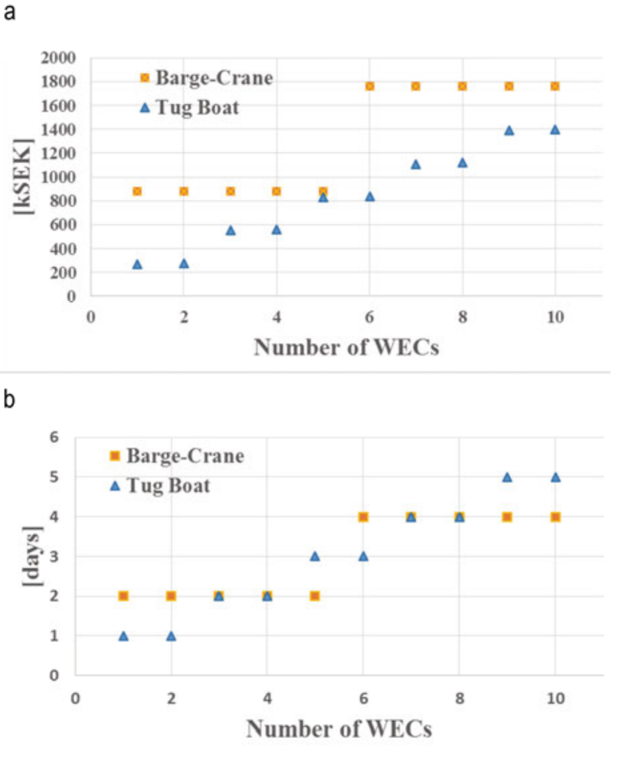


Figure 28. The deployment costs (a) and time (b) for the barge – crane and tugboat methods for one to ten WECs.

To deploy one WEC costs 270 kSEK and takes 1 day with the tugboat strategy, in contrast to about 780 kSEK and 2 days, using a barge with a crane. The second method requires one full day of preparation per 1 to 5 WECs, while the barge operated for consecutive 12 h. On the other hand, the tugboat operates 24 h with shifting crews and demands a minimum preparation time per device, thus can deploy up to 2 WECs per day, with or without their buoys.

The installation of 10 WECs cost 1,4 kSEK for 5 operational days using a tugboat, while hiring a barge the expenses are 1,8 kSEK for 4 days (one preparation and one deployment day for every 5 WECs). A "sudden jump" observed in Figure 28 (a) at the costs using a barge, is because when the operational days are doubled, the costs are doubled as well. Deploying three to four and seven to eight WECs, takes the same time for both methods.

From a cost perspective, the higher efficiency lays on the tugboat method for one device deployment and mass installations. Although time-wise the installation strategy using a barge appears the most efficient, in practice the time efficiency depends in the number of devices to be deployed. Thus, summarizing all aspects, the tugboat methodology is the most efficient, being less costly by several kSEK and for about the same operational time as the barge-crane strategy.

7.2 Suggested deployment methodology for WECs, MSs and MCECs

By reviewing different installation strategies for UU type WECs, MSs and MCECs, a methodology depending on the deployment type can be recommended, as follows in Table 19.

Table 19. Recommended installation method according to operation type

Type of WEC installation	**Suggested method**
Single or two – device deployment	Tugboat
Multiple device deployment with budget restriction	Barge-crane
Multiple device deployment without a budget restriction	Specialized vessel
Simultaneous installation of WEC with its buoy	Tugboat
One MS	Small boat, medium crane, lifting buoys, weights, divers
MCEC of UU type	towing boat, barge, medium crane, ROVs, medium sized truck
MCEC of UU type with double cross- sectional area	towing boat, barge, medium crane, ROVs, large truck with a trailer

7.3 Automatization in deployments

The use of automatic pressurization tools and ROVs facilitate diverless deployments. There are numerous technical challenges in the full automitization of offshore operation using ROVs, for instance the absence of inexpensive and maneuvrable middle class vehicles that could be useful for this kind of operation. Furthermore, there are more ROVs developed for deep waters use in contrast to shallow waters. The wide-spread use of ROVs in such operations would be further promoted with advances in ROV-friendly tooling such as grippers, manipulators, docking systems for stabilization, and drums for cable dragging. Also, ROV-friendly slings, shackles, and electrical connectors, will optimize the use of ROVs [89]. Lastly, experienced and adequetly trained crew to operate the ROVs is a prerequisite.

Using ROVs instead of divers in deployment of WECs can reduce the overall operation duration, and the expenses for installing more than 7 WECs at a time, while the procedure's safety is optimal. For instance, deploying 20 WECs hiring ROVs costs three times less than hiring divers, in the case of UU WEC installations in Lysekil.

7.4 Impact of the hook lowering velocity in deployment operational sea states using a barge for deployment

The results of the investigation of the hook velocity impact on the operational sea states, for V_c equal to 0.25 m/s, 0.5 m/s and 0.6 m/s, are shown in the following *Figures 29, 30* and *31*, respectively.

For V_c equal 0.1 m/s (*Figure 27*) and 0.25 m/s *(Figure 29)*, the permissive operational sea states do not differ notably, with $V_c = 0.25$ m/s increasing the restrictive area of operation from significant wave height 2 m and zero crossing period from 4.5 to 13 s, to significant wave height 1.75 m for zero crossing periods of 4 s to 13 s. The calculations for $V_c = 0.5$ m/s are shown significantly altered permissive sea states *(Figure 30)* compared with the initial (*Figure 27*), resulting in permissive operational wave weather window for 0 m of significant wave height for zero crossing periods of 3 s to 13 s, a warning zone for significant wave heights 0.25 to 1 m for the same zero crossing periods, and prohibitive zone for significant wave height of 1.25 m to 3 m and zero crossing periods of 3.5 s to 13 s. For $V_c = 0.6$ m/s, no permissive operational zone exists, but a warning area for 0 m to 0.75 m significant wave height and zero crossing periods of 3 s to 13 s, and the prohibitive zone is expanded for 1 m to 3 m significant wave height for 3 s to 13 s zero crossing periods (*Figure 31*). In conclusion, as the hook lowering velocity rises, the restrictive installation sea states expand, while the permissive areas lessen.

Hs/Tz	3 s	3.5 s	4 s	4.5 s	5 s	5.5 s	6 s	6.5 s	7 s	7.5 s	8 s	8.5 s	9 s	9.5 s	10 s	10.5 s	11 s	11.5 s	12 s	12.5 s	13 s
0 m	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
0.25 m	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
0.5 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
0.75 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1.25 m	N/A	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1.5 m	N/A	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1.75 m	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.25 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.5 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.75 m	N/A	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
3 m	N/A	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no

Figure 29. Representation of the permitted and restrictive significant wave height amplitudes for each zero crossing period for V_c = 0.25 m/s

Hs/Tz	3 s	3.5 s	4 s	4.5 s	5 s	5.5 s	6 s	6.5 s	7 s	7.5 s	8 s	8.5 s	9 s	9.5 s	10 s	10.5 s	11 s	11.5 s	12 s	12.5 s	13 s
0 m	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
0.25 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
0.5 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
0.75 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1.25 m	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
1.5 m	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
1.75 m	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.25 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.5 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.75 m	N/A	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
3 m	N/A	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no

Figure 30. Representation of the permitted and restrictive significant wave height amplitudes for each zero crossing period for V_c = 0.5 m/s

Hs/Tz	3 s	3.5 s	4 s	4.5 s	5 s	5.5 s	6 s	6.5 s	7 s	7.5 s	8 s	8.5 s	9 s	9.5 s	10 s	10.5 s	11 s	11.5 s	12 s	12.5 s	13 s
0 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
0.25 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
0.5 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
0.75 m	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution	caution
1 m	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
1.25 m	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
1.5 m	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
1.75 m	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.25 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.5 m	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
2.75 m	N/A	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
3 m	N/A	N/A	N/A	N/A	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no

Figure 31. Representation of the permitted and restrictive significant wave height amplitudes for each zero crossing period for V_c = 0.6 m/s

8. Conclusions

Offshore deployment operations are complex procedures where many key aspects must be considered, besides the technical ones. The use of appropriate equipment and precise planning is crucial in these operations.

The most cost and time efficient WEC deployment method for single or two-device deployment, simultaneously with their buoys, is the tugboat method. The overall cost of this method is 270,000 SEK/day and the completion time 5 to 6 h per WEC.

The UU MCEC can be safely deployed using a barge of "Svitzer Arc" type, for up to 0.25 m significant wave height and 3 s to 13 s zero crossing wave periods. In the operational safety calculations, the hook lowering velocity (V_c) plays a significant role, considering that the higher it gets, the more restricting it is to deploy.

9. Future work

A risk assessment of a crane hoisting system during installing a device in different sea states should be extended to some other types of vessels (e.g. multipurpose, tugboats) and different types, dimensions and number of devices. Moreover, advanced vessel-device simulations of responses in the hoisting system can be performed, where the hydrodynamic model includes impact of vessel moorings, currents and/or wind.

Advances towards automatization in offshore procedures should be implemented. For example, ROV-friendly shackles and lifting points, used on the devices, would lower the overall operational time and promote the extensive use of ROVs.

The number of marine energy converters to be deployed in contrast to their dimension should be further investigated. This will determine whether it is more efficient, in terms of power output and cost, to install more of the smaller devices or fewer in number but larger in cross-sectional area.

Lastly, the design and construction of a state of the art vessel, particularly for offshore installation of WECs, MSs and MCECs should be implemented. This vessel should have the ability to install many types of marine energy devices of various dimensions. This vessel would substantially facilitate and optimize the installation procedure from a cost, time and safety perspective.

10. Svensk sammanfattning

Elproduktion från förnybara energikällor blir alltmer populär i vårt samhälle. Detta är främst en följd av de negativa effekterna på klimatet, men beror även delvis på vetskapen att fossila bränslen är en begränsad energikälla. Förnybar energi kommer från sol, vind, värme, biomassa och vatten. Dessa energikällor är oändliga och omvandlingsteknologin har dessutom begränsad miljöpåverkan i kontrast till nuvarande konsumtion av fossila bränslen. Avdelningen för elektricitetslära vid Uppsala universitet har mångårig erfarenhet inom förnybar marin energi (sedan 2002). Vågkraftgruppens fokus ligger på att extrahera energi från havsvågor och konstruera och bygga vågkraftverk (WEC), medan marin strömkraftgruppen har utvecklat ett marint strömkraftverk (MCEC) i syfte att utvinna energi från marina strömmar.

Vågkraftverket är en punktabsorbator med direktdriven permanentmagnetiserad synkron linjärgenerator (PTO). Det marina strömkraftverket är riktningsoberoende när det gäller energiabsorption. Den vertikalaxlade strömturbinen är ansluten till en direktdriven permanentmagnet synkrongenerator. Vågkraftverket placeras på havsbotten i en vattentät behållare, monterad med ett betongfundament, medan strömkraftverket använder ett stålstativ som förankringfundament.

Marina energiomvandlare är komplicerade, kostsamma och tidskrävande att installera. De höga kostnaderna i samband med offshore-installation av marina energiomvandlare är ett hinder för en utvidgad kommersialisering. Vidare innebär offshore-utplaceringar ökade risker, exempelvis finns restriktioner som gäller dykare vid undervattensarbete och det finns en risk för haveri hos liftsystemet. Även havsmiljöns förrädiska väderlekar begränsar och försvårar verksamheten.

För att säkerställa att offshore-installationerna ska genomföras smidigt och riskfritt bör design och planering vara noggranna och väl genomtänkta. Dessa skall noga granska och ta hänsyn till utbyggnadplatsens rådande väder och sjöförhållanden. Den bör innehålla en detaljerad granskning av både tidsplan samt ekonomisk kalkyl över installationens förfaringssätt, uthyrning av fartyg, utrustning och den aktiva besättningen. Detta för att optimera och identifiera den mest effektiva operativa metoden. Slutligen bör planeringen innehålla riskbedömningar, exempelvis över liftsystemets begränsningar och skick för att garantera säkerheten i drift.

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12. Summary of papers

Paper I

Offshore deployments of Wave Energy Converters by Seabased Industry AB

This paper reviews and evaluates the offshore deployments of WECs that were carried out by and for Seabased Industry AB. The WECs manufactured and deployed by SIAB are for commercial purposes. All these deployments were successful. The most important conclusions derived from this study were that the overall costs increase the deeper the deployment waters become; a large, specialized crew and a DP system are necessary; the use of ROVs can lower the costs and a specialized vessel can optimize the deployments.

The author performed most of the work in writing this paper which was accepted and published online in the Journal of Marine Science and Engineering on the 25th of March 2017. doi:10.3390/jmse5020015.

Paper II

Offshore deployments of Wave Energy Converters by Uppsala University

This paper studies and evaluates the offshore deployment methods followed by Uppsala University during a time span of eleven years. All WECs deployed were designed and manufactured by UU. By studying the three methods of deployment, namely, a) the barge–crane method, b) the hydraulic wire jacks method and c) the tugboat method, the last proved to be the best in terms of economic efficiency and time efficiency.

The author performed most of the work in writing this paper and participated in some of the deployments described. This paper is re-submitted to Marine Systems & Ocean Technology Journal in 2018 as a technical paper after the editor's suggestion.

Paper III

Marine Current Energy Converters deployments modelling

Paper III, presents a marine current energy converter deployment case study for Norway. Using actual cost and time data, two deployment scenarios are evaluated in cost and time efficiency terms, for a MCEC of the UU type. The same scenarios were repeated for the same type of MCEC but with bigger turbine cross-sectional area, to deliver double power output. The research was conducted for the installation of 1 to 100 devices. The main method of this study was a MatLab implementation of Monte Carlo method. The deployment methods described in the paper can be implemented in more MCECs of various types. The most efficient installation scenario reviewed is III, using a barge for offshore deployment and a large truck for inland transportation of the MCECs.

The author performed most of the work in writing this paper, which was submitted for peer review at the Journal of Cleaner Production.

Paper IV

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

This paper evaluates the use of ROVs vs the employment of divers for the installation, maintenance and monitoring of UU WECs at the Lysekil research site. The evaluation is conducted from a safety, cost and time efficiency perspective. Although it is shown that using ROVs is preferable over hiring divers, the broad automatization in this operations is hindered by the lack of appropriate tooling and ROV-friendly shackles and grips. Moreover, a comparison of the cost efficiency of renting and of buying an ROV is presented.

The author contributed in writing this paper, which was published in the Journal of Marine Science and Engineering on 12 of April, 2018. https://doi.org/10.3390/jmse6020039.

Paper V

Hydrodynamic responses of a barge deploying an Uppsala University Wave Energy Converter in different sea states

Paper V focuses on the hydrodynamic responses of a deployment barge–WEC system with the waves during the WEC's submersion. The hydrodynamic simulations performed for both the barge and WEC for wave heights 0 m to 3 m and wave periods 3 s to 13 s. The formulas of total, hydrodynamic, static, drag, hydrodynamic mass and characteristic impact slam were utilized to calculate all forces for the above wave conditions. The outcome of this study is a safety-in-operations table that shows the permissive, cautionary and restrictive combinations of wave heights and wave periods, under which an installation operation is performed.

The author performed most of the work in writing this manuscript that is submitted to Reliability Engineering & System Safety Journal for peer review.

Paper VI

Offshore deployment of point absorbing Wave Energy Converters with a direct driven linear generator power take-off at the Lysekil test site

In this paper, the basic principle of the UU WECs is described briefly and the basic steps of a WECs offshore deployment are presented. Also, the main problems occurring at a deployment are presented, namely, the technical problems and the time efficiency and the economic efficiency. In conclusion, these offshore operations entail both avoidable and unavoidable expenses but good management and accurate organization can optimize the process.

The author performed most of the work in this paper that is a peer-reviewed contribution at the 33rd International Conference on Ocean, Offshore and Arctic Engineering conference, OMAE2014, at San Francisco, California.

Paper VII

Offshore Deployment of Marine Substation in the Lysekil Research Site

In this conference paper, a brief description of the MS's electrical and mechanical layout as well as its characteristics are presented. After choosing the MS positioning for the specific UU operation, which is on the seabed, a deployment method was chosen and described. Moreover, the advantages and disadvantages of this method are discussed and the deployment method is evaluated.

The author performed most of the work in peer-reviewed contribution at the ISOPE 2015 conference, at Kona, Big Island.

Paper VIII

Wave Energy Research at Uppsala University and the Lysekil Research Site, Sweden: A Status Update

The focus of this conference paper is to present the Lysekil project updates that occurred since 2013. The UU WEC and MS concepts are described and an overview of all the different components installed at the site is given. Moreover, the latest results of the wave power group are described, notably, the use of ROVs for underwater connections, research on the environmental impacts of large energy farms, the deployment operations, the new buoys and force measurements, a tidal compensation system and the improved electrical and measuring systems

The author has participated in the deployments and experimental work at the site from the year 2013 until today. This paper is a conference peer-reviewed contribution, presented by Arvind Parwal at the 11th European Wave and Tidal Energy Conference, EWTEC 2015, at Nantes, France.

Paper IX (a)

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

An electric power conversion system is comprised by various components, such as rectifiers, filters and inverters. Paper IX (a) presents Lysekil's electric power conversion system, with the focal point being on the inverter and the filter used. The experimental results from Lysekil's wave power system (WEC park and power conversion unit) grid integration are included. The importance of the power smoothing in grid connection is emphasized.

The author participated in the experimental work described in this paper. This peer-reviewed paper is included in the 5th International Conference on Electric Power and Energy Conversion Systems (EPECS), 2018; DOI: 10.1109/EPECS.2018.8443488.

Paper IX (b)

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

Paper IX (b) focuses on the grid connection of an array of WECs in Lysekil, located at the west coast of Sweden. This connection is accomplished through an electric power conversion system (EPCS) specifically designed for the Lysekil wave energy park. The control system used in Lysekil research site is furtherly analyzed.

The author participated in the experimental work described in this paper. This manuscript is an extension of conference paper IX (a) and is submitted to IET Smart Grids.

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