THREE YEARS PROMOTING THE DEVELOPMENT OF

MARINE RENEWABLE ENERGY IN CHILE

2015 - 2018

marine energy research & innovation center

2015

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MARINE RENEWABLE ENERGY IN CHILE

2018

MERIC (Marine Energy Research & Innovation Center)
Energia Marina SpA
www.meric.cl
Apoquindo Avenue 2827, 12th floor, Las Condes, Santiago de Chile.

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THREE YEARS PROMOTING THE DEVELOPMENT
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Edited by Dernis Mediavilla
dernis.mediavilla@meric.cl

Design and Layout by Yasna Saravia
yasna.saravia@meric.cl

Detailed editing of Research and Development chapters by Philip D. Somervell and Felipe Somervell Baudoin.

CONTENTS

The goal of this document is to present and share the R&D work performed by MERIC - Marine Energy Research and Innovation Center during its first three years of implementation (2015-2018). There are ten main chapters, representing each of the R&D projects that have been actively contributing to MRE applied knowledge and know-how in Chile. These are organised in three main general sections: Resource Assessment and Technology, Interaction with Marine Ecosystem, Social and Economical Aspects. An effort has been made to preserve the original character of the texts, aligned with the intrinsic heterogeneity of the project teams, which gather academic, private and public participants.

We thank the support given by all MERIC's team to create this document. Being fully aware that is a magnanimous task to condensate such amount of work in a document, we hope that this Report honors the effort made this three years to trigger the development of Marine Renewable Energy in Chile.

EXECUTIVE DIRECTOR

Luc MARTIN

INTRODUCTION OF OUR DIRECTOR

I am proud to present the first three years of MERIC's researchers and experts team work: a first step of accomplishment in building new competences in Chile, in publishing interdisciplinary R&D results in Marine Renewable Energy for Latin America and in involving Chile as a major actor in Marine Renewable Energy at worldwide level.

Chilean renewable energies´ policy has been a real success within the past five years, drawing up the benefit of Chilean unique natural resources, taking advantage of long and anticipated R&D investments made decades ago in the rest of the world in solar and wind technologies, and demonstrating the competitiveness of non-conventional renewable energy (NCRE) projects against fossil fuel market-based energy production. There is a long way to go before Marine Renewable Energy (MRE) can become competitive at grid connection level; but already in Europe, some MRE projects are showing economical pertinence for isolated or far remote sites.

Chile is one of the most gifted countries in the world for its MRE resources. To comply with the 2040-2050 objective of 100% of Renewable Energy in Chile, the development of a portfolio of Renewable Energy technologies production adapted to Chilean environmental conditions and including MRE is mandatory. More than 6000km of Pacific Ocean shoreline with permanent availability of energy coming from wind, waves and tides make Chile an attractive country, not only for its energy potential production, but also as a unique natural laboratory, offering possibilities to study real extreme events' impacts on systems at sea.

The insertion of MRE into the energy matrix will induce innovative solutions in terms of prediction, availability and stability. As an International Center of Excellence, MERIC is triggering exchanges at international level, gathering in Chile high level researchers in interdisciplinary fields and collaborating at national and at international levels. It answers challenges of site characterization and technology adaptation altogether; its researchers and experts work on corrosion resistance, biofouling comportment, sustainability and survivability, environmental and social impact and technology design adaptations.

MERIC's R&D is driving the sustainable development of MRE in Chile. It suggests solutions for technology survivability under extreme conditions and builds competence in order to develop opportunities locally. I invite you to know more and to be a part of our work, where Chile is an international reference on MRE generation.

MERIC'S TIMELINE

2013 | December: The Ministry of Energy together with CORFO, launched public call for fundings "Attraction of International R&D Centers of Excellence in Marine Energy".

2014 | April: MERIC's proposal is submitted.
October: Awarding of the call for fundings to Naval Energies' proposal.

2015 | Signing of the agreement by Energía Marina SpA.
March: 1st Annual Coordination Meeting.
October: Initiation of activities of MERIC - Marine Energy Research and Innovation Center.

2016 | March: 2nd Annual Coordination Meeting.
July: MERIC's inauguration at ECIM-UC, Las Cruces, Valparaíso Region.
November: MERIC, Universidad Austral de Chile and Pontificia Universidad Católica de Chile, jointly organized the "2nd International Wave & Tidal Energy Workshop".

2017 | March: 3rd Annual Coordination Meeting.

2018 | March: 4th Annual Coordination Meeting.
October: Celebration of "The 3 years of MERIC", at Hotel Crowne Plaza, Santiago.
November: MERIC, Universidad Austral de Chile and Pontificia Universidad Católica de Chile, jointly organized the "3rd International Wave & Tidal Energy Workshop".

2019 | March: 5th Annual Coordination Meeting.
October: Concluding MERIC's Stage 1.

2023 | October: Concluding MERIC's Stage 2.

ABOUT US

Project supported by

Funded by

Partners

OUR ORGANIZATION

The Marine Energy Research and Innovation Center - MERIC- was established in 2015, funded by Naval Energies with Enel Green Power, as a result of the public call for fundings launched on 2013 by The Ministry of Energy together with CORFO, called “Attraction of International R&D Centers of Excellence in Marine Energy”.

In MERIC we develop applied research of international level, conducted by a multidisciplinary team of professionals committed with our mission. Our Partners are Pontificia Universidad Católica de Chile, Universidad Austral de Chile, Fundación Chile, Inria Chile and Enel Green Power.

OUR MISSION

To drive sustainable development of Marine Renewable Energy, from a multi-disciplinary Research and Development open platform, suggesting solutions for technology survivability and enabling the sustainable development of Marine Renewable Energy in extreme conditions from Chile.

OUR VISION

Becoming an international reference in Marine Renewable Energy applied research, delivering global solutions for extreme conditions survivability and sustainability.

R&D PROJECTS

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Resource Assessment and Site Characterization
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Numerical Modelling of Hydrokinetic Turbines Immersed in Complex Topography Using Non-Rotative Actuator Discs.
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RESOURCE ASSESSMENT AND SITE CHARACTERIZATION

Cristián Escauriaza, Rodrigo Cienfuegos
Leandro Suárez, Felipe Lucero, Jorge Sandoval
Clemente Gotelli, Jaime Cortés

Pontificia Universidad Católica de Chile, Santiago, Chile
Marine Energy Research & Innovation Center (MERIC), Santiago, Chile

INTRODUCTION

Technologies for extracting energy from waves and tidal currents have not yet reached a full state of maturity to enable them to be incorporated extensively on power grid interconnected systems. Recent studies have identified the potential of many coastal areas that can provide significant energy resources in the near future, but their implementation will need to overcome challenging technical, environmental and economic aspects, which are also specific to each site. In this research project, we intend to focus on research and development to identify and quantify tidal and wave energy potential and interactions with Marine Renewable Energy (MRE) devices at selected sites.

For marine energy devices to optimize their production, it is also necessary to predict the natural resource behaviour and its future evolution, providing also information to anticipate the cost of energy on the long term. At the same time, we need to consider the extreme events, such as earthquakes, tsunamis and storm surges that are present along Chile. All this information will impact the operation and maintenance of MRE technologies, and, therefore, site selection, supply chain needs and final cost of energy.

To advance on resource assessment R&D, we must analyse the natural water systems in a wide range of spatial and temporal scales, from local impacts at a device scale, to the long term impacts at a regional scale. The level of precision varies according to requirements and the stage of development of the MRE project, ranging from pre-site selection to turbulence dynamics and its impact on turbine performance.

All the skills we are developing, along with the advanced body of knowledge we are building, will facilitate the planning, installation, operation, and maintenance of devices in future energy developments. A reliable estimation of the energy resource is of great importance to assess the available power to extract from the ocean and select the suitable sites for a marine energy project development to be sustainable in the long run. On the other hand, a detailed and accurate resource estimation is fundamental to find and characterize the potential locations for future installations, and evaluate the impacts and interactions between the devices themselves.
The objective of our project is to support the different stages of MRE project development along Chile in the phases of resource assessment and physical site characterisation. To obtain a detailed characterisation of marine energy resource, from tidal and wave, we combine laboratory experiments, numerical modelling and fieldwork.

Wave Energy Resource Assessment

The coast of Chile is affected by one of the most complex and energetic wave climates around the globe. This creates a truly unique energy opportunity for the country, but also poses a major challenge for the design of Wave Energy Converters (WEC), their deployment and operation. It is thus necessary to greatly improve the knowledge on wave conditions and processes that affect the coast of Chile, both from a scientific point of view and for future operational purposes. Chile has often been identified as a region with large wave energy potential in global wave energy resource assessments (40~90 kW/m). However, wave energy can have a substantial variability both in space and time which needs to be properly characterized in order to identify and quantify the supply potential of each location, and eventually identify optimal locations for development. To accomplish this objective, numerical models are used to properly characterize wave energy behaviour along the Chilean coast. In a first step, these models must be calibrated and validated using fieldwork to compare between the model's output data and measurements. After this process is successful, these models are coupled with other type of models which are capable to work with a finer resolution, and thus estimate the wave power range in the study site. All this information generated is useful for solving the substantial lack of measurements currently existing in Chile.

A. Wave Energy Assessment in the Central-South Coast Of Chile

An assessment of the wave energy resource in nearshore waters along the central coast of Chile (Lat.:32.5˚S to 42.5˚S) was performed (Figure 1 and 2). The assessment is built upon the combined use of hindcast and measured data collected specifically for this goal. Offshore and nearshore data at a number of locations were collected with buoys and ADCPs (Acoustic Doppler Current Profiler), with dwell times ranging from three up to 12 months. These were used to assess the accuracy of modelled data at both offshore and nearshore locations. Modelled offshore data comprises three hourly sea states obtained from a third generation ocean wave model, covering the 1989-2013 period, thereby allowing long-term estimates. By using the SWAN (Simulating Waves Nearshore) wave model, this data was propagated to the nearshore shallow waters to obtain modelled wave climate along the entire section of coast. Validation results indicate good model performance, where both offshore and nearshore results are within 10% of the measured data, with an over prediction of wave power. The long-term wave power estimates show an increase of the median power with increasing latitude, fluctuating between 20 and 35 kW/m in areas near to the coast. Monthly and seasonal variability also increase with latitude, with higher energy events present during the winter season. These results are qualitatively consistent with previous assessments in the area, albeit the present results are consistently 5e10 kW/m smaller, which suggests that previous non-calibrated assessments may have overpredicted the wave power by about 20%.

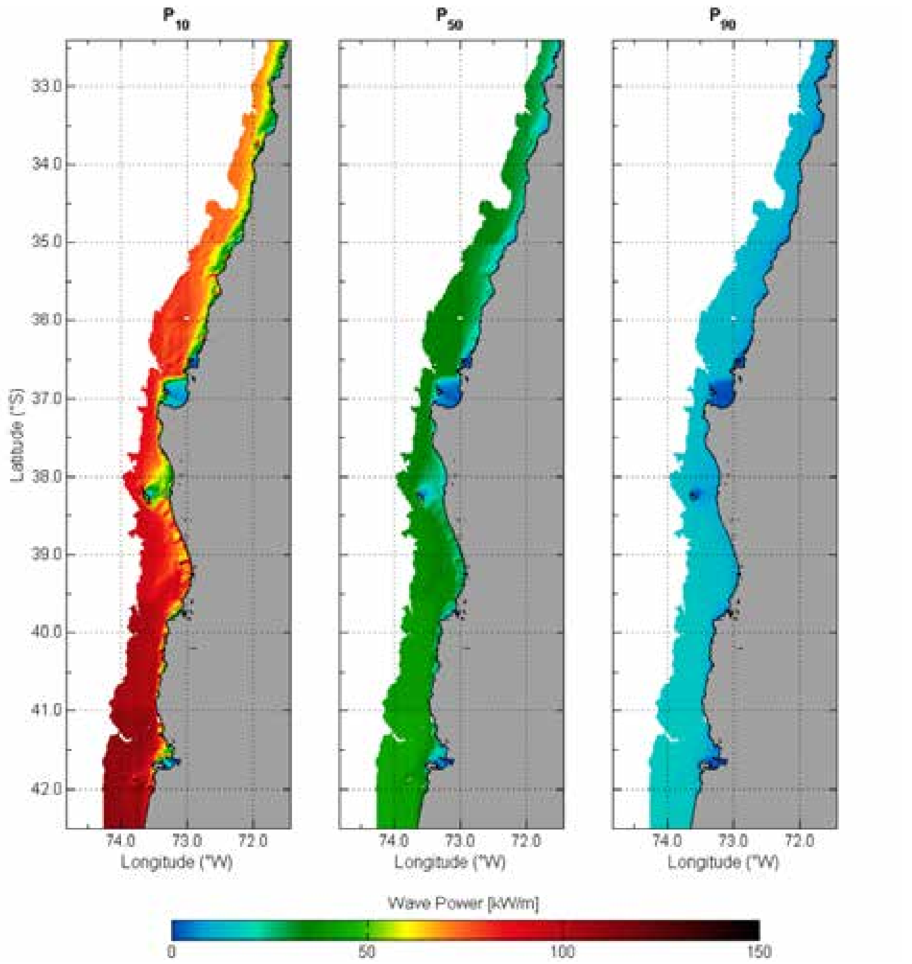


Figure 1: Wave power map (P10, P50, P90), total study site. (source: Lucero et al., 2017)

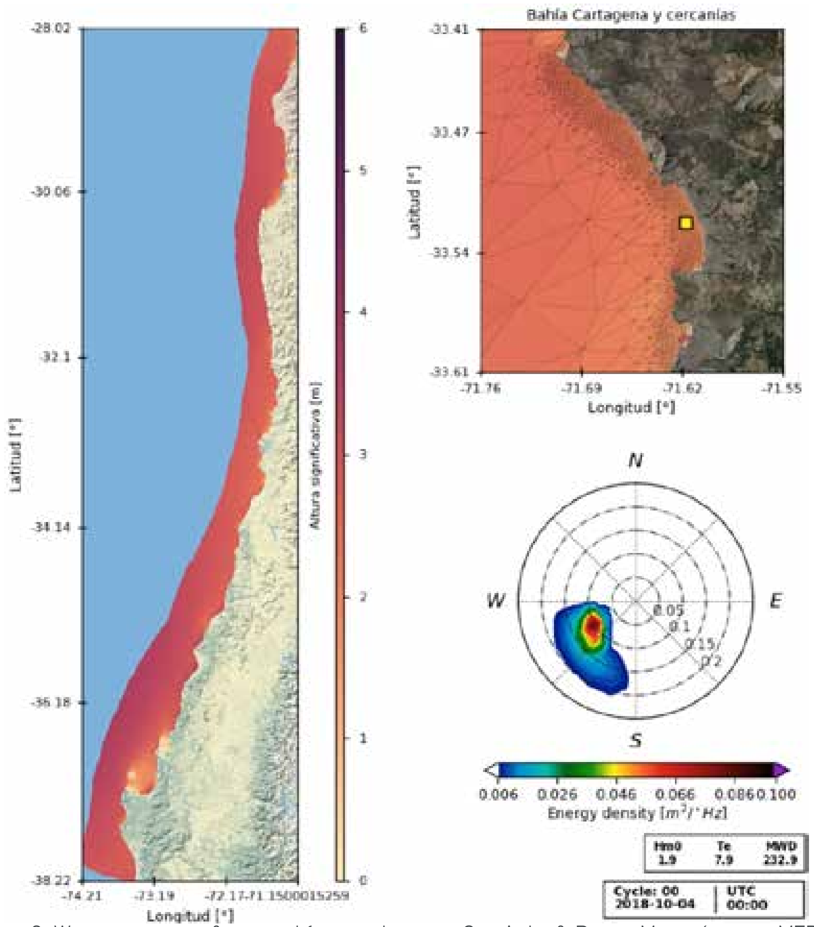


Figure 2: Wave parameters & spectral forecast between Coquimbo & Puerto Montt. (source: MERIC)

B. Forecasting

Worldwide wave forecasting systems are well developed in countries such as the United States, Spain, France and Australia, where most of them use WaveWatch III model as a global model. The main results of the forecast show significant wave height and average wave direction in a time window of up to a week. The information is available to the entire community through their respective websites.

Up to now, in Chile there is a wave forecast system[1] that presents its results in the same way, using regular grids with the WaveWatch III model. Nearshore (specifically state ports) a forecast is available from a node in each of the ports, where a spectral transfer technique was used for its estimation. This technique has been validated but presents problems which are typical of the consideration of linearity in their assumptions, thus in bays that are protected from the predominant incident wave, and in general where processes such as diffraction and reflection occur.

1 http://oleaje.uv.cl/pronostico.html

Therefore, it is necessary to complement the forecast in deep waters with forecasts that are able to reach the areas of interest of the community (ports, beaches, coastal cities, among others) as well as for the development of marine energy, since having this information as public knowledge will help to generate resilience in the community when faced with frequent events on the Chilean coast, such as storms. On the other hand, it will help to evaluate the potential impacts caused by waves at the coastal areas, in order to alert both port authorities and the coastal community as a whole (fishermen, nautical tourism, sportsmen, etc.) and so eventually offer prevention alerts, avoiding damage to infrastructure as well as the safeguarding of human lives.

This forecast will impact the development of marine energy in Chile, mainly helping technology developers to manage windows of maintenance and operation of the devices. On the other hand, it could also be coupled to time-domain models, so the information delivered by this model in real time (over a forecast window for the next 12 hours for example), will help some types of devices to adapt to optimal conditions in this time window and thus improve technical efficiency.

C. Sea State Partitioning

Valparaiso (33°S, 71.6°W) is one of the main commercial and touristic harbours in Chile. This study area presents frequent annual storm events that generate floods and port closure, while also damaging the infrastructure. Although the damages in each storm event are quite similar, their origins differ noticeably according to the season of the year. Extreme events (energetic events in terms of significant wave height) do not systematically generate significant damage on the coast.

Using a sea state partition, it is possible to identify undetectable sea states arriving from non-dominant directions to the study zone. Damages in the study zone might be related not only to the presence of an energetic event, but also to the direction where the bay does not have protection (NW direction for Valparaiso Bay, see Figure 3 for an example). These events are present in 3% of the cases (same order of magnitude as energetic events).

When modelling the propagation of these events to near-shore, the use of wave parameters (without partition) will not propagate events with less energy and more than one direction. This could generate uncertainties on the estimation of extremes, which will affect to the dimensioning, configuration or installation of MRE systems.

In conclusion, an analysis of a potential site of interest for the installation of MRE devices must contain not only energy resource characterisation, but also: propagation of waves to near-shore with spectral data; extreme (energetics) analysis, and impact assessment of sea state coming from different directions to the study site, even if they are considered to be "less energetic".

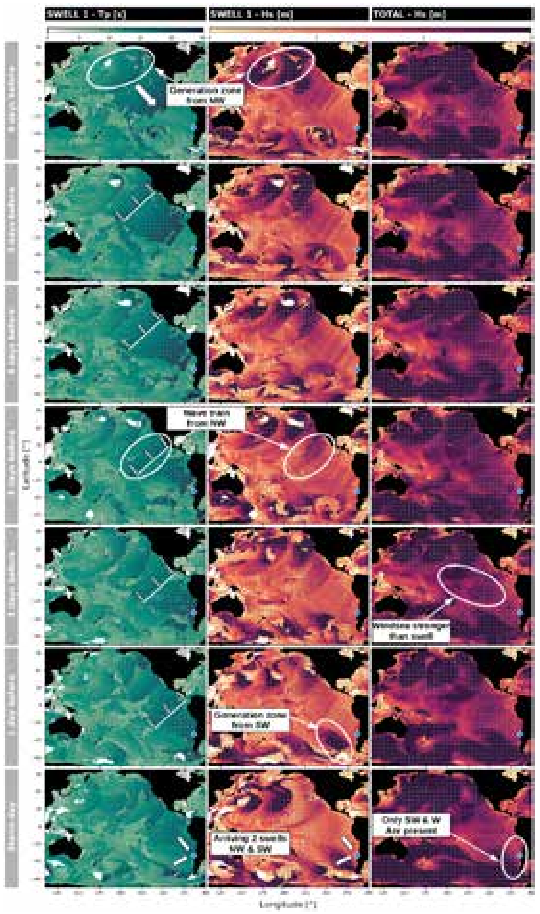


Figure 3: One week time-lapse of summer storm: 1st & 2nd column Swell (Tp, Hs) and total Hs in the 3rd column). (source: Lucero et al., 2018)

Tidal Energy Resource Assessment

The development of new technologies to harness energy from tidal currents in coastal areas requires an in-depth understanding of the interactions between the natural flow over arbitrary bathymetries and the marine hydrokinetic (MHK) turbines that can be potentially installed at a given site. Tidal energy is an attractive alternative to generate clean and reliable electricity, but many of the effects that turbines have on the environment are yet to be fully understood. The design of turbine farms and the evaluation of their environmental impacts also require a multi-scale approach, from a local scale in the vicinity of the devices to a larger scale comprising the entire coastal region.

In spite of recent advances in the study of the flow hydrodynamics in the presence of turbine arrays, there is still the need to develop numerical models and experimental research, coupled with field data, to understand the interactions generated by multiple devices and their impacts on aquatic environments. The greatest difficulty for MHK flows research arises from the complex interactions that occur among the turbines, and their local and large-scale environmental impacts. These are closely linked to the flow field generated by multiple devices, which can alter the local and regional hydrodynamic conditions, along with potential sediment transport, potential chemical, acoustic, and electromagnetic effects.

A. Laboratory Experiments: Scaled Turbine Models In Flume Tanks

By using scaled models of existing turbines, we can study the interaction between multiple turbines, and their design and relative position optimisation. Laboratory experiments and numerical modelling are used to estimate the impact of several devices at a larger scale.

Experiments were performed in laboratory flumes with scaled turbines of OpenHydro and Sabella (Figures 4 to 7) to understand the wake formation, as well as the interaction of the turbines with a mobile bed. These experimental results are then used to validate advanced numerical models at local scales and assess the device efficiency, the interaction between devices and the potential environmental impacts.

To obtain experimental results in a laboratory flume that can be scaled to real MHK turbines, it is necessary to ascertain that the physical phenomena are similar to those that happen at the original scale. In our case, for the scaled turbine design, we apply a geometric similitude, and Tip Speed Ratio (TSR) similitude (a dimensionless number that represents the ratio between the flow velocity and the rotation velocity of the turbine blades). We are currently working on a scaled turbine control system to perform experiments at a fixed TSR, and on a device that measures the torque inside the turbine hub to obtain more detailed results regarding the forces acting on the turbine blades.

In the laboratory flume of the Departamento de Ingeniería Hidráulica y Ambiental (DIHA) at the Pontificia Universidad Católica de Chile (PUC), we study the interaction between the flow at a constant speed and a scaled turbine, measuring mean velocity and Turbulent Kinetic Energy profiles using ADVs (Acoustic Doppler Velocimeters) in various flume sections. Acoustic experiments are also underway, to estimate the noise impact on a scaled turbine.

Figure 4: Acoustic measurements performed at the laboratory flume at DIHA-PUC, using an AS1 hydrophone, with a scaled Sabella turbine.

We are collaborating with the Saint Anthony Falls Laboratory, from the University of Minnesota, studying the interaction between two scaled turbines in terms of efficiency, but also erosion patterns on the mobile bed. Preliminary results show that the turbine downstream has an efficiency loss and an increase in the variability of its performance.

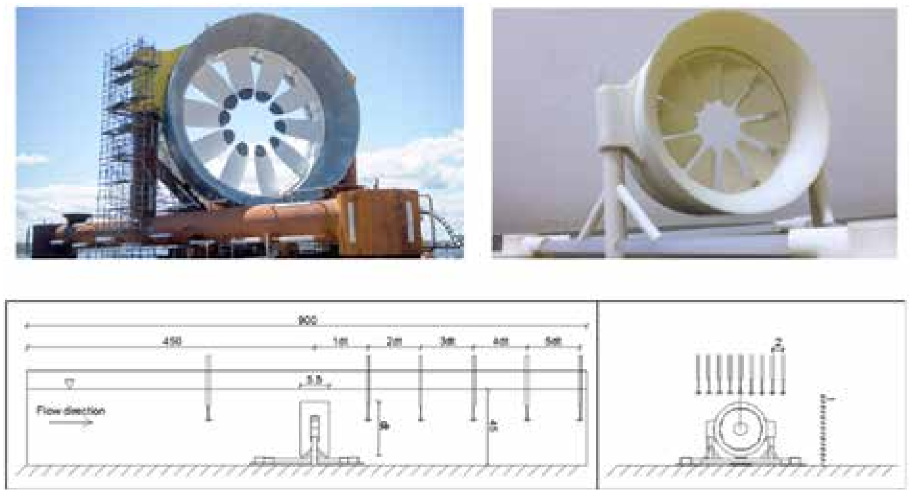


Figure 5: Experimental setup of the ADV measurements on the laboratory flume at DIHA-PUC. Scaled turbine from the OpenHydro turbine.

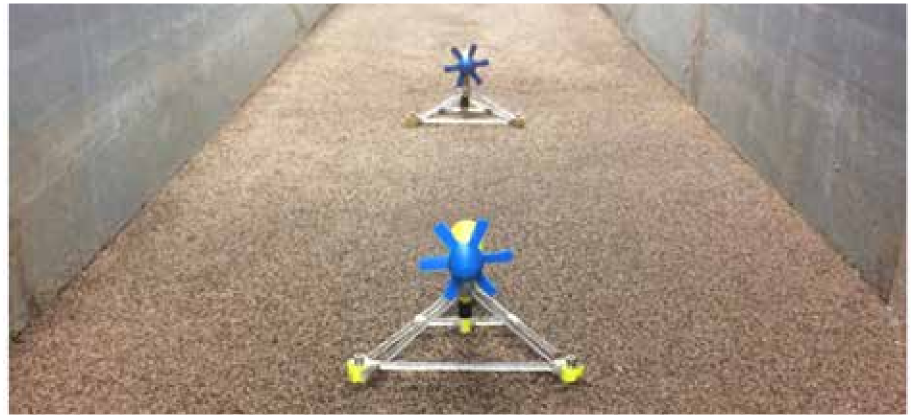


Figure 6: Experiments performed at the Saint Anthony Falls Laboratory, University of Minnesota, using scaled Sabella turbines.

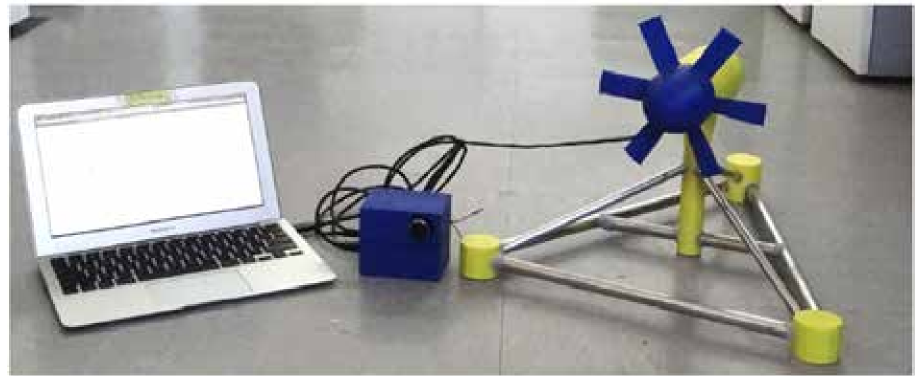


Figure 7: system to control the blade rotation and measure torque in a Sabella scaled turbine, using Arduino.

B. Numerical Modelling: Flow-Turbine Interactions

The interaction of turbine wakes in an array increases the complexity of the flow and it can change the turbine performance. Numerical approaches have been performed to analyse these flows, but there have been few studies that incorporate flows with multiple devices. Questions remain about the selection of turbulence models and turbine representations, since more realistic but computationally expensive methodologies do not necessarily produce an improvement of the understanding of these flows. During this research, we perform simulations of turbine arrays to study the hydrodynamics of wakes and their interactions, comparing with experiments and previous simulations (Figures 8 to 10). We propose a methodology that couples detached-eddy simulations (DES) with Blade Element Momentum (BEM), showing that, by capturing the dynamically-rich coherent structures of the flow, we improve the description of mean quantities and turbine performance. The results show that for downstream turbines, there is an accelerated wake development, increasing the temporal variability of the shear stress on the bed, and the power and thrust coefficients.

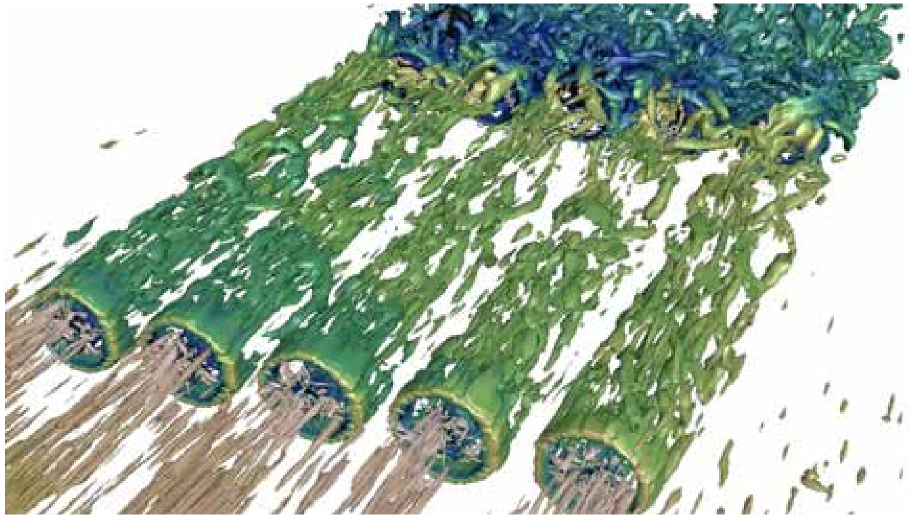


Figure 8: Q-isosurfaces from an array of 10 turbines modelled using Blade Element Momentum (source: Gajardo et al., currently under peer review)

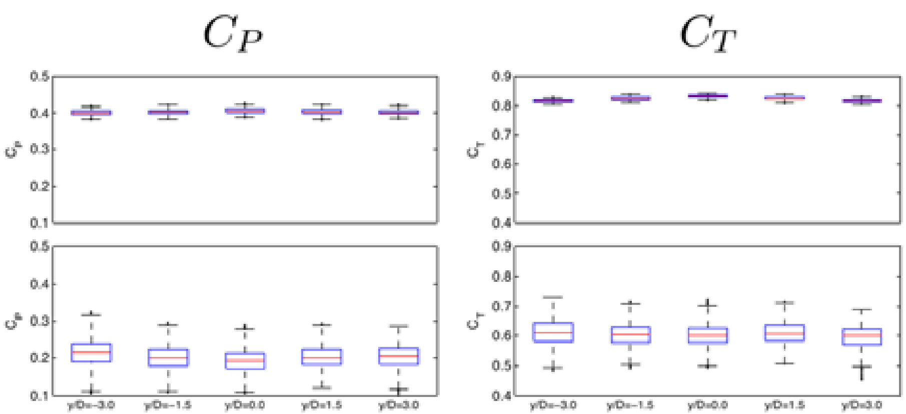


Figure 9: Power and thrust coefficient for upstream and downstream rows showing the wake effects on the performance of the turbines (source: Gajardo et al., currently under peer review)

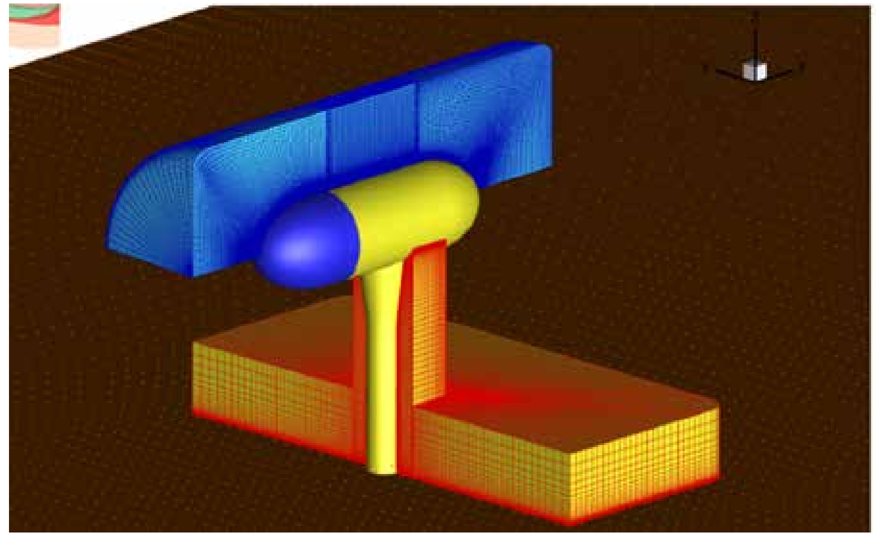


Figure 10: Numerical grid details for the Sabella turbine

C. Numerical Modelling: Tidal Resource and Forecasting

The resource characterization of tidal currents is of great importance for the installation of MRE devices, in order to estimate the energy potential at specific sites and the magnitude of the currents that the technology will encounter. We use numerical modelling to simulate the tides in the areas of interest, and obtain an estimation of the currents in these areas by means of harmonic analysis.

Even though the estimation of current magnitudes and directions during tides are the most important features, it is also necessary to study the non-linear interactions between the tidal flow and the flow resistance at the bottom (leading to vorticity and residual eddy formation) and also the stratification that may arise from the interaction of water of different salinity and temperature. For example, the two main regions for tidal energy extraction are in this latter situation: Chacao Channel connects the open ocean and Chiloe's Inland Sea (Figures 11 and 12), and Magallanes Strait is located between the Pacific Ocean and the Atlantic Ocean. Another topic of importance is the influence of bottom friction and numerical grid resolution in the numerical estimation of the tidal energy potential.

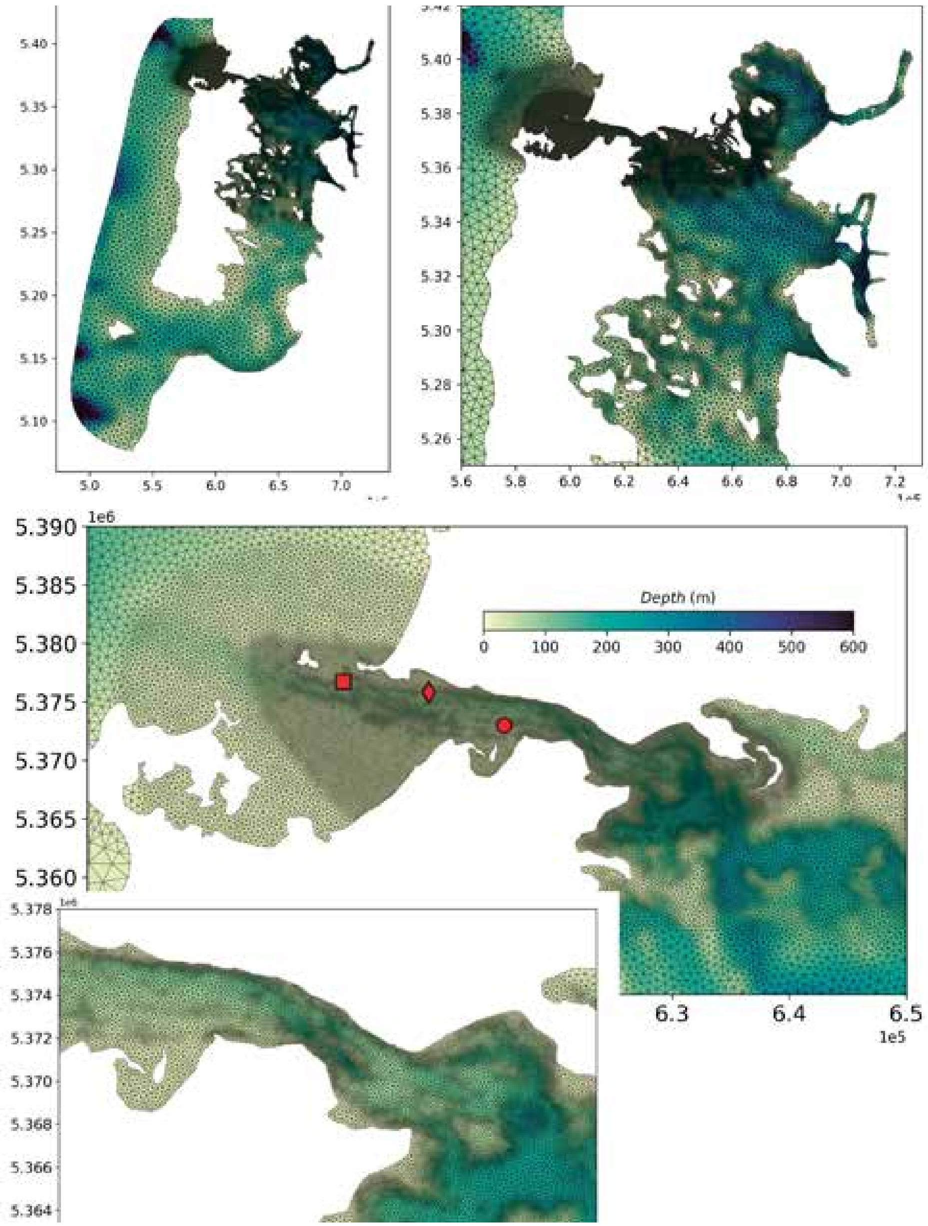


Figure 11: Details of the numerical grid used on Chacao Channel with the FVCOM (Finite Volume Community Ocean Model) numerical model. The triangle resolution is of 5,000 m on the outer limit, up to 25 m in the Chacao Channel. (source: Suarez et al., 2018)

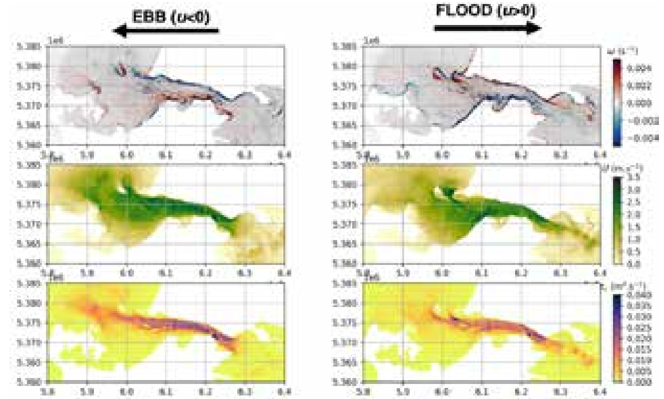


Figure 12: Vertically averaged vorticity ωthe velocity magnitude U, and the bottom shear stress ω averaged over the ebb and flood during one tidal cycle in Chacao Channel, using the numerical model FVCOM. (source: Scheuch et al., 2018)

Fieldwork

Numerical models' results are validated and calibrated with in-situ data obtained from fieldwork, both in wave and tidal energy resource assessment.

A. Las Cruces (March & November 2018)

The first wave field campaign, in collaboration with MERIC biofouling research project and FONDECYT 1170415 project from the Universidad Técnica Federico Santa María, was performed in the Cartagena Bay, near the PUC's Estación Costera de Investigaciones Marinas (ECIM), a Las Cruces, Valparaíso Region (see Figures 13 to 16).

This field campaign was carried out in March 2018 and included the following measurements:

- Beach topography using differential GPS and drones
- Free surface water level in the swash zone using 4 pressure sensors
- 2 ADCPS at 20 m depth to obtain wave spectra and currents
- 1 ADV at 6 meter depth to measure free surface water level and cur-rents
- 3 custom-made Lagrangian drifters for surface currents.

The purpose of this first field campaign for waves is to obtain preliminary data to characterize physical phenomena inside the bay and validate the numerical models developed within the research line, presented before. A second campaign is planned for November 2018 at the same site, with additional measurements and a longer period of observations.

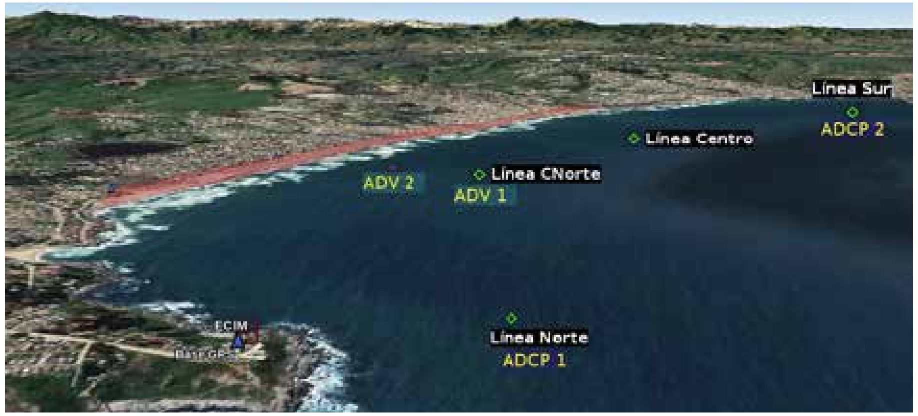


Figure 13: Localization of the measurement instruments for March 2018 field campaign(source: Google Earth)

Figure 14: Pressure sensors installation during field campaign, March 2018 field campaign in Cartagena Bay.

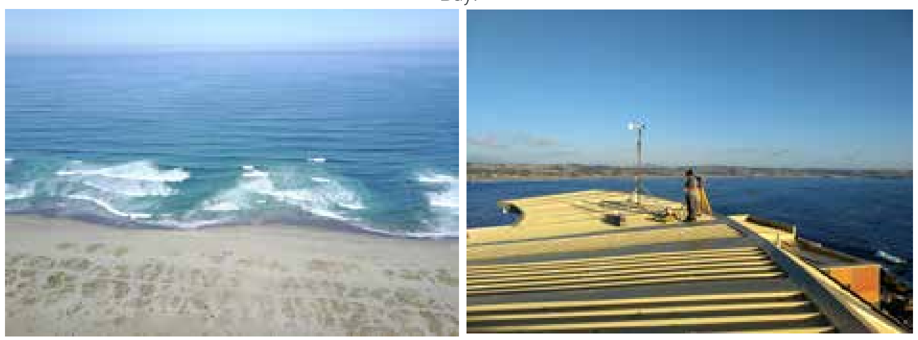


Figure 15: Topography measurements using differential GPS and drones, March 2018 field campaign in Cartagena Bay.

Figure 16: Lagrangian drifters, March 2018 field campaign in Cartagena Bay.

B. Magallanes Strait (October 2018 and March 2019)

Regarding tidal currents, a field campaign is under preparation and planned for March 2019 in the Magallanes Region. A preliminary field campaign in October 2018 gave us useful information in terms of tidal currents characteristics in the region (Figures 17 and 18). We aim to characterize different environmental phenomena with a multidisciplinary approach, in collaboration with University of Notre Dame. Currents will be measured principally with ADCPs, and tidal gauges, drifters, underwater CTDs, microstructures profiles, among others, will be deployed. The information obtained during this field campaign will be useful to validate numerical models (ADCIRC, FVCOM) and identify potential sites for marine energy development.

Figure 17: Magellan Strait, the numbers indicate the First and Second Narrows (source: Google Earth)

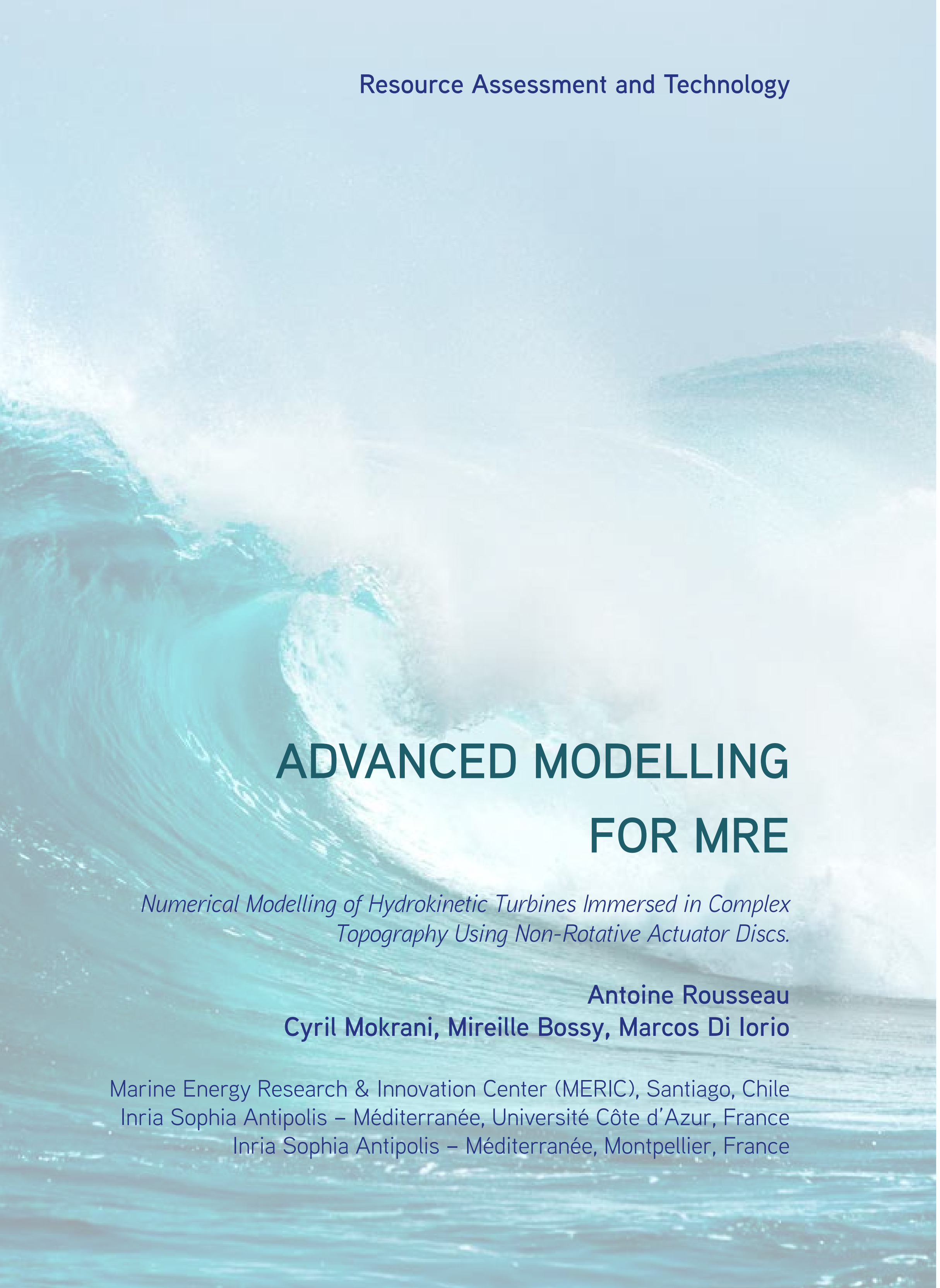
Figure 18: Deployment of a CTD during October 2018 Magallanes field campaign

Conclusions and Future Work

Using this integrated approach that combines laboratory experiments, numerical modelling and field campaigns, we look forward to developing capabilities to perform site studies at different scales to provide the necessary information for marine energy site characterization. This means not only developing multiple tools for marine energy device design and array optimization, but also for marine energy resource monitoring and forecasting at a detailed and accurate level, to support the devices operation and maintenance planning as well as environmental impact monitoring.

Future work of the line of research include the following:

- WEC performance analysis on the central coast of Chile, to estimate power ratings, capacity factor and operation times for some WEC devices
- Coupling spectral models for wave propagation with time-domain models, to obtain more accurate resource estimates near the coast
- High-resolution operational wave forecasting on the Chilean coast using unstructured grid to obtain finer resolutions in selected sites
- High resolution experimental data from a 1m wide laboratory flume at DIHA-PUC, that is being upgraded with an automated measurement system and flow control for marine energy research
- Improvements in the design of scaled turbines for laboratory experiments, that includes motor control and custom-made sensors.



ADVANCED MODELLING FOR MRE

Numerical Modelling of Hydrokinetic Turbines Immersed in Complex Topography Using Non-Rotative Actuator Discs.

Antoine Rousseau
Cyril Mokrani, Mireille Bossy, Marcos Di Iorio

Marine Energy Research & Innovation Center (MERIC), Santiago, Chile
Inria Sophia Antipolis – Méditerranée, Université Côte d'Azur, France
Inria Sophia Antipolis – Méditerranée, Montpellier, France

INTRODUCTION

Technologies for extracting energy from tidal currents using hydrokinetic devices have not yet achieved a sufficient degree of maturity to enable their widespread integration into power grid interconnected systems (Khan et al., 2008; Güney et al., 2010). Recent studies have identified potential in many coastal areas which could provide significant renewable energy resources in the near future, although their implementation would require the overcoming of challenging technical, environmental and economical aspects, all of them site-specific.

Along the 6,400km coast of Chile, in the South Pacific Ocean, the Chacao Channel has, according to initial estimates (Garrad-Hassan, 2009), been identified as an important energy source that could potentially contribute to a total power capacity of between 600 and 800 MW. Motivated by the need to learn more about the physical and environmental processes of highly energetic areas similar to the Chacao Channel, we are developing a numerical model that aims to comprehensively describe flow past turbines for a wide range of scales, to optimise turbine arrays and evaluate their environmental effects.

To improve device installation and performance through numerical predictions, it is necessary to model turbulence flows. Indeed, the Chacao Channel presents current velocities of up to 10m/s and a complex bathymetry with high depth variations, which naturally generates turbulent flows. In addition, this ambient turbulence may be significantly increased by turbine blade interaction with the incident flow, mainly due to high shear stress generated downstream from the turbine.

Among the existing numerical methods for modelling turbulent flows, one can separate the Eulerian Averaged Models (EAMs) and Lagrangian Stochastic Models (LSMs). Those two approaches are fundamentally distinct for various reasons: first, Eulerian methods compute solutions (velocity and pressure fields) on a fixed mesh grid (see figure 1-(a)) and thereby provide a snapshot of the flow at every instant. Conversely, Lagrangian methods follow water particles during the simulation and compute their velocity at each time step. Contrary to Eulerian models, the Lagrangian approach provides the trajectory (positions) of fluid particles (see figure 1-(b)).

In addition, EAMs provide pressure and velocity fields averaged over a characteristic duration or length (chosen a priori). This is equivalent to saying that only large-scale turbulent processes are solved. Small-scale effects are included in the EAM description, however they are 'added' to the numerical solutions through an additional input variable (see Reynolds tensor or sub-grid tensor). Conversely, the LSM computes instantaneous fields of each water particle, and provides solutions which include both large and small-scale turbulent effects. An important point is that it is possible to deduce averaged fields from LSM solutions but not vice-versa.

Among the EAMs, the Reynolds-averaged Navier-Stokes (RANS) (Zahle and Sorensen, 2011) and Large-Eddy Simulation (LES) methods (Sezer-Uzol and Long, 2006) have been widely developed to model turbulent flows induced by tidal turbines. LES have been used to model blade motions, predict forces and torque induced on the stator (Sezer-Uzol and Long, 2006; Kang et al., 2012), and improve the prediction of the power generated by the turbine (Kang et al., 2012). RANS models have also provided excellent predictions, especially regarding the local flow/structure interactions occurring during the extraction process.
However, these methods have proved to become very intensive and demanding in

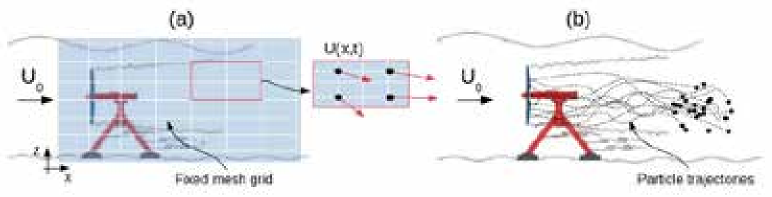


Figure 1 : Two different approaches used to model turbulent flows – (a) Eulerian approach, (b) Lagrangian approach.

terms of computational resources. Accurate predictions of RANS require at least 6 million grid nodes, with a large number concentrated in the wake region (Turnock et al., 2011). This requirement can be even more important for LES models, for which a total of 185 million grid nodes are required to resolve the flow field around one single turbine device (Kang et al., 2012). These computational needs clearly lead to prohibitive computation processing times, which become unfeasible if multiple interacting turbines are considered in the simulation. So far, the need to reduce the demand on computer resources for EAMs has motivated a number of researchers to propose innovative methods such as coupling approaches or hybrid methods with the objective of saving computational resources associated to EAM.

Contrary to EAMs, LSMs are more recent and fewer studies have been published so far. LSMs have been originally developed by Haworth and Pope (1986), based on stochastic differential equations whose solutions are the instantaneous positions and velocities of fluid particles. The main usage of LSM models in engineering is to provide information for the instantaneous velocity of the flow seen by dispersed physical particles. Such approaches have been extensively used for turbulent flows in combustion engineering, in association with an EAM for the computation of the mean flow information (Minier, 2016). Recently a standalone version of LSM has been developed as a simulation solution for turbulent flows and mainly applied to atmospheric flows: Polagye et al. (2010) used an LSM for meteorological frameworks and predicted turbulent flows fields in a realistic case of wind refinement. Originally, standalone LSM for wind computation is a downscaling method that provides a local model limited to a given region, forced by meteorological large scale information. In order to reconstruct the mean flow field from the fluid-particle motion, a Particle-in-cell (PIC) technique is retained (see further details in Bossy et al., 2016) that introduces a fixed mesh according to some characteristic flow length. (Zahle and Sorensen (2011) and Bossy et al. (in press) computed the wind circulation around mills and obtained very promising estimations of the wind variability in the wake of a wind turbine. However, even now, no studies based on tidal or ocean flow are available and the question of LSM ability to describe turbulent flows generated by tidal turbines remains unresolved. More important is the assessment of their performance. Given the high computational times associated to EAMs, reducing computational times should be very welcome.

The present study aims to evaluate the performance of the LSM "Stochastic Downscaling Method – Ocean Power Simulation (SDM-OceaPoS)" with the purpose of developing an inexpensive computation tool capable of simulating interaction between high Reynolds flows with both multiple turbine devices and complex bathymetry.

Section II provides details of the numerical methods employed in this study. Section III presents one verification case based on the boundary layer generation. Sections IV and V present two benchmarks, based respectively on turbulent flows generated by a bathymetry (from Almeida et al., 1993; Loureiro et al., 2007) and instantaneous wake dynamics generated by an non-rotative turbine (from Myers and Bahaj, 2010; Myers and Bahaj, 2012). Since Section II is a preliminary study, conversely Sections IV and V intend to establish a framework for future optimisation of turbine arrays on specific sites.

A. Numerical Methods

I. Numerical Approach

The development of the SDM-OceaPoS model is based on an existing code that models air flows named SDM-Windpos. The 'air' version has been validated on atmospheric flows (Myers and Bahaj, 2012), although its translation to the water version is still under development.

In the current version, the water is described as an incompressible flow by a Lagrangian approach, using a stochastic differential system of a diffusion process (see continuous Markov processes in Pope, 2003). The time evolution of particle velocities is described and computed from three acceleration terms, including (i) the pressure gradients contributions, (ii) the advective and convective effects of the fluid displacement, and (iii) a diffusive term governed by a Brownian motion. These three terms allow to take both small and large scale turbulent processes into account in the simulations.

One of the main advantages of the SDM-OceaPoS approach is that in addition to providing the instantaneous fields particles, it also provides averaged fields, similar to a classical EAM. This Eulerian description of the flow is possible thanks to a fixed regular mesh grid superposed to the numerical domain. During the computation, spatial averages of Lagrangian velocities of particles located in the same cell are assessed, together with the variance and covariances. These Eulerian fields are computed at each time step after particle advections. In practice, the number of particles in each cell is kept constant in order to guarantee the incompressibility constraint. This step is performed using the optimal transport method (see Villani, 2008). Using this approach, the user has to set two input parameters which are (i) the mesh size used to assess the Eulerian fields, and (ii) the number of particles per cell.

II. Method for Including Bathymetry Effects on the Flow

SDM-OceaPos uses a wall treatment method to reproduce the momentum exchange present in the interaction between fluid particles and arbitrary bathymetries. The method implemented consists of reflecting any particle that enters into the sub-viscous layer. In this manner, the sub-viscous layer is not solved but its effects are included in the simulations. To make this possible, a 3-dimensional topology file is first generated prior to the computation with the main ground characteristics (that is to say, the ground position, the local slope of the ground, and the frictions coefficients). During the computations, SDM-OceaPos assesses each reflected velocity of particles that cross the sub-viscous layer from the input ground data. This step is performed by assuming that the covariances before and after the reflection remain equal.

More especially, this method is applied in three steps:

1. SDM-OceaPos first detects particles that enter the sub-viscous layer at a given iterative step. During this step, the position the particle would reach without terrain ("virtual position") is computed.
2. The position of the reflected particle is calculated according to the local ground inclination, and his virtual position in the sub-viscous layer. The particle is then re-introduced into the fluid domain
3. The reflected velocity vector is computed according to the friction and the covariances assessed before the reflection.

This original method is particularly interesting since it allows for the inclusion of the effects of the sub-viscous layer without solving it. It is applied in Section III on a case involving a 2D hill introduced in a turbulent flow.

III. Model of Hydrokinetic Turbines

The implemented model of a non-rotative turbine is based on the theory of porous discs (Pope, 2003; Myers and Bahaj, 2010). Such discs, introduced into a turbulent flow, may disturb the flow field by generating a turbulent wake as illustrated in Figure 2, left.

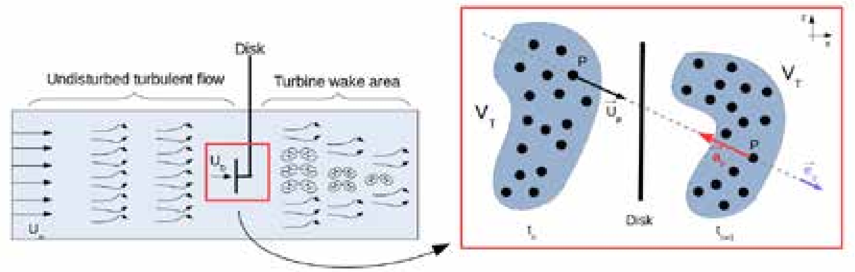


Figure 2: Illustration of the wake generated by the porous disc (left), and (right) the approach of the implemented model: particle accelerations are estimated from the total force applied on the volume VT - The particle force direction is the same as the disc-crossing particle velocity (vector ep).

Turbine models were initially implemented in the air version of SDM (Bossy et al., 2016). They consisted of applying a correcting velocity to particles located at the disc location. This correcting velocity was assessed from a theoretical expression of the force generated by the disc on the fluid.

However, several problems related to this approach have been pointed out: first, this corrected velocity was added after the advection step, and therefore the turbulence generated upstream from the disc was generated indirectly by the velocity deficit, but not by the disc itself. This may lead to a misrepresentation of the wake recovery and impacts in realistic scenarios. Other limitations were that the corrected velocity was applied in a fixed control volume – typically the disc volume - and therefore any particle crossings the disc without staying in this control volume was not corrected. This not only provided a non-realistic behaviour of the fluid particle but also resulted in a flow description very sensitive to the space step and the time step.

A new approach has been developed to solve these problems. It involves adding an acceleration source term to the momentum equation. In this manner, the turbulent effect induced by the turbine itself can be included in the simulation. Additionally, this source term is applied to a new control volume, defined as the volume of all particles that cross the disc between two iterative steps. With this variable control volume any particle which crosses the disc undergoes the hit effect.

From a mathematical point of view, the source term acceleration is assessed from the ratio between the total force applied on the control volume and its corresponding total mass, as illustrated in Figure 2, right.

The expression of the total force is given in Simisiroglou et al. (2016). For the present study, this force is assumed to be exerted in the direction of the disc-crossing particle velocity, as indicated in Figure 2. Usually, the force is given according to the porosity coefficient, the area of the disc and the fluid velocity vector in the disc's vicinity. However, for the present model we used the induction factor (denoted a, see Bossy et al., 2016) instead of the porosity coefficient because this coefficient allows for the linking of the instantaneous particle velocities at the disc location (see UD in Figure 2, left) to the particle velocity away from the disc (see U∞ in Figure 2, left).

The total mass of the control volume is estimated by the product between the total number of particles that cross the disc and the mass of one single particle. The latter is calculated by assuming that the volume of each grid cell equals the sum of the volumes of all particles in this cell. From this assumption, the particle mass can be easily deduced.

Finally, the corrected acceleration term is re-assessed at each time step for each particle that crosses the disc. This approach allows for obtaining a flow description independent from the numerical input parameters: when changing the mesh grid size (respectively the time step), the control volume changes and the subsequent acceleration keeps the same order of magnitude so that the effect of the disc on the flow remains similar.

In the following, one verification test and two benchmarks are presented. All these computations have been performed with the multi-threaded open Multi-Processing (openMP) version of SDM-OceaPoS, and using 23 cores, having a frequency of between 2 and 2.4 GHz. The hydrokinetic turbine model is applied in Section IV for cases involving turbine diameter D of about one-third of the depth h (D~h/3).
The next section is dedicated to benchmarks carried out on cases of flows without turbines. Emphasis is placed on the generation of boundary layers and the effects of a given bathymetry on a turbulent flow.

B. Generation Of The Boundary Layers

A first study has involved considering verification test cases in order to assess the ability of SDM to reproduce the basic physics of a turbulent flow without turbine. The objective is to recreate an experiment in channel and assess the numerical accuracy of the computed velocity fields by comparing numerical and theoretical results.

I. Experiments

The following results are based on the experimental study from Nezu and Rodi (1986) (cf. Figure 3-a). It involves 2D flow evolving in a 20m long, 60cm wide and 65cm deep open channel with smooth ground (cf. Figure 3, left). During experimental tests, the water is stably recirculated with maximum discharge reaching 80 l/s, which generates a turbulent flow with a Reynolds number of about Re ~ 104. The friction velocity is assessed at 0.44 cm/s.

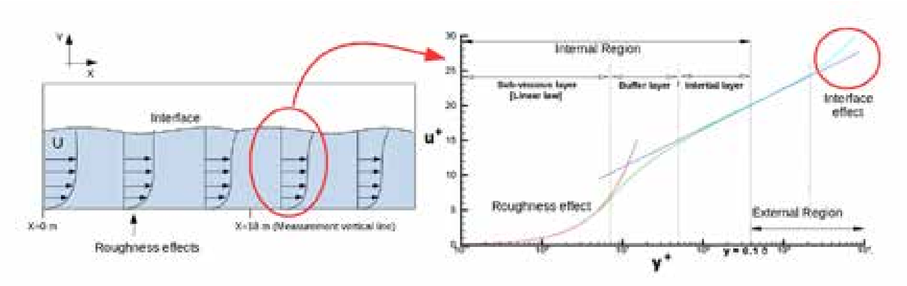


Figure 3: (Left) Sketch of the experiment from Nezu et al (1986) - (Right) Theoretical average velocity profiles in each sub-layer of a turbulent 2D flow – y+ = yU* / v, U+ = U/U*, U* = 0.44cm/s.

Results from Nezu and Rodi (1986) show the generation of mainly four boundary layers in a steady state (cf. Figure 3-b) whose structures depend both on the ground roughness and interface motion. The ground roughness generates the viscous sublayer in which the velocity profile follows a linear law. Above this first boundary layer, a transition region appears in which the velocity profile tends towards a classical 'log' law. Above the log-law region, the free-surface motion disrupts the velocity profile resulting in a new boundary layer (see Nezu and Rodi, 1986). For the present study, focus is only on the intermediate, and log-law regions, and neglects the effect of the free-surface and the sub-viscous layer. The latter assumption is justified by the fact that the sub-viscous layer has very small dimensions in relation to those of the turbine deployed in this study (D~h/3).

II. Results

Numerical tests have been made using the parametrisation of the turbulent viscosity proposed in the study from Nezu and Rodi (1986) derived from laboratory measurements. This is the only modification made from the air version in order to model water flow.

Computations have been performed using 128,000 cells in total, and 80 particles per cell in a numerical domain of ~ $1m^3$.

Figure 4 presents the mean velocity profiles and variances of the vertical and horizontal velocities. Theoretical solutions are also represented in the same figure in order to assess the numerical accuracy to model the boundary layers. As observed, results from SDM-OceaPos provide excellent trends of velocities in the intermediate and outer log-law regions of the flow. Mean velocity predictions are slightly under-predicted in the interface vicinity, since the effect of interface on the flow is neglected. Also, the sub-viscous layer is poorly modelled due to the assumption previously mentioned. Maximal relative error according to theoretical results reached less than 10%.

Variances of horizontal and vertical velocities are compared to the mean velocity fluctuations in Figure 4 (b) and (c). Both global trends and order of magnitudes are in good agreement with theoretical values. Maximal error reached about 13% compared to theoretical results.

Regarding the numerical performances, all computations have been performed over 200 iterations using a constant time step of 0.2s. The corresponding time calculation for one iteration is about 0.05s, which means that one second in the physical experiment could be modelled in about 0.25s.

Finally, these predictions, together with the corresponding performances observed lead to the conclusion that the main structure of a high Reynolds number flow can be accurately reproduced at very reasonable computation times.

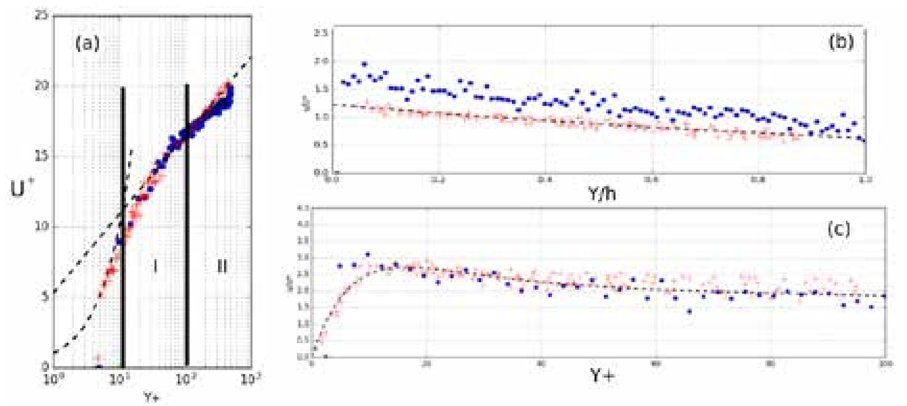


Figure 4: Comparisons between numerical predictions (oo), theoretical predictions (- -) and measured (++) mean velocities (a), averaged horizontal (b) and vertical (c) fluctuations velocities in intermediate I and II outer sub-layers flow - Y+ = yU* / v, U+ = U/U* with U* = 0.44 cm/s, h=10 cm.

C. Influence of Bathymetry on the Flows

The second tests are focused on the influence of the bathymetry on the flow, modelled by using the numerical method presented in Sub-section II.2. It involves reproducing the experiments performed in the laboratory and comparing them to the numerical predictions. The objective is to assess the ability of SDM-OceaPos to describe the turbulent flow dynamics involved in controlled configurations.

I. Experiments

All numerical results presented hereafter have been compared to experimental measurements performed by Almeida et al. (1993) and Loureiro et al. (2007). These studies consider a 2D hill placed in a water tunnel to measure its effects on turbulent flow (cf. Figure 5-a).

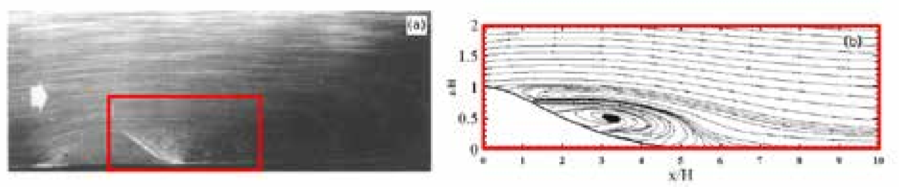


Figure 5: (a) Visualisation of the considered flow with hill - (b) Zoom of the downhill zone and illustration of the recirculation zone generated by the presence of the hill.

The water tunnel is made of perspex and is 0.170m deep, 0.2m wide and 7m long. During the experiments, the water flow passes through straighteners located upstream of the duct inlet in order to ensure hit uniformity. Experiments correspond to Reynolds number flows of about 6.104. The model hills are made of plastic moulded with a wooden former. Their shape corresponds to the inverse of a fourth-order polynomial function, with a maximal height and length in the streamwise direction of 28mm and 108mm respectively.

During the experiment, the curvature of the flow affects the velocity field, which results in the establishment of a zone of high-intensity velocity fluctuations along the shear layer downstream of the top of each hill. The hydrodynamical effects of the hill on local turbulence can be observed in Figure 5, especially the emergent structures upstream and the recirculation zone downstream of the hill. Two specific points, named detachment and reattachment points, are defined as the positions where the shear stress changes sign. These points determine the main flow structure generated by the hill. According to Almeida et al. (1993), the detachment point extends up to x/h = 4.8, as can be observed In Figure 5 (b).

II. Results

The following results correspond to computations performed using 96,000 cells in total and 50 particles per cell. To reduce convergence times, a first computation was done without a hill and stopped when all the mean velocity, first and second order moments fields reached stabilised trends. These fields were imposed both as a boundary at the left side of the domain, and initial state in the whole domain.

Simulations including the hills have been performed using smaller time steps and more iterations to obtain converged results. In total, we ran 2,000 iterations which lasted about ~ 5 hours. This corresponds to a CPU rate of 9 iterations per second.

Figure 7 shows the stream lines obtained after 1,000 iteration steps. It can be observed that the recirculation zone is well described by the code and that its dimensions are very close to those observed experimentally. The detachment point location has been assessed at 4.28h against 4.8h from Almeida et al. (1993). The generation and stabilisation of this recirculation zone proved to be sensitive to the time step parameter, especially when low values of this parameter were set. Using the value dt=0.0005s provided a stable computation and resulted in positive alignment with laboratory data.

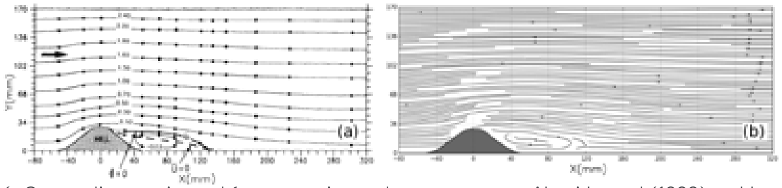


Figure 6: Stream lines estimated from experimental measurements Almeida et al (1993) and Loureiro et al (2007) (a) and calculated by SDM-OceaPoS (b) - The maximum input speed is U0 = 2.147 m/s, and the height of the hill is h = 28mm.

Figure 8 presents the vertical profiles of the mean horizontal velocity predicted at different locations upstream and downstream of the hill. As observed, numerical predictions are very close to measurements for all the considered distances to the hill. Maximal error on the mean velocity is about 10% and is reached at the hill top.

The interested reader can find more information about this benchmark case in Di Iorio et al. (2018).

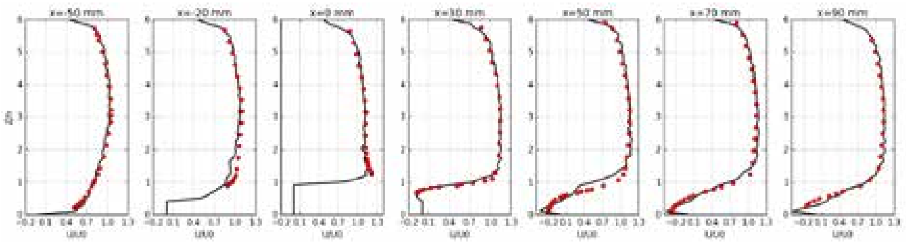


Figure 7: Vertical profiles of horizontal velocities at different x positions of the domain (x = 0m corresponds to the position of the centre of the hill) - (-): Numerical predictions, (oo): Measurements from Almeida et al. (1993) (h = 28mm).

D. Cases Involving Non-Rotative Turbine(s)

The following validation tests are based on experiments from Pope (2003) and Myers and Bahaj (2012) involving porous discs introduced in a turbulent 2D flow. In order to estimate the ability of SDM-OceaPos to describe both the velocity deficit and the turbulent intensity generated by one or various porous disc(s), we reproduced similar experiments using the method presented in Sub-section II.3.

I. Experiments

Pope (2003) and Myers and Bahaj (2012) carried out flow measurements in the wake of the discs to determine the flow recovery as a function of the thrust produced by the devices and analyse flow interaction in turbine arrays. The experiments were performed in a 21m long by 1.35m wide flume with a water depth of H = 0.3m. The mean velocity of the flow equals 0.25 m/s, which yields a Reynolds number of Re = 75,000 and a Froude number of Fr = 0.14 based on the flow depth H. Measurements were obtained by varying the number of discs, the disc immersion depth and the disc porosity. Figure 9 shows the experimental set-up with one and two discs in the laboratory channel.

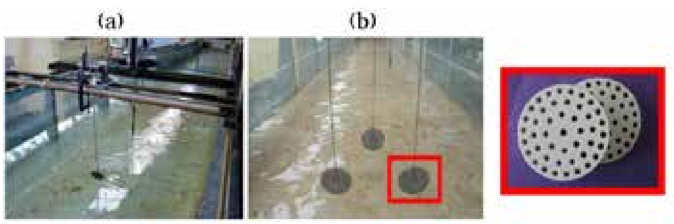


Figure 8: Experimental set-up of the research carried out by Myers and Bahaj (2013) - (a) Single disc configuration, (b) Three-discs configuration.

Diameter of the actuator discs (ADs) remained constant, equal to D = 0.1m for all tests that were performed. Porous discs were located in a section of the flume which had already reached a fully-developed turbulent channel flow. They were mounted on a rig with a pivot to amplify the forces and measure the total thrust with good accuracy. To vary the disc thrust, different porosities from 0.36 to 0.91 were tested using the same upstream flow conditions. The data provided also includes tests performed with different disc immersion depths. In any case, the measurement area extends from 3D to 20D downstream, where instantaneous velocities were measured using a vertical resolution of 0.1H.

II. Results

The following results correspond to computations performed on a 275,000 point grid and 100 particles per cell. For all cases, simulations were performed over 500 iterations with a time step of 0.1s, which corresponds to a CPU rate of about one iteration per 10s. The following figures correspond to results obtained at the last iteration of the computation.

Validation tests have been conducted by comparison analysis based on turbulence intensity and velocity deficits. The velocity deficit quantifies the velocity reduction induced by the porous disc. The results presented are also compared to numerical predictions from Johnson et al. (2014). Johnson et al. (2014) used a RANS numerical code with a k-ωturbulent model and a source term in the momentum equation to include the presence of the porous disc.

Figure 10 presents the vertical profiles of turbulent intensity computed and measured at different positions upstream from the turbine. For this case, the porous disc immersion depth was half the total domain height. In general, numerical tests performed by SDM-OceaPoS provide very good predictions for all available porosity values. The turbulent intensity is slightly under-estimated for low values of porosity coefficient. Conversely, they are overestimated for high values of CT, especially in regions close to the disc position. Relative errors decrease away from the disc, reaching about 10% for CT = 0.62 and 8% for CT = 0.99.

Numerical predictions from Johnson et al. (2014) provide a maximum relative error of 40% for turbulence intensity and 30% for speed deficit. In addition, they do not correctly reproduce turbulence intensity in the disc vicinity. Results obtained with SDM-OceaPoS are significantly better at this location.

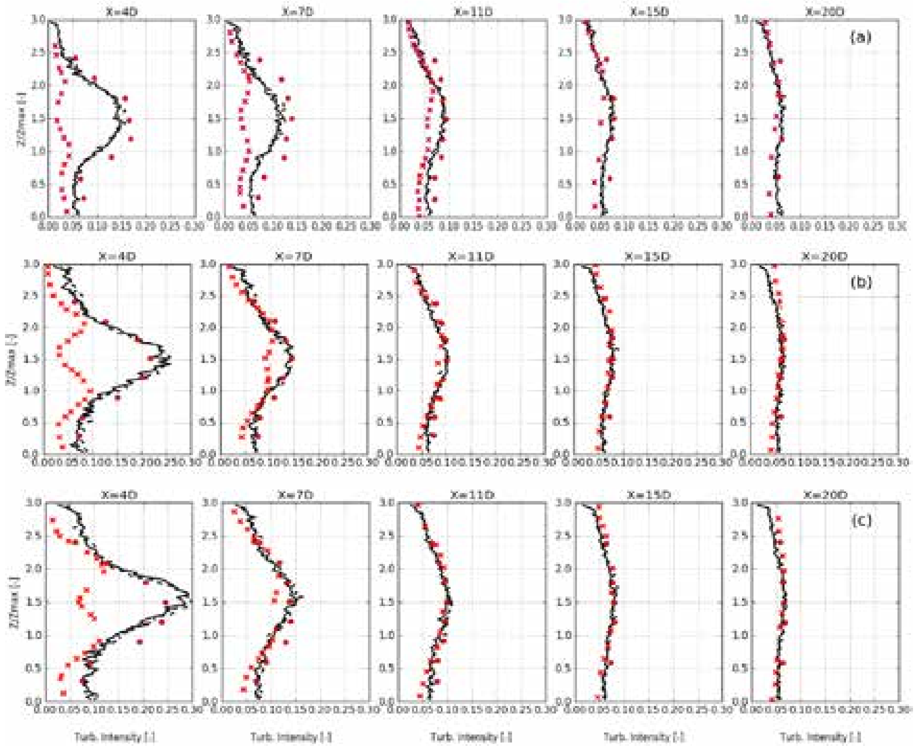


Figure 09: Vertical profiles of turbulence intensity at different downstream positions of the turbine - (-): Numerical predictions from SDM-OceaPoS, (oo): Measurements, (XX) : Numerical prediction from Johnson et al. (2014) – (a) : CT = 0.62, (b) : CT = 0.91, (c) : CT = 0.99 - Position x = 0 corresponds to the position of the disc centre.

Other results obtained on velocity deficit (not presented here) revealed corresponding maximum relative errors of the order of 7% for any porosity coefficient.

Figure 11 shows predictions of speed deficit where CT = 0.86 and the disc is immersed at mid-depth. Comparisons with experimental data reveal that SDM-OceaPoS provides a good prediction of the spatial distribution of the speed deficit.

The wake shape and dimensions are close to the experimental data. Low errors are observed, especially far from the disc or in the disc vicinity, where the deficit speed is slightly overestimated. Overall, the numerical results are fairly satisfactory.

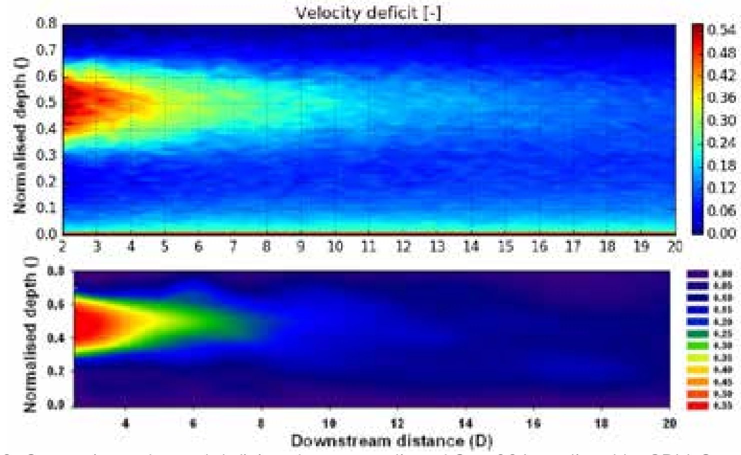


Figure 10: Comparison of speed deficits of a porous disc of Ct = 086 predicted by SDM-OceaPoS (up) and measured in channel Johnson et al (2014) - Downstream distance is defined as (X-XD)/ D where XD is the centre disc position and D the diameter of the porous disc.

Similar conclusions can be drawn for cases involving various discs. Figure 12 presents results obtained for one case involving three discs disposed in a two-row array. The first row is two discs at 1.5D lateral separation and the second one is the third disc disposed downstream at a distance of 3D. As observed in figure 12, for a downstream distance higher than 7D, numerical prediction of the velocity is in good agreement with experimental measurements. However, for a shorter distance, the numerical prediction is significantly overestimated. For this case, further studies are needed to understand and improve results.

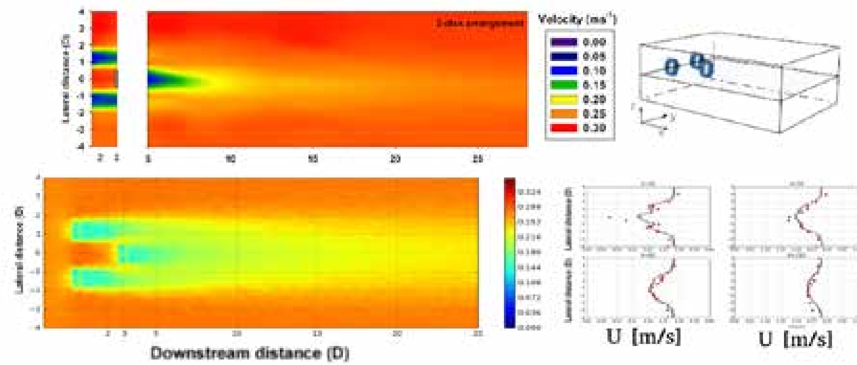


Figure 11: Comparison of deficits in the case of three porous discs spaced by 1.5D - (a): measured in channel Myers and Bahaj (2012), (b): Numerical predictions from SDM-OceaPoS, and (c) : vertical profiles of velocity, (oo) : Experimental, (–) : SDM-OceaPoS

CONCLUSION

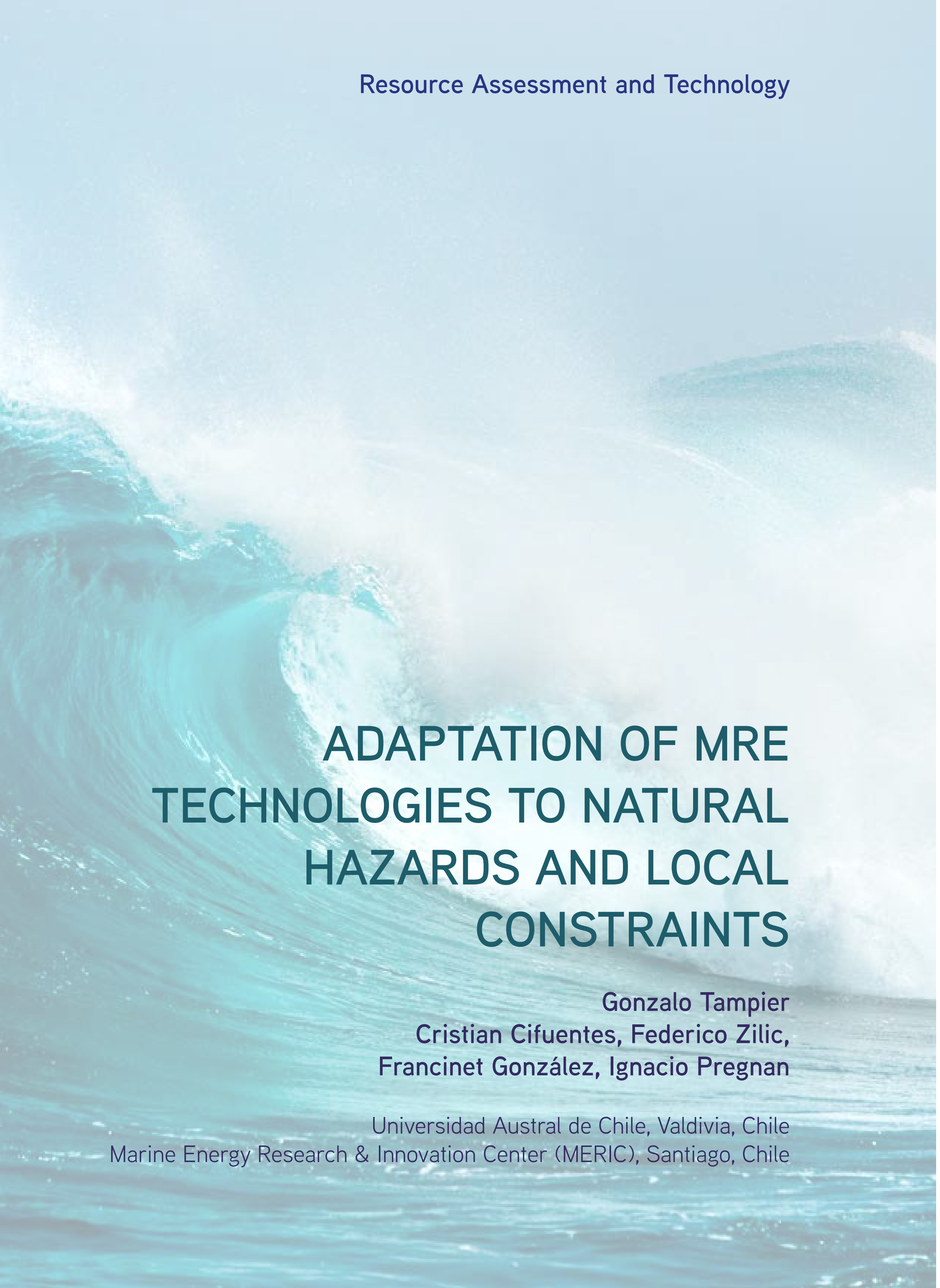
The present research aims to reproduce basic turbulent flows generated in rivers and seas both upstream and downstream of an AD device by using a Lagrangian stochastic model. From the results obtained from one verification test and two benchmarks, it can be concluded that the SDM-OceaPoS model is able to accurately represent the flow structure generated at high Reynolds numbers, the effects of bathymetry on the mean velocity field in 3D cases and the effects of AD on the local turbulence generated past the turbine device. More specifically:

The flow structure generated in a domain volume of about ~ $1m^3$ at a Reynolds flow of Re ~ 104 could be described with a CPU rate of about one iteration per 0.05 seconds, with all computed mean horizontal and vertical velocities and variances properly predicted in intermediate and external boundary layers. These results were obtained by implementing the parametrisation of turbulence viscosity of Nezu and Rodi (1986), which does not include the presence of the interface, even if this does not seem essential for current industrial applications.

A new method based on the reflection of particles has been validated using the experimental cases of Almeida et al. (1993) and Loureiro et al. (2007), involving a 2D hill immersed in a turbulent flow. Present benchmarks showed that this method provides accurate velocity profiles both upstream and downstream from the AD device, with a maximum error of horizontal velocity reaching less than 10% at the top of the hill. The numerical simulations accurately describe the generation and stabilisation of the recirculating area, which shows that the present numerical model is able to predict the main turbulent pattern associated with this benchmark case. Together with previous results, this highlights the fact that SDM-OceaPoS can be used to predict the behaviour of most of the turbulent main flows observed in rivers and seas without a turbine device.

A new turbine model has been implemented based on the porous disc theory. This model can reproduce with quantitative concordance all the features measured for channel flows with actuator discs used in the recent experiments of Pope (2003) and Myers and Bahaj (2012). The numerical solutions and comparisons with experimental data confirm the reliability of the PDF model in simulating turbulent flows generated by AD devices. This model can resolve the mean flow velocity deficit and also the turbulence statistics of the wake at high Reynolds numbers for various discs, while employing relatively low grid node numbers. The 3D dynamics of the flow field characterised by the asymmetric formation of arch vortices that emerge from the disc edges and interact downstream are properly reproduced only by adding an additional acceleration term in the Lagrangian equation of particle motion. This is very promising since these mechanisms are essential for predicting the interaction between the AD device and the environment. Another important concluding remark is that this approach, first developed for application in the atmospheric frame, can be easily adapted to ocean flows, especially by changing the parametrisation of the turbulent model. Moreover, predictions obtained by SDM-OceaPoS can be used to reconstruct water particle trajectories, which can yield an accurate description of physical processes inherent to turbulent flows generated from both an arbitrary bathymetry and also by a single or several AD devices (see Di Iorio et al., 2018).

Future work will focus on implementing an improved turbine model which includes the presence of rotating blades on a free-surface. In future, we expect this model to become a powerful tool for designing array turbines in the Chacao Channel and other similar sites, as it is ideally suited to better understanding the complex flows in natural marine environments, estimating available power and evaluating the impact of new technologies in local ecosystems.



ADAPTATION OF MRE TECHNOLOGIES TO NATURAL HAZARDS AND LOCAL CONSTRAINTS

Gonzalo Tampier
Cristian Cifuentes, Federico Zilic,
Francinet González, Ignacio Pregnan

Universidad Austral de Chile, Valdivia, Chile
Marine Energy Research & Innovation Center (MERIC), Santiago, Chile

Adaptation of MRE Technologies to Natural Hazards and Local Constraints

INTRODUCTION

Today, non-conventional renewable energies (NCRE) are starting to play an important role in the Chilean energy market and economy, raising important new challenges (Araneda et al., 2010; von Hatzfeldt, 2013). In that respect, marine renewable energy (MRE) is the latest NCRE technology still under development and less technologically advanced than other NCRE sources such as wind or solar energy. There are four different MRE energy sources currently being developed today: wave, tidal, offshore floating wind and ocean thermal gradient energy. In Chile, wave, tidal and offshore floating wind energy are considered to have a high potential, both in the mid and long term. Each one is considered to be at a different technological development stage. In general terms, tidal technologies are considered to be most mature ahead of wave energy technologies, and offshore floating wind very promising thanks to the far advanced development of offshore wind technologies. In this context, each technology is related to several technological and scientific challenges, which need to be addressed by R&D and industrial innovation processes (MacGillivray et al., 2013).

For wave, offshore floating wind and tidal energy, current main challenges are to prove the reliability, cost-effectiveness and minimal environmental impact of MRE arrays are known. Adequate competencies exist in industrialised countries to tackle these challenges and therefore lead the development of MRE technologies. Nonetheless, Chile can also play a leading role transferring these competencies and developing its own, e.g. in the fields of extreme environmental conditions or adaptation and optimisation of manufacturing, installation and maintenance techniques considering Chilean local conditions.

Therefore, the general objective of this "Adaptation of MRE technologies to natural hazards and local constraints" R&D project is to adapt and develop proven MRE technologies for our local environmental conditions and local infrastructure network. The project involves studying cost-effective solutions that withstand

Chilean specificities and maximise energy production. In order to achieve this objective, competencies need to be developed in Chile where, in return, international collaboration can be nurtured with Chilean competencies and capacities in all its local aspects. Such a collaborative scheme generates new competencies, new products, and triggers emergence of an MRE market capable of responding to Chilean conditions and needs as well as worldwide ones. In that context, our project accelerates the technology implementation process by bringing its applied research for answering both general and Chilean specific technical questions arising from deployment of MRE technologies in Chile and the rest of the world.

This research project is divided into two sub-projects: Mooring-based technology adaptation and Foundation-based technology adaptation. The first sub-project addresses floating wave energy converters (WEC) and floating wind platforms (FWP), while the latter addresses seafloor-based tidal energy converters (TEC). These sub-projects are closely related to each other and partially rely on results from other MERIC projects. Numerical methods and model-scale experiments play a central role, but also real seas experimentation is considered, in collaboration with the "Open Sea Lab" project. Results are intended to be of use for future research on floating wind technologies and/or other offshore technologies combining more than one application (e.g. different energy sources, energy + aquaculture platforms, etc.).

2. Subproject

2.1. Mooring-Based Technology Adaptation

Chile has environmental conditions and industrial network characteristics that must be taken into account, in order to adapt, rethink or optimise mooring-based wave and wind energy systems (WECs, FWPs). From a preliminary analysis, the following local specificities have been identified:

- Specific wave climate (long wave period and limited weather windows for maintenance and installation)
- Bathymetry (steep slope in most locations)
- Seismic events (tsunami and earthquake risk)
- Storms with specific characteristics ("marejadas")
- Specific biological conditions (high biofouling levels and presence of marine mammals)
- Limited infrastructure (ports, shipyards, etc.), limited equipment (tugs, floating cranes, etc.) and large distances (between potential sites and infrastructure).
- Potential adaptation of installation and/or operation procedures from the already existing fish farming industry.
- Specific local needs (water desalination, energy for isolated communities, etc.)

In that context, those aspects cause direct and/or indirect effects, which should be considered in the design, manufacture, installation, operation and maintenance of MRE technologies. The following key challenges need to be addressed:

1. Adapt manufacture, installation and maintenance techniques to cope with limited infrastructure, limited equipment, large distances, and very limited weather windows in a cost-effective way.
2. Develop methods and capabilities to predict the loads related to local extreme events on moored structures.
3. Develop and/or adapt mooring systems considering 1 and 2.
4. Develop and/or adapt survival mode(s) considering 1 and 2.

Additionally, interdisciplinary collaboration with the remaining MERIC projects addresses aspects related to biofouling, biocorrosion, collision risk with marine mammals, legal aspects and MRE CAPEX and OPEX analysis.

To answer these challenges, the activities of this subproject consider the adaptation of a generic, moored WEC and the adaptation of a generic, moored FWP. The use of generic technologies ensures the use of results for a broad number of technologies and allows open collaboration with industry and other research institutions. The following activities are considered:

- Design process of concepts best suited for local conditions for:
  - A small-sized generic WEC.
  - A medium-sized generic floating platform for Offshore Wind applications.
- Hydrodynamics of extreme events and response of floating structures by means of numerical methods and model-scale experiments.
- Optimisation of mooring arrangements and survival mode(s) by means of numerical methods, model-scale tests and potentially with site tests (in collaboration with the "Open Sea Lab" project).
- Design for low production, installation and O&M cost, considering local production and installation capabilities.

For each generic technology (small-sized generic WEC and mid-sized generic FWP), a study site is defined in order to consider realistic conditions. These site data will further be delivered by the "Resource Assessment and Site Characterisation" project and used as input information within a design process (presented in section 3.1).

2.2. Foundation-based technology adaptation

As for the mooring-based technologies, Chilean local conditions require us to adapt, rethink or optimise foundation-based tidal energy systems (bottom-based tidal turbines). From a preliminary analysis, the following local specificities have been identified:

- Bathymetry (large depths in some channels).
- Seismic risk at seabed (tsunami and earthquake risk).
- Specific biological conditions (high biofouling levels and presence of marine mammals).
- Limited infrastructure (ports, shipyards, etc.), limited equipment (tugs, floating cranes, etc.) and large distances (between potential sites and infrastructure). Potential adaptation of installation and/or operational procedures from the existing fish farming industry.

In order to address those challenges, the activities of this subproject consider the adaptation of **a generic, foundation-based TEC.** The following activities are considered:

- Design process of a generic TEC concept best suited for local conditions.
- Assessment of seismic risk and seabed response in areas of interest.
- Design considerations for extreme events (e.g. tsunamis, earthquakes) and environmental aspects (e.g. marine mammal collision risk).
- Design considerations for low production, installation and O&M cost, considering local production and installation capabilities.

For the generic technology (foundation-based TEC), a study site is defined to take in account realistic conditions. These site data will further be delivered by "Resource Assessment and Site Characterisation" projects within a design process (presented in section 3.1).

3. Methods and Materials

The project considers different levels of depth for the main tasks related to the design of MRE technologies, within an iterative design methodology. A strong emphasis is given to hydrodynamics and structural analysis, to understand crucial aspects for the adaptation of technologies to Chilean conditions. Additionally, interaction with field experience from the "Open Sea Lab" project is expected.

3.1. Design Methodology

The main requirements for the operation of MRE technology are high energy production availability, lifecycle system integrity and human safety assurance at sea under any circumstances (mainly during installation and maintenance), as shown in Figure 1.

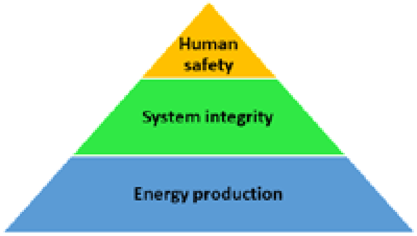


Figure 1: Main operational requirements for MRE technologies.

To fulfill those requirements, the design process must consider a large number of aspects. Considering the complexity of such a system, the process is developed iteratively, as for other marine environment technologies such as offshore Oil & Gas structures or ships (see e.g. Clauss et al., 1992; Evans, 1959). In Figure 2, a design process for MRE technologies is proposed. Within the project, this design process shall be refined and used for the generation of **generic designs (WEC, FWP and TEC)**, providing the framework for a process of **MRE technology adaptation to Chilean conditions.**

Within the proposed design process for MRE technologies, two kinds of inputs can be identified:

Site data
- Atmosphere
- Water surface
- Water body
- Seafloor
- Biology

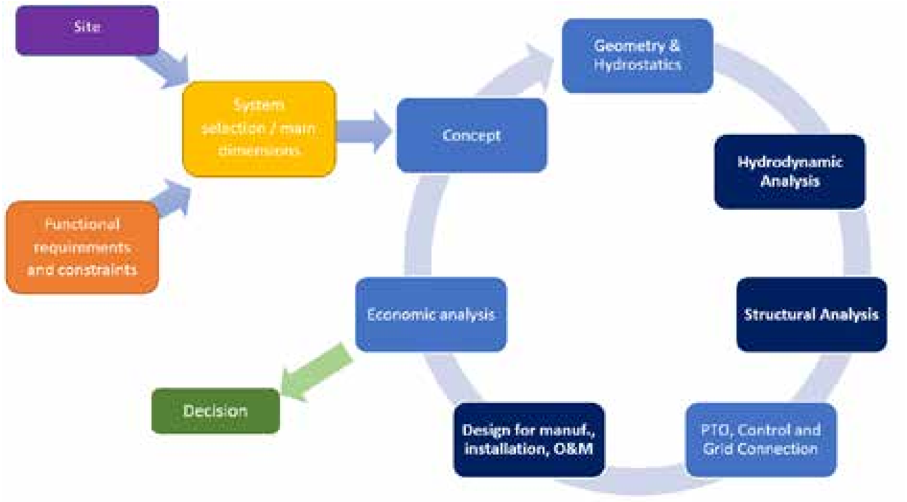


Figure 2: Design process for MRE technologies.

Functional requirements and constraints

- Energy price
- Project size (single vs. farm)
- Logistical conditions / availability
- Technical / technology constraints
- Legal constraints
- Environmental constraints
- Other economic activities (fish farming, fishing, tourism)

From these data, a process of system selection and definition of main dimensions can be started, which provides the first input of the iterative design process. The design process, as shown in Figure 2, can be divided into at least seven main tasks. In Table 1, each stage is described and typical materials (or required resources) are mentioned. Considering the importance and complexity of hydrodynamic and structural analysis in the design process, further details about these stages are provided in sections 3.2 and 3.3.

The design methodology presented is an integrated and iterative approach considering a large amount of data and requires very different capacities, which is part of the strategy of transfer between MERIC partners. This allows the adaptation and optimisation of MRE technologies and subsystems for specific operational conditions. Although this methodology is only applied for the Chilean case in the present study, it can be applied to other geographic regions in future.

Stage	Description	Materiales
Concept design	The stage of concept design refines basic details of the selected system in order to obtain major intended characteristics affecting cost and performance.	CAD software (e.g. Rhinoceros, SolidWorks) Spreadsheet / programming env. (e.g. MS Excel, Matlab)
Geometry & hydrostatics	External geometry (platform / moving parts / rotor / etc.) and mooring arrangements (if applicable) are defined and hydrostatic characteristics (buoyancy and stability) are calculated.	CAD software (e.g. Rhinoceros, SolidWorks) Naval Arch. software (e.g. MaxSurf Suite)
Hydrodynamic analysis	Hydrodynamic analysis provides key information about the performance of the system and the hydrodynamic loads that can be expected. **Details are given in 3.2**	CFD software (BEM: e.g. WAMIT. RANS-CFD: e.g. STAR-CCM+ / OpenFOAM) Experiments (UACh Wave Tank)
Structural analysis	Structural analysis considers the analysis of the structure itself (floaters, fixed elements, external energy conversion components, etc.) and its mooring or foundation system. **Details are given in 3.3**	Structural analysis software (SolidWorks, Ansys) Mooring analysis software (e.g. OrcaFlex)
PTO, control and grid connection	Selection or design of PTO and control systems. Design of grid connection (if applicable).	This stage will only include selection and interaction with technology developers. Deeper insight is not considered part of Mooring-based technology adaptation sub-project.
Design for manufacture, installation, O&M	This stage refines the design considering relevant local conditions related to infrastructure (e.g. shipyards, ports, etc.), equipment (e.g. mooring services, floating cranes, etc.) and aspects related to operation & maintenance (e.g. weather windows, safety, etc.)	CAD software (e.g. Rhinoceros, SolidWorks) Spreadsheet / programming env. (e.g. MS Excel, Matlab)
Economic analysis	From previous stages, an economic analysis is obtained, at each stage of iteration. Important data will be obtained from MRE CAPEX & OPEX project (led by Fundación Chile)	Spreadsheet / programming env. (e.g. MS Excel, Matlab)

Table 1. Design stages, description and materials

3.2. Hydrodynamic Analysis

The hydrodynamic analysis of MRE technologies provides key information about the performance of the system, the main loads that the structure is subject to (e.g. under extreme conditions) and information for operational purposes (e.g. motions under maintenance activities).

From a hydrodynamic perspective, the adaptation of technologies to local conditions in Chile requires:

- Performance analysis of MRE systems under local environmental conditions.
- Hydrodynamic response analysis (loads and motions) of MRE systems and subsystems (e.g. mooring system) under extreme local conditions.
- Hydrodynamic analysis of MRE systems for selected operational scenarios (e.g. installation, maintenance, emergency, etc.).

Under the MERIC programme, hydrodynamic analysis is performed using both numerical and experimental methods. For the numerical analysis, two different CFD (Computational Fluid Dynamics) methods are used:

- **For the mooring-based systems,** BEM (Boundary Element Method) tools in a first stage to obtain results for a large amount of conditions, obtaining performance, motions and loads. Due to the limitations of BEM methods, RANS-CFD tools help to analyse selected cases of the system under extreme conditions.
- **For the foundation-based systems,** only RANS-CFD methods, potentially in collaboration with other MERIC partners.

In parallel, experiments are undertaken at Universidad Austral de Chile´s Wave Tank in collaboration with other national and international institutions. Preliminary experimental research by the participants can be seen in Grüter (2016), Tampier and Grüter (2017) and Pregnan (2018).

Work is currently being done in collaboration with the Technical University of Berlin, where loads from natural sea spectra, storm surges and rogue waves are being determined experimentally for a generic WEC (e.g. Figure 3) for different mooring configurations.

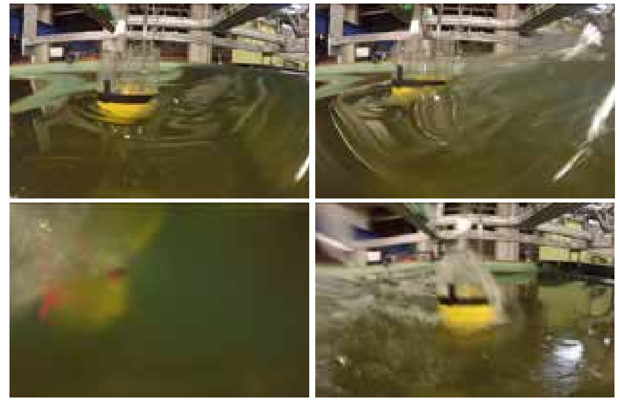


Figure 3: Rogue wave experiment (New Year Wave). Time-lapse images of wave breaking on generic WEC.

The results from these experiments (e.g. Figure 4) will serve as a valuable starting point for future research, as well as for the application and development of experimental and numerical techniques.

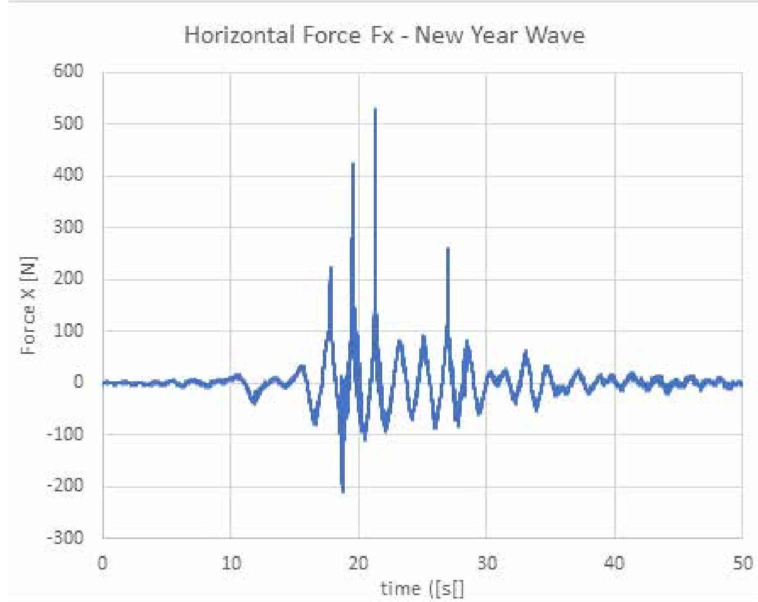


Figure 4: Measured horizontal force (New Year Wave).

3.3. Structural Analysis

The structural analysis of MRE technologies is another key aspect within the design process, and requires the use of advanced methods. For the generic TEC, WEC and FWP designs, however, structural design of the technology itself is not a critical aspect since:

- A detailed structural design is required,
- The capabilities for structural analysis by numerical methods are available in the market and,
- Important advances can be expected from regulatory organs in this regard (e.g. classification societies).

In this context, only global structural analysis of the technologies should be required.

On the other hand, advanced structural methods and hydrodynamic coupling are required for the development of mooring configurations, considering extreme loads and aspects related to installation, operation and maintenance, as well as analysis of particular events such as ship impacts and loss of mooring lines. The information obtained from the hydrodynamic studies represents the foundation on the mooring design process. The coupled response of the integrated system including a floating structure and moorings, allows the study of different mooring configurations to achieve optimal performance of the PTO and assess structural reliability.

The first approach will be to perform an uncoupled analysis in which it is assumed that the mooring lines do not alter the hydrodynamic response of the floater. This is valid for catenary mooring configurations in which the pretension on the mooring lines is small compared to the weight of the floating structure. This technique is used as a first approach for a mooring design.

Second, a fully coupled analysis will be completed with software such as OrcaFlex. In this tool the information from a BEM code is used to characterise the hydrodynamic response of a floater coupled with the effect of the mooring system. Several scenarios can be evaluated including superposition of waves, currents and wind loads allowing the simulation of a complete set of operation scenarios.

The previously described studies will provide output on the tension and deformation on mooring lines and local loads over the floater from the mooring system, enabling the detection of possible weak points on the station maintenance system and identifying future improvements.

Related work in our team has included evaluation of open source numerical tools for uncoupled analysis of mooring systems (Ampuero, 2017), studies of submerged moored slender bodies (Cifuentes et al., 2015), the fully coupled response of vessels, (Eom et al., 2014) and flexible structures for fish farming applications (Cifuentes and Kim, 2015).

3.4. Field Tests

Field tests will be performed aligned with the programming of the Open Sea Lab project deployment.

4. Results and Products

While preliminary work started in collaboration with the Technical University of Berlin since 2016, it's from 2018 until 2022 that the following main results can be expected from the projects:

- Relevant considerations and specific knowledge and developments of use for local manufacture, installation, operation and maintenance of moored devices (WEC and FWP). This considers extreme design loads, mooring configurations, aspects related to marine operations and local manufacture, among others.
- Relevant considerations and specific knowledge and developments of use for local manufacture, installation, operation and maintenance of foundation-based devices (TEC) considering, among others, seismic risk in areas of interest, extreme design loads, and aspects related to marine operations and local manufacture.

These results will be presented as the following products:

- Publications on the design and/ or adaptation of technologies considering the local conditions and natural hazards found in Chile. This knowledge should be relevant for different aspects, especially for survivability, installability, operability and affordability.
- Best practice guidelines (from experience with generic designs and collaboration with developers and international partners).
- Transfer of outcomes to relevant stakeholders (national and international developers, government agencies, etc.).
- First steps towards standards and certification in Chile.
- Availability of human resources, experimental facilities and numerical tools in Chile (MERIC researchers and bi-directional international exchange opportunities).
- Protectable products.
- Expertise in technologies and site measurement.

These outcomes allow for accelerated development and an upscaling of marine renewable energy in Chile. The project positions Chile as an interesting site to test technologies under harsh environmental conditions and allows MERIC, along with the outcomes of the remaining projects "Resource Assessment and Site Characterisation" and "Marine Corrosion", to support other countries in their own marine energy development. Additionally, the application of these outcomes into other fields such as floating wind technologies, aquaculture or coastal engineering, can open new opportunities for MERIC and MRE technologies in general.

Preliminary Planning and Collaboration

Project "Adaptation of MRE Technologies to Natural Hazards and Local Constraints" begins in 2018 (fourth year of MERIC project). In the following table, a general plan is outlined:

		MERIC Project years			
		Year 4 (2018)	Year 5 (2019)	Year 6 (2020)	Year 7 (2021)
Mooring-based technology adaptation	Moored small-sized generic WEC	Preparation of facilities (irregular waves generator) and site (subject to Open Sea Lab project).	Critical analysis, concept(s) selection and "Resource Assessment and Site Characterisation" data.	Numerical and experimental mooring tests. Site tests (Subject to Open Sea Lab project).	Site tests (Subject to Open Sea Lab project). Data analysis & results.
	Medium-sized moored platform	Training and preliminary tests with numerical and experimental tools.	Design of generic systems. Numerical and experimental hydrodynamic analysis	Numerical mooring tests	Data analysis & results
Foundation-based technology adaptation	Foundation-based TEC	Seismic risk assessment.	Geophysical studies.	Design of generic system	Numerical analysis & results.

Within MERIC, other projects interact with the "Adaptation of MRE Technologies to Natural Hazards and Local Constraints" project, delivering interdisciplinary results through fruitful interactions:

- Resource assessment and site characterisation (Pontificia Universidad Católica de Chile)
- Wave device validation test bench / Open Sea Lab (Enel Green Power)
- Cost analysis of MRE (CAPEX & OPEX) in Chile (Fundación Chile)
- Drawing up new guidelines for MRE in Chile (MERIC).
- Ecosystem assessment and perceptions (Pontificia Universidad Católica de Chile)
- Marine mammal characterisation and habitat use (Universidad Austral de Chile)
- Marine corrosion and biofouling (Pontificia Universidad Católica de Chile)

Along with international collaboration, external exchange is considered to play a central role. Specifically, following collaboration aspects are considered in order to fulfill our research goals and consolidate these research projects beyond the planned project (e.g. by additional funding):

Task-specific collaboration:

- Specific task solving
- Exchange of experiences (e.g. Workshops, visits, researcher internships, etc.)

Education:

- Student exchange (bi-directional)
- Research / professional internships (for foreigners in Chile and for Chileans abroad)
- PhD / MSc scholarships abroad

Further collaboration:

- Joint applications in related tasks (Chilean and international funds)
- Joint research contracts (e.g. from developers or government agencies).

SEISMIC HAZARD STUDY OF THE CHILEAN AUSTRAL-SOUTH REGION FOR ADAPTATION OF MARINE ENERGY TECHNOLOGIES

Galo Valdebenito Montenegro
Marisella Ortega Arroyo, David Alvarado Coello

Universidad Austral de Chile, Valdivia, Chile
Núcleo de Investigación en Riesgos Naturales y Antropogénicos (RINA)
Marine Energy Research & Innovation Center (MERIC), Valdivia, Chile

INTRODUCTION

Chile's Austral-South Region is located in a large subduction zone between the Nazca and South American plates, which converge at an average rate of 6.6 cm/y (Kendrick et al., 2003). Beyond the triple point, southwest of Tierra del Fuego, the Antarctic plate subducts below the South American plate at a rate of 2.4 cm/y (DeMets et al. 1990) and below Scotia plate at a rate below 1.1 cm/y (Pelayo y Wiens 1989). Given these tectonic configurations, large earthquakes have stricken the South of Chile, such as the Magellan earthquake of 1879 (magnitude 7.3), the Valdivia earthquake of 1960 (magnitude 9.5) and the Aysén earthquake of 2007 (magnitude 6.2), among others. Seismic generation mechanisms in the Austral-South zone include subduction earthquakes but also earthquakes of cortical type or by strike-slip faults, due to the presence of superficial faults, such as the Liquiñe-Ofqui or Magallanes-Fagnano faults.

In this context, it becomes absolutely essential to evaluate the Uniform Seismic Hazard for the Chilean South-Austral zone, enabling the identification of seismotectonic mechanisms that generate earthquakes and their recurrence, to then characterise a design earthquake in terms of intensity and expected rock acceleration, and the corresponding occurrence probability in a certain period of time. In addition to this, in this study the Local Seismic Hazard will also be characterised, which assesses the dynamic response of soils in specific locations, where potentially vulnerable structures exist, or in locations where future marine energy devices installation could be expected, consistent with high generation potential. This field study is integrated with the assessment of the Uniform Seismic Hazard and the available geological information in order to define the seismic demand at specific locations on the bottom of the strait and borders, where the installation of facilities can be possible. In order to perform this analysis, geophysical surveys at Magellan Strait were carried out, specifically on the First and Second Narrows, which are zones of high tidal energy potential. Therefore, eventual dynamic amplifications, topographic amplifications or other local hazard conditions (site effects) can be afterwards integrated into the seismic demand of marine energy structures to be installed.

General objective:

Perform an estimation and characterisation of Uniform Seismic Hazard and Local Seismic Hazard in the Chile's Austral-South region, looking for the inclusion of seismic threats and local restrictions facing marine energy technology adaptation.

Specific objectives:

- Characterise the geological context of the South of Chile and identify dominant seismogenic sources, as well as main active faults.
- Construct a seismic catalogue for the Austral-South zone, and constitute a representative database of historic and instrumental seism, classified by their seismogenic source.
- Characterise each seismogenic source based on recurrence and attenuation laws.
- Prepare seismic hazard maps for southern Chile.
- Perform a measurement field campaign at Magellan Strait's First and Second Narrows, in zones with tidal energy potential.
- Generate a seismic microzoning of the Magellan Strait, oriented towards local seismic demand evaluation.

Methodology

Uniform Seismic Hazard

Uniform Seismic Hazard studies aim to determine the ground's level of movement which could be found in different areas of the region, on a scale of hundreds of kilometres, without considering specificities of the emplacements. The final outcome leads to establish Uniform Seismic Hazard maps according to the expected values of the study parameters, which themselves are often seismic intensities or maximum horizontal accelerations for different return periods. In order to be able to generate these maps, the following stages must be performed, as described below:

a. Study area definition

The study area spans from Chacao Channel down to Chile's extreme South. In order to evaluate the Uniform Seismic Hazard, it's necessary to define an influence area of the region of interest, which was set to 300km. Thus, large magnitude seism which are not in the study area, but which could affect it, are also considered. The study area is defined as 39°S-58°S y 62°O-80°O.

b. Austral-South zone seismic catalogue generation

Once the influence area is defined, information is compiled from all seism that have taken place to date in the area. Seismic information is used from the Centro Sismológico Nacional (CSN) database, which includes historic earthquakes and seism between 2000 and 2018, from the International Seismological Center (ISC), between 1960 and 2014, and from the United States Geological Survey (USGS), which includes seism between 1919 and 2018.

c. Homologation of different magnitude scales to Ms and separation by seismogenic source

Given the use of different scales in the databases consulted, the homologation of seism to the same magnitude becomes necessary. The scale used is the Superficial Waves Magnitude (Ms), and therefore all other magnitudes will be transformed to Ms with linear regressions. Afterwards, seism are separated by seismogenic sources by means of geographic location of the epicentre and focal depths.

d. Study zone characterisation through recurrence laws

Seismogenic sources are characterised according to Gutenberg-Richter (1994) laws, showing seismic occurrence frequency related to recorded magnitude.

e. Study zone characterisation through attenuation laws

Maximum horizontal acceleration data registered by accelerometers located in the Chilean South available at the CSN is used. Also, maximum horizontal acceleration information available from USGS is included. Finally, Modified Mercalli Intensity data is also considered, provided by the Oficina Nacional de Emergencia of Chile's Ministerio del Interior. With all this information, attenuation laws will be formulated and adapted for the Austral-South region of Chile, according to the identified seismogenic sources. It is worth noting that this stage of the project is being performed by a research student associated with MERIC, Ingrid Vargas.

f. Uniform Seismic Hazard estimation

Seismic hazard probabilistic maps will be obtained in terms of accelerations and intensities for different return periods, which are translated to a seismic hazard zoning of Chilean Austral-South region. Also, with results post-processing, return period curves and exceedance probability curves are estimated.

Local Seismic Hazard

With respect to local characteristics of ground response evaluation, it's important to mention that, after the seismic event of 27 February 2010 (Mw=8.8), normative changes were introduced, in order to improve local ground response evaluation, mainly in dynamic terms. With the purpose of including this into the evaluations, geophysical methods application is contemplated at the locations to be evaluated, specifically techniques based on environmental micro-vibrations records and surface seismic refraction. The main stages of the methodological definition of this evaluation are presented below.

a. Definition of sites to be evaluated

After a review of prior studies that characterise large tidal potential sites, sectors where seismic measurement will be performed for the evaluation of local dynamic characteristics of ground response. As described below, Magellan Strait First and Second Narrows are the ones with larger energy potential. Advance planning of field work also took climatic conditions and site access into account.

b. Field campaign

Once the specific sites for evaluation have been selected, the geophysical surveys are a critical milestone of local seismic hazard assessment. During the field campaign, seismic profiles by means of Refraction Microtremor technique (ReMi) are generated. For this, 120 m length seismic arrays were installed, with 4,5 Hz vertical geophones, 5 m each, at specific locations, in order to obtain relevant data of the stratigraphy and soil dynamics, essential for a seismic microzonation. In addition, ambient microtremor records (HVSR method) to characterise the basin dynamics were obtained in the same places. For the ambient microtremors campaign, triaxial seismographers are used. Seismographs and geophones field installation must be adapted to the climatic conditions of the area, in particular regarding low frequency responses generated by strong winds while registering ambient microtremors.

In order to correlate these results with the available geological data, and to obtain the local seismic demand of the bottom of the Strait in the specific zones defined, the geophysical surveys above described were performed in the areas with more potential in terms of energy generation, implying field campaigns side-by-side in Tierra del Fuego and the continent, in order to interpolate and generate relevant data of the bottom of the Strait and the borders, were specific facilities can be installed.

c. Results post-processing

After the field work, post-processing takes place of the information gathered. Ambient microtremor records enable us to generate spectral ratio H/V Nakamura (1989) curves. These curves are analysed from a taxonometric point of view, with the aim of estimating the unidimensionality of the exploration medium and determining predominant periods of ground vibration. Regarding the post-processing of seismic profiles, dispersion curves are generated from geophysical inversion processes, allowing us to adjust synthetic models to obtain Vs profiles, applying the Constrained H/V hybrid technique for deeper prospecting.

d. Seismic microzoning of sites

The results obtained are analysed from the point of view of local dynamics of the assessed sectors, determining correlations between predominant soil vibration periods, Vs30 values and the possible local amplifications observed from a taxonometric analysis of H/V curves. From this analysis, a seismic microzoning of sites is generated, leading to a general mapping of the spatial distribution of ground dynamic properties in different emplacements, including the bottom of the Strait and borders (Tierra del Fuego, Continent). The results obtained, complemented with uniform seismic hazard studies, constitute a basic input that allows us to later specify local seismic demands of the different areas included in the evaluation, according to the above explained.

Results

Previous Theses

There are two previous works related to the subject, performed at the Escuela de Ingeniería Civil en Obras Civiles at Universidad Austral de Chile, by Oscar Santibáñez: "Uniform Seismic Hazard evaluation in Los Ríos Region using deterministic and probabilistic approaches", and Danilo Oyarzo: "Seismic productivity and seismogenic sources re-evaluation of Chilean Austral-South Zone".

State of the Art

There are several studies performed up to date about seismicity, seismogenic sources classification and seismic hazards in different zones of north and central-southern Chile. The first antecedent related to seismic hazard in Chile was by Greve (1984), who determined safety coefficients of seismic response structures for different areas of Chile. Lomnitz (1969) performed the first probabilistic estimations, creating the first seismic hazard map of Chile, considering only events of a magnitude Ms above 7.5. Afterwards, different studies have been performed using probabilistic methodology for seismic hazard estimation along Chile (Barrientos, 1980; Martin, 1990; Algermissen et al., 1992; Leyton et al., 2009, 2010). For Chilean Austral-South zone, the number of studies declines considerably, with Adaron (2003) research on seismicity and tectonics being worthy of mention.

Theses Associated to MERIC

There are two people performing their Thesis work related to MERIC. The first, Ingrid Vargas, researcher from the School of Civil Engineering at Universidad Austral de Chile, entitled: "Seismotectonic source attenuation curve estimations for the Chilean Austral-South zone". Her progress to date covers a review of previous studies, the current processing of 16 records of CSN accelerometers, intensity records for seism between 2014 and 2018 handled by ONEMI (National Emergency Office), and the recorded intensities for some seism in the study area by the USGS. The second researcher is Matías Burgos, also a researcher from the School of Civil Engineering at Universidad Austral de Chile, who is working on "Seismic microzoning of the Magellan Strait", which can be performed thanks to the seismic field campaign to Magellan Strait supported by MERIC. His main progress covers a review of previous work, georeferencing of prospections made at the seismic campaign and environmental micro-vibrations processing recorded during his field work.

Seismic Catalogue

By unifying data from CSN, ISC and USGS, a total of 2,682 seism are obtained for the Austral-South Region of Chile, between 1919 and 2018, finding four seismogenic sources of interplate type, intraplate, cortical and outer-rise faults.

Seismic Campaign at Magellan Strait's First and Second Narrows

According to the study performed by AQUATERA, entitled "Recommendations for Marine Energy Strategy in Chile: an action plan for its development", the Magellan Region is theoretically valued for its tidal resource of 3,560 MW, and for its wave resource of 88,600 MW, converting this Region into one with the largest energy potential in Chile. The Energy Resource Studies Center at Universidad de Magallanes (CERE-UMAG), from an initiative of the Ministry of Energy of Chile, in the study "Elaboration of an Energy Matrix Proposal for Magellan 2050" identifies the main sites with tidal energy potential in Magellan. These are shown in Figure 1.

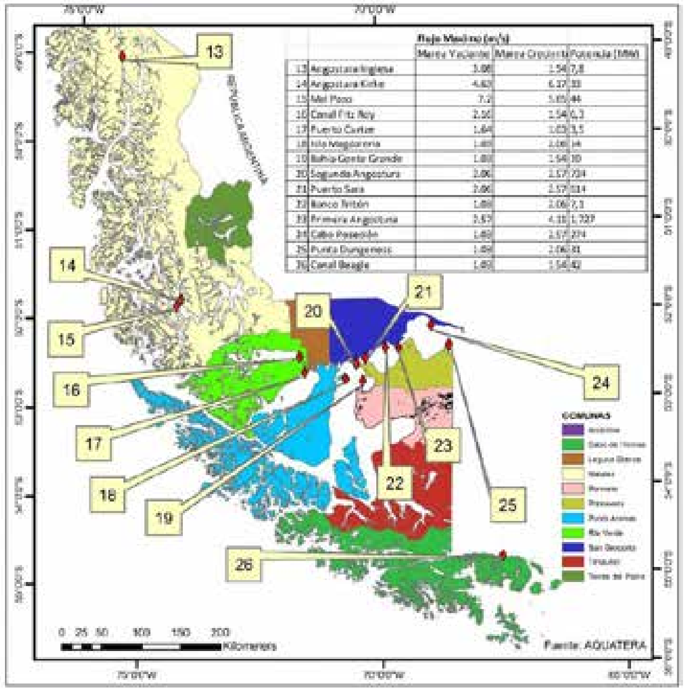


Figure 1: tidal energy sites in Magellan (AQUATERA, 2014).

Figure 1 demonstrates that Magellan Strait's First and Second Narrows are the zones with the highest energy potential, of 1,272 MW and 734 MW respectively, and this is why a seismic measurement campaign was performed at these sites on 7-15 October 2018. These locations would be optimal candidates for marine energy installations, and therefore this campaign aims to incorporate local restrictions to future constructions. MERIC's related professionals in charge of the field campaign were Galo Valdebenito, PhD, David Alvarado, MSc and geophysicist Marisella Ortega, MSc (Figure 2).

Figure 2: MERIC related professionals performing seismic risk campaign at Magellan Strait's First Narrow. From left to right: Dr Galo Valdebenito, Marisella Ortega MSc and David Alvarado MSc.

Seismic measurements were focussed on the locations of special interest for marine energy: San Gregorio, ENAP San Gregorio, small farm Cuatro Hermanas, Puerto Percy, Tierra del Fuego, First Narrow mainland side and the First Narrow, and Tierra del Fuego. Also, seismic measurements were performed at Cabo Posesión and at Punta Dungeness (Figure 3).

The seismic campaign was successful, in covering the First and Second Narrows, and also Cabo Posesión and Punta Dungeness, and therefore seismic characterisation of these areas, including the bottom of the Strait and borders, was achieved, in terms of amplifications and local hazards.

Figure 3: location of measurements taken during the Magellan Strait seismic campaigns.

OPEN SEA LAB

Enel Green Power Chile

INTRODUCTION

The Open Sea Lab (OSL) is designed to be a catalyst to accelerate the development and validation of studies performed within the MERIC research program. Its main objective is to test MRE technologies adapted to work according to local environmental conditions.

Enel Green Power Chile (EGP), as the ‘implementing partner’, is in charge of the delivery and the installation of the Open Sea Lab, which will allow MERIC to study different topics such as: resource assessment, modelling and coupling with power generation forecasts, biofouling, mooring technology adaptation, bio-corrosion and abrasion models, among others.

The heart of the Open Sea Lab is the wave energy converter (WEC) which will convert the mechanical energy of waves into electrical energy, delivering it to all sensors and tools. Other equipment and instrumentation will be installed, combined with the wave energy converter and corresponding telecommunications infrastructure.

The Open Sea Lab has a key role in MERIC’s context and all partners will benefit from this important facility, with its availability for performing studies and research that will leverage the development of marine energy in Chile. Below, a small brief of the Open Sea Lab will introduce the reader to its main features and critical issues, such as:

- Technical overview
- WEC selection methodology
- Components, layout and scheme
- Lab site selection

Technical Overview

The Validation Test Bench (VTB) project embedded in MERIC's program has the goal of deploying, operating and testing the Wave Energy Converter (WEC) as the first application in real offshore oceanic conditions along the Chilean coast. EGP is in charge of the design, construction and deployment of the VTB. Operation of the VTB will be shared between MERIC's scientific partners involved in the project. The main aim of the VTB will be to verify the power production of the ocean waves taking into account all local environmental variables. This is why the VTB has been defined as the 'Open Sea Lab'.

Operation of the VTB will allow MERIC to analyse and understand interferences between the devices and the marine environment surroundings. EGP has selected the most adequate WEC technologies to ensure suitability with the Chilean wave climate and compatibility with the geo-morphological condition of the seafloor. It will guarantee the correct functioning of the entire 'Open Sea Lab'.

Wec Selection Methodology: Safety and Reliability

When evaluating the different technologies available on the market, EGP normally uses several evaluation criteria, which correspond to different aspects of the device (mechanical, performance, cost, adaptability, acceptability and so on). In MERIC's program, EGP is focused on all those aspects, with a special emphasis on safety and reliability. For example, the level of technology maturity as measured in Technology Readiness Levels (TRL)[1] impacts directly on both of them.

The Chilean coast is generally a highly energetic zone in terms of wave height. This potentiality requires technologies with a high TRL to guarantee a high level of reliability and continuity over time. This is therefore a first criterion that EGP is considering when evaluating the various technologies available on the market. Other aspects are technology replicability and safety. With this in mind, EGP has evaluated various technologies that are as appropriate as possible for the Chilean wave climate and compatible with the geo-morphological condition of the seafloor.

1 TRL is a method for estimating technology maturity of Critical Technology Elements of a programme during the acquisition process. They are determined during a Technology Readiness Assessment that examines programme concepts, technology requirements, and demonstrated technology capabilities.

Selection of the WEC has to meet the following main requirements:

- To be an electrical standalone and with a small capacity power supply system, capable of supplying load for many days in a full calm wave climate condition;
- Proven technology with high TRL, no less than TRL6. Already tested in real oceanic conditions over a long period of time.
- Easy deployment in Chilean coasts, where the resource is very energetic.
- A technology with a slack mooring system, suited to being installed in different conditions of the seafloor morphology and depth.
- To minimise Operations and Maintenance (O&M) costs and simplify the removal operation from deployment site guaranteeing lowest environmental impact.

Components, Layout and Scheme

Bearing in mind that the main scope of MERIC's VTB project is a first global approach to the issues involved in a wave energy application in the Pacific Ocean, the main goal is to provide scientific and industrial partners with an offshore open platform around an operative WEC prototype. The VTB design is characterised by the following main functional parts (some of them installed onshore):

A. Wave Radar

An innovative system to measure the wave climate and the surface water stream in a wide area surrounding the WEC. In this specific case, an X-Band Wave Radar located at the VTB onshore station will be installed;

B. Long Range Wi-Fi Network

A high capacity long range Wi-fi Local Area Network (LAN), extended offshore up to 5 km from the coast, that delivers in real time high definition data transfer from the sensor systems located offshore to terrestrial data acquisition and management systems;

C. Internet Connection

A suitable capacity (in the order of 30 Mbps) Internet connection between the onshore station and the web applications. In the first stage, the Internet connection will be realised by means of a radio link, in expectation of a fibre optic connection.

D. Web Cloud

Use of sufficient storage and computational capacity leased by an Internet Cloud provider to make available data collected from the VTB sensors and systems. This Data Lake will be accessible in real time to all partners involved in the VTB project. Via the Web Server interface, some SCADA functionalities, located on the Web Cloud space, will be remotely accessible allowing for easy surveying and maintenance of faults. This, in order to have a clear, real time graphical and numerical presentation of the OSL operational status and with predictive functionality on sensor cleaning needs.

E. Offshore Sensors

Sensors will be deployed to monitor:

- Mooring loads analysis: three loads cells installed close to the WEC on the connection of the mooring lines;
- A junction box will be connected by umbilical cable to the WEC, and it will serve as a hub for several sensors (already defined or to be defined in the future);
- Water physical/chemical composition sensors will be connected to the junction box
- ADCP will be connected to the junction box ad will allow for real time data transfer to a cloud server;
- Biofouling and bio-corrosion tests will be made on some materials attached to the platform

The OSL is designed as follows in terms of its components and their relative location.

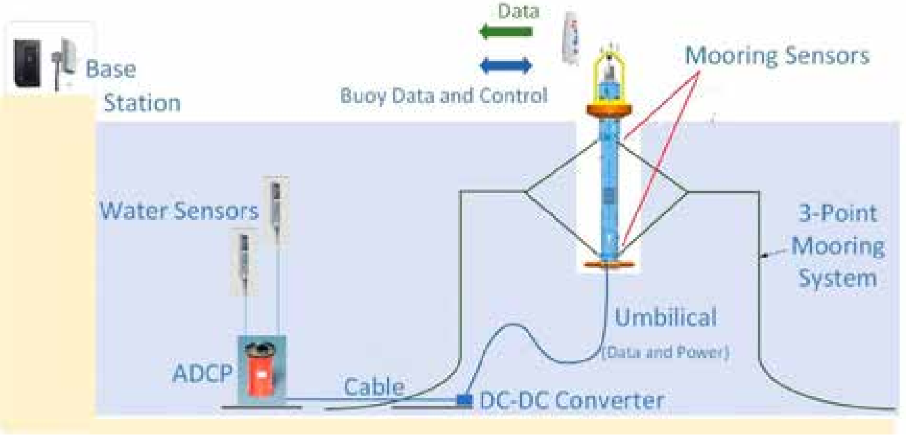


Figura 1: The Open Sea Lab Layout

Lab Site Selection

At a global level, the Chilean coast has one of the highest worldwide wave energy potential. It could provide an abundant, clean and environmentally friendly energy. The inclusion of wave energy in the energy matrix of Chile will be a significant contribution, and for this reason EGP is supporting the development of a wave energy project.

An ideal site for the installation of projects to take advantage of wave energy should have, first of all, a good resource (wave energy: 15 (kW/m) to 40 (kW/m)), it should not interact with other activities (fishing, military, industrial, navigation, sports, etc.) and it should be located at a prudent distance from protected areas (archaeology, landscape, public heritage, etc.).

On the mainland there are several requirements, such as: appropriate surface and access, facilities for personnel, warehouses and workshops, water and sewer availability and finally, feasibility for connection to the electrical and telecommunications networks. In addition, some sustainability issues are important: environmental impact must be minimised, acceptance by communities must be guaranteed, and installation and O&M costs have to be reasonable.

The general methodology for site selection includes the following steps:

- Selection of areas with high resource potential
- Collect information on site characteristics
- Carry out a study of environmental relevance
- Make a pre-selection of sites with information gathered in previous steps
- For pre-selected sites, verify oceanographic, environmental and geomorphological suitability
- All information gathered should be integrated into a geographic information system (GIS)

Finally, a classification of the sites must be made according to their energy potential, site characteristics, environmental impact and economic considerations. The present report details the information that must be gathered about potential sites for the use of wave energy.

In Chile, the potential for wave energy increases from North to South, with values close to 20kW/m in the extreme north and more than 75kW/m from the island of Chiloé to the south. In general, low resolution wave energy maps available provide area information, so the specific wave energy potential of a site must be determined separately.

Location Characteristics

The pre-conditions for a site depend heavily on the technologies adopted. For this reason, appropriate sites for one technology may not be suitable for others. It is essential that the location has access to the coastal edge and space where instrumentation, observation towers, etc. can be installed. The maintenance and operation of a wave farm will require boats and port facilities in accordance with the technology used. On land, facilities for personnel and others for workshops, wareshops or warehouses are required. The availability of these resources will affect the investment, maintenance and operation costs of the OSL.

In addition, property, surface and land boundaries, access to the site, distance to resources that are not on site (ports, shipyards, etc.), distance to airports and to nearest bays, have to be included. Regarding interferences with other activities, it is important to be informed if the proposed maritime area is used for other activities such as navigation, military activity, fishing or aquaculture, submarine cables, gas pipelines, wastewater pipes, mining on the seabed, recreational or sports activities. In most cases, these activities are incompatible with the wave farm, so it must be ensured that the chosen area is free of maritime concessions. This information is collected during the environmental relevance study.

Environmental Relevance Study

In preliminary form, for each proposed site an Environmental Relevance Study will be carried out with the purpose of detecting the main environmental factors that may affect a project located on the respective site. It should consider geo-social elements both on the coast (existence of communities, cemeteries, archaeological sites, protected areas, industries) and at sea (existence of archaeological sites, sighting of protected species, protected areas). At the same time, it is important that the presence or future creation of ecological reservoirs that may prevent the construction of facilities or the laying of transmission lines also be reported.

BIOFOULING

Sergio Navarrete
Miriam Fernández, Juan Carlos Castilla, Mirtala Parragué, Jessica Bonicelli, Francisca Rojas, Simone Baldanzi, Nicole Osiadacz, Randy Finke
Clara Arboleda, Alejandro Pérez-Matus

Pontificia Universidad Católica de Chile, Santiago, Chile
ECIM, Estación Costera de Investigaciones Marinas, Las Cruces, Chile
Marine Energy Research & Innovation Center (MERIC), Santiago, Chile.

INTRODUCTION

Virtually all human-made structures that are deployed at sea are colonised in a matter of hours or weeks by marine microscopic and macroscopic organisms, algae and invertebrates. Depending on the purpose of the structure and the time they must be exposed to marine conditions, these organisms, collectively called fouling or biofouling, can represent a comparatively minor problem, like barnacle growth on piers, or they may represent an immense, sometimes unsurmountable problem for some human enterprises. The Greeks in ancient times were well aware of the problems that biofouling imposed on vessel navigation and attempted to reduce its impact by coating their ships with copper sheets. Today, the shipping industry alone spends over 60 billion dollars every year in anti-fouling paints and coatings to reduce biofouling growth from hulls and propellers, which can increase fuel consumption by up to 40%. Similarly, the marine aquaculture industry identifies biofouling as one of the major problems that threatens the operation, and the consequent economic returns, of the activity in coastal and oceanic waters. The emerging marine renewable energy (MRE) industry is also facing the problems of biofouling and must rapidly learn about strategies that can reduce biofouling accumulation, and must do so in an environmentally-friendly manner, so that the new technologies are mechanically sound, economically profitable and ecologically and socially acceptable.

After the worldwide ban of TBT (Tributyltin) in anti-fouling paints - one of the most toxic substances ever released by humans in the natural environment - the anti-fouling industry switched primarily to the use of copper and zinc as biocides. But since these substances also accumulate in marine sediments and affect marine life, the research race is on to find substances and strategies that can be effective against the most troublesome fouling organisms, and at the same time have zero or minimal environmental impacts. Since the effectivity and durability of this new generation of anti-fouling strategies varies with the type of marine organism and general environmental conditions (e.g. temperature, depth), biofouling research must be conducted with the local flora and fauna to which the structures and technologies will be exposed. Moreover, since MRE technologies must be deployed for long periods of times, usually several years, the more short-term strategies used in other industries (aquaculture) may not work over the expected much longer MRE deployments.

Over the past decade, experimental research conducted in laboratory and field conditions has shown the importance of biofilms for the settlement of macroalgae and invertebrate larvae. Indeed, the establishment and growth of biofouling can be visualised as an ecological succession that begins with the settlement of bacterial and other microscopic organisms in a matter of minutes. Such microorganisms increase in diversity and complexity forming a rich microbial community collectively called 'biofilm', which later facilitates, or in some cases deters, the settlement of macroscopic organisms (invertebrates, macroalgae). Once macroscopic organisms are established, ecological succession proceeds by processes of facilitation and interference competition to reach a final state where one, or very few, dominant species, usually of high biomass, dominate the surfaces. Thus, the early interaction between biofilms and settling invertebrate larvae is critical to initiate the biofouling succession and is one of the foci of active research worldwide, especially now that genetic tools (e.g. metagenomic, next generation sequencing) are available. Of course, the successional pathways, the rates of biomass accumulations, and the identity and attributes of the species that colonise the surfaces, and of those that outcompete others later in succession, vary across biogeographic regions and environmental conditions.

Biofouling research addresses many simple and broad questions at the interface of marine ecology and engineering design, as well as some quite complex issues about the mechanisms of biofouling settlement at the interface of larval ecology, microbiology and material sciences. Questions such as: are there differences in susceptibility to fouling among the different materials that can be employed in the MRE and other industries; or what is the effectivity of anti-fouling paints in high-energy environments? are of practical and ecological importance. From the ecological standpoint this amounts to asking whether initial differences in colonisation of different materials lead to alternative biofouling community development. From a practical standpoint, the issues raised are whether some materials may present much lower biofouling risks and that coatings effectively used in protected habitats may fail in others, such as high wave-energy environments. Which properties of human-designed materials (e.g. hydrophobic or super-hydrophobic polymers) affect which components of the biofilm community and, in turn these facilitate or deter invertebrate larval settlement is a matter of active research worldwide. Objectives and work methodology

Objectives and Work Methodology

Considering the disparity of knowledge about biofouling risks present in the different marine environments of Chile and the wide diversity of MRE technologies that are being developed, we follow a four-level approach:

1. We are conducting experimental studies to characterise the biofouling community of the different high-energy environments where MRE technologies can be deployed, including wave-exposed subtidal and high current ecosystems. Useful information about biofouling communities requires not only lists of species, but a quantification of rates of colonisation, seasonal variability, rates of biomass accumulation and successional pathways towards dominant species. We are conducting studies at different depths in wave-exposed habitats of central Chile, in Chacao Channel near Puerto Montt and in the Magellan Strait near Punta Arenas. To this end, we have developed comparatively inexpensive mooring systems and testing frames that can be deployed in highly wave-exposed environments and in the strong currents of tidal channels. In these systems, we install biofouling settlement plates of varying materials and at different depths, which can be monitored by SCUBA diving and replaced to characterise colonisation, measure biomass accumulation rates, and examine successional pathways. A biological archive with reference species is held at the Estación Costera de Investigaciones Marinas (ECIM) at Las Cruces.

In addition, this aspect of our work includes the quantification of critical attributes of all common biofouling species, including body size (mass), growth rates, body flexibility, buoyancy weight (under water), and estimates of drag coefficients. Estimates of drag coefficients are conducted by constructing 3D printing models of different sizes of the most common species, and then quantifying drag forces in the flow channel of the Escuela de Ingeniería Naval of Universidad Austral de Chile at Valdivia. At this point we are working with two model species, the 'picoroco' (barnacle) Austromegbalanus psittacus and mussels. The species-specific attributes are used in constructing risk assessments for different types of technologies and applications.

2. We have developed a 'testing bench' where different commercially available anti-fouling products, as well as new materials and coatings that are being developed by different scientists and research and technology companies, can be tested. The testing bench has two components:

a) An invertebrate larvae laboratory (Figure 1), where detailed observations and experimental tests can be conducted under controlled environmental conditions (temperature, photoperiod, oxygen concentration, etc.). To this end, we have developed the techniques to culture larval stages of the most common and dominant biofouling invertebrates, which are cultured through competent larval stage, when they are challenged with different settlement surfaces and anti-fouling coatings. Our laboratory is now prepared to work with larvae of the barnacles Austromegabalnus psittacus and Notobalanus flosculus, as well as the tunicate Pyura chilensis. These are the species that dominate the biofouling community at wave-exposed environments of central Chile. Laboratory tests with settling larvae are also used in the development stage of new anti-fouling coatings and strategies since they permit better control of condition and fast (and frequent) observation of the settlement process.

b) A field-testing bench (Figure 2) where different settlement surfaces and anti-fouling coatings can be exposed to the large diversity of species that naturally forms part of the biofouling community, and harsh environmental conditions. These tests are conducted in the mooring system at wave-exposed subtidal habitats of Las Cruces. These testing benches are open to all developers who wish to collaborate with our team in the development and testing of their own products. We have already tested four different materials commonly used in the shipping and aquaculture industry and a commercially available and commonly used, copper-based anti-fouling paint.

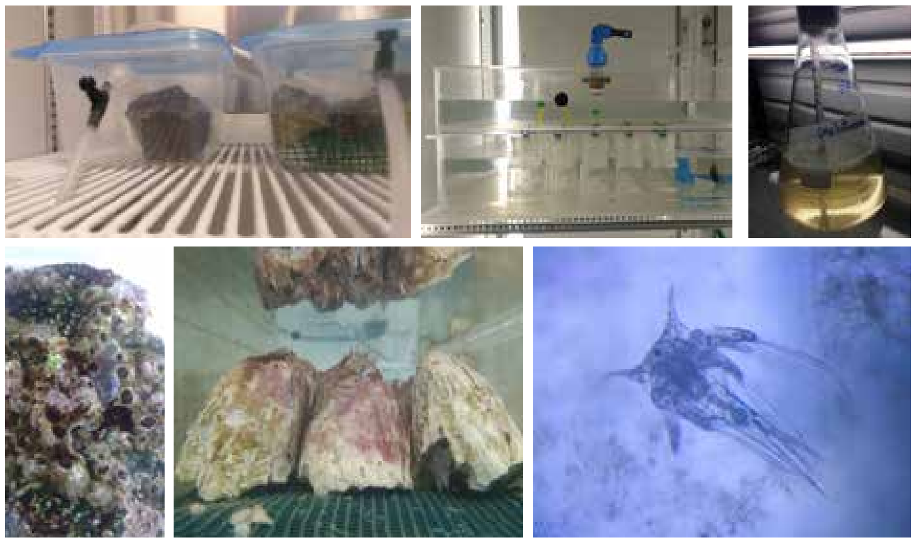


Figure 1: invertebrate larvae laboratory at ECIM-UC, Las Cruces.

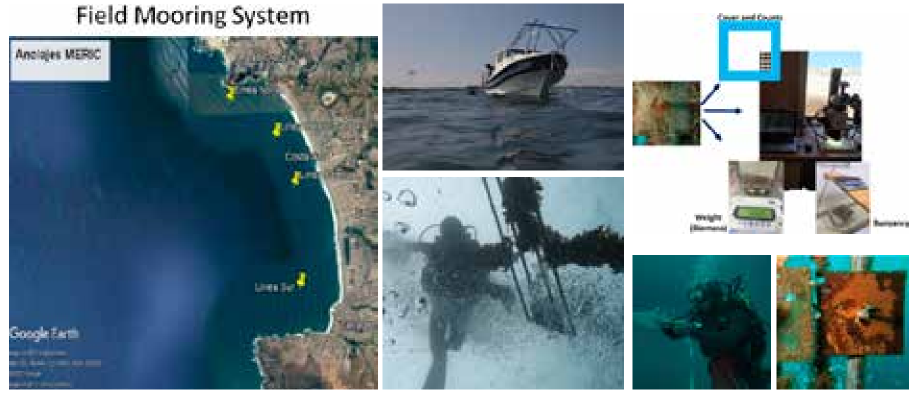
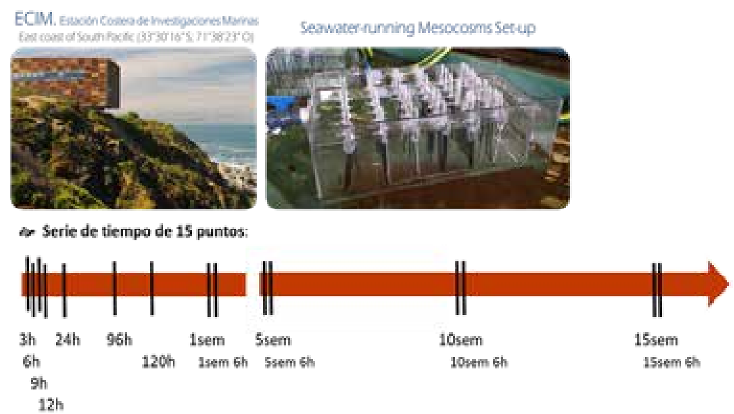


Figure 2: field testing bench, deployments at Cartagena Bay and laboratory set up.

3. After the detailed characterisation of the biofilm community and microbial succession patterns already conducted by researchers from MERIC's Marine Corrosion project, we are now examining the interaction between biofilm community composition and settlement of dominant fouling species (Figure 3). Through the use of metagenomics and epi-fluorescence and confocal microscopy techniques, we are investigating the association and mechanisms of interaction between larvae and components of the biofilm. We are interested in elucidating inhibitory and facilitatory interactions with components of the microbial community, and how a modified biofilm can alter (decrease or increase) settlement rates of dominant invertebrates.



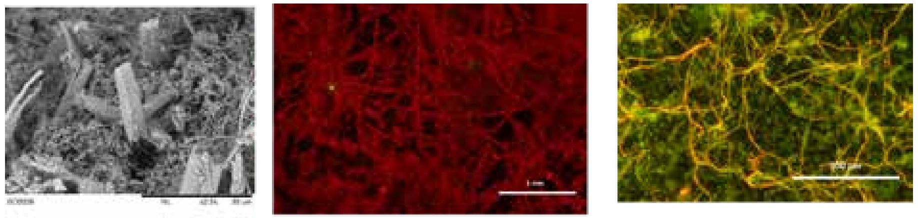


Figure 3: Examples of images from the work on interaction between biofilm community composition and settlement of dominant fouling species.

4. We are also developing new anti-fouling approaches, including the use of different experimental polymers. In collaboration with scientists from MERIC's Marine Corrosion Project, and the biofilms team in particular, and from the Chemical School UC, we are now testing the deterrent capacity of 'clean' and copper-based polymers in the laboratory (Figure 4).

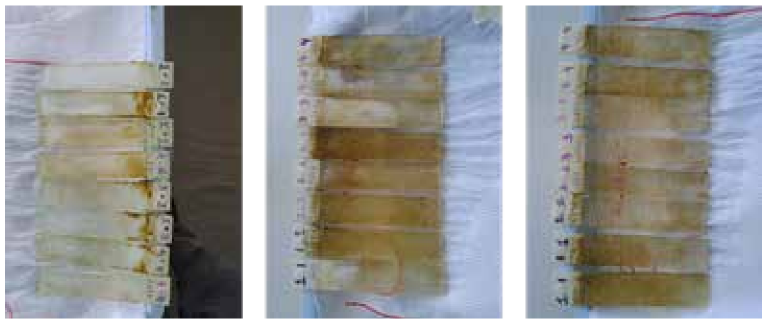


Figure 4: example of samples used in anti-fouling approaches testing.

Some of our results

A 23-month long experimental study on the coast of central Chile allowed us to characterise biofouling colonisation, rates of accumulation and succession patterns at two different depths and different substrates (Figure 5). Throughout the study, we recorded 62 species, 36 of which were sessile. Biomass accumulation rates were among the highest ever recorded in the literature for any place in the world, with significantly higher and more seasonal rates above than below the thermocline. Slightly but significantly higher biomass was observed in ceramic tiles than acrylic or safety-walk surfaces, suggesting that different materials may represent different biofouling risks, but such differences varied with depth and month of the year. In all materials, surface cover reached nearly 100% within about a month of exposure at 5m deep in spring and summer months, and over 70% at 15m deep, with lower cover in winter months.

The patterns of total biofouling biomass measured in air (weight) were quite different to those measured submerged in seawater, highlighting the importance of species attributes (body density) when assessing risks of biofouling for different human-made structures. The hydrozoan Obelia geniculata was by far the fastest colonizing macro-invertebrate species throughout the year and at both depths, covering the entire plate surface in spring-summer months. Community composition shifted in favor of large-bodied, heavier species when surfaces were exposed for more than six months. Succession in shallow waters followed a deterministic path from hydrozoans, to the large-bodied barnacle Austromegabalnus psittacus to dominance by the tunicate Pyura chilensis. Final successional stages appear to be the same in deeper waters, but dominance was not achieved before the end of the experiment. Ecological perspectives and simple recommendations to developers and the productive sector are discussed.

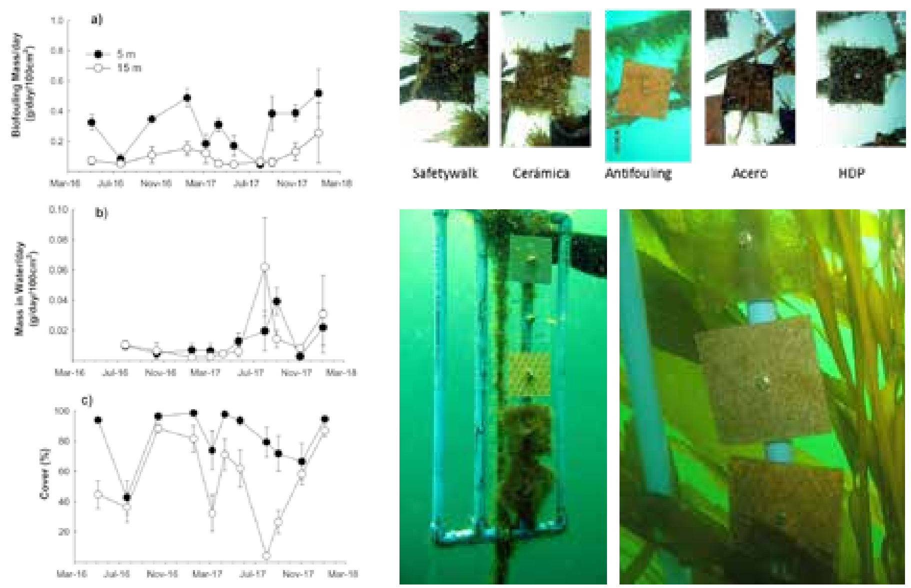


Figure 5: (left) biofouling mass and coverage variation and (right) images of field experiments at Cartagena Bay.

We have also assessed whether biofouling colonisation, main species and biomass accumulation rates were different among three materials, aluminum, high-density polyethylene (HDPE), and Steel A36 and at two different depths of a wave-exposed shore in central Chile (Figure 6). We hypothesised that either colonisation was material-specific and/or that the adhesion of foulers to the different materials (tenacity) was sufficiently different that waves could remove them from some surfaces more than others. Additionally, we evaluated the performance of an anti-fouling paint widely used in shipping and aquaculture operations. Our results show that, after nearly eight months of exposure to field conditions, there was no significant settlement of macrofouling species on plates coated with the selected anti-fouling paint, and its effectiveness was similar above and below the thermocline. In contrast, the surface of all other materials was almost completely covered by fouling within three months of exposure, with no significant differences in either composition, cover or the rate of biomass accumulation among them.

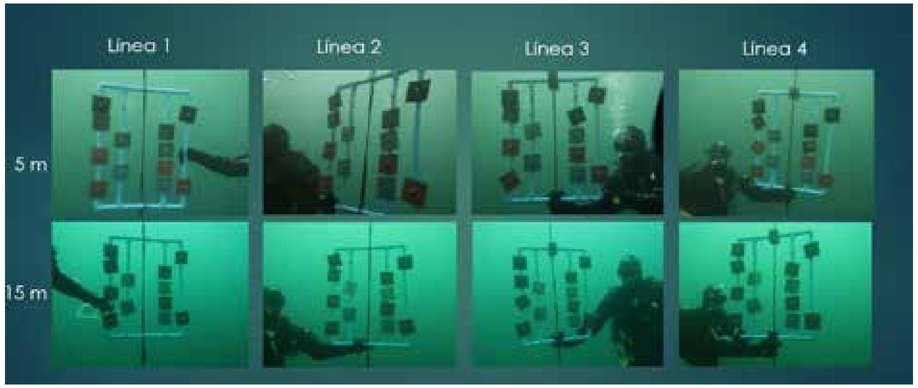
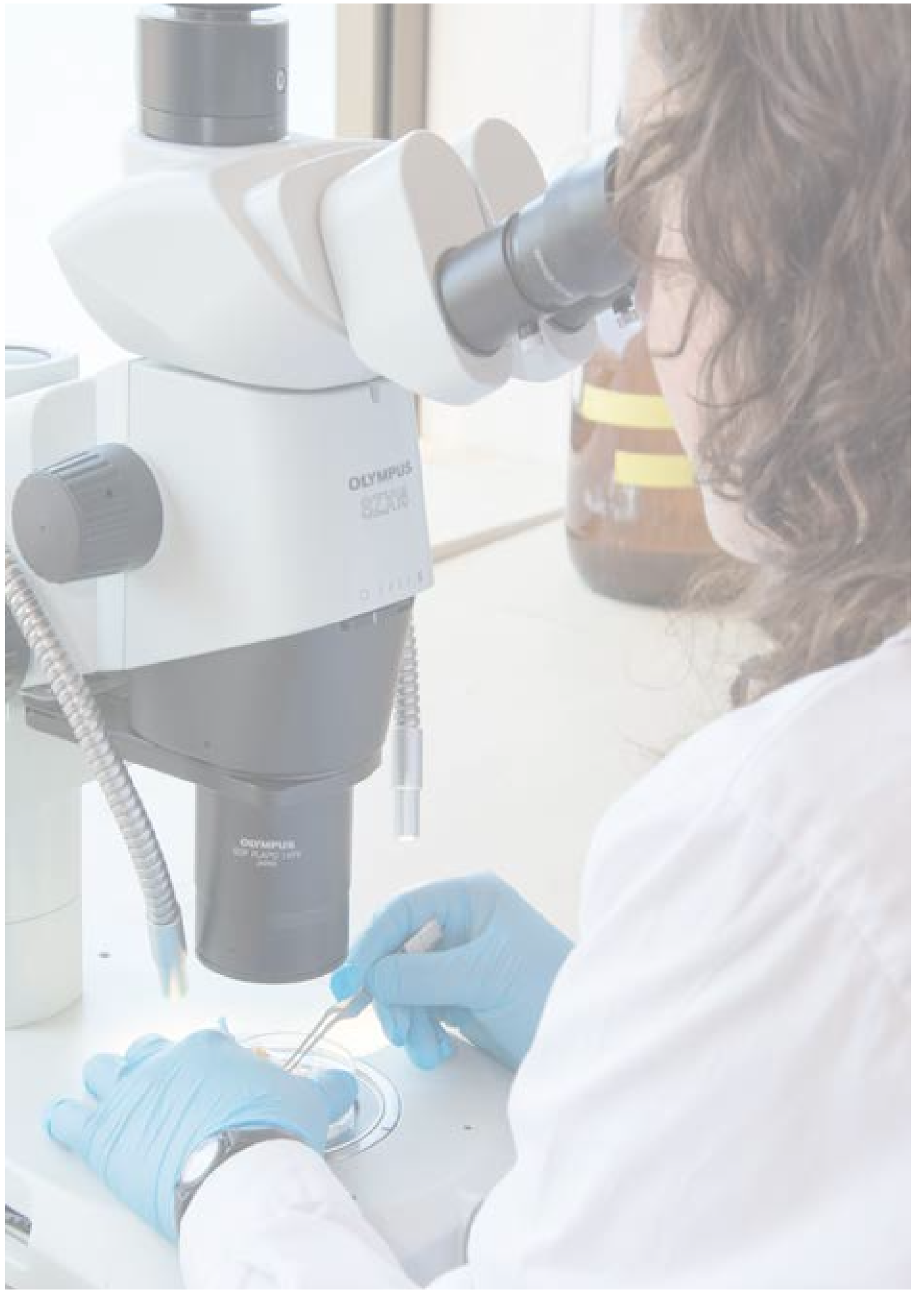
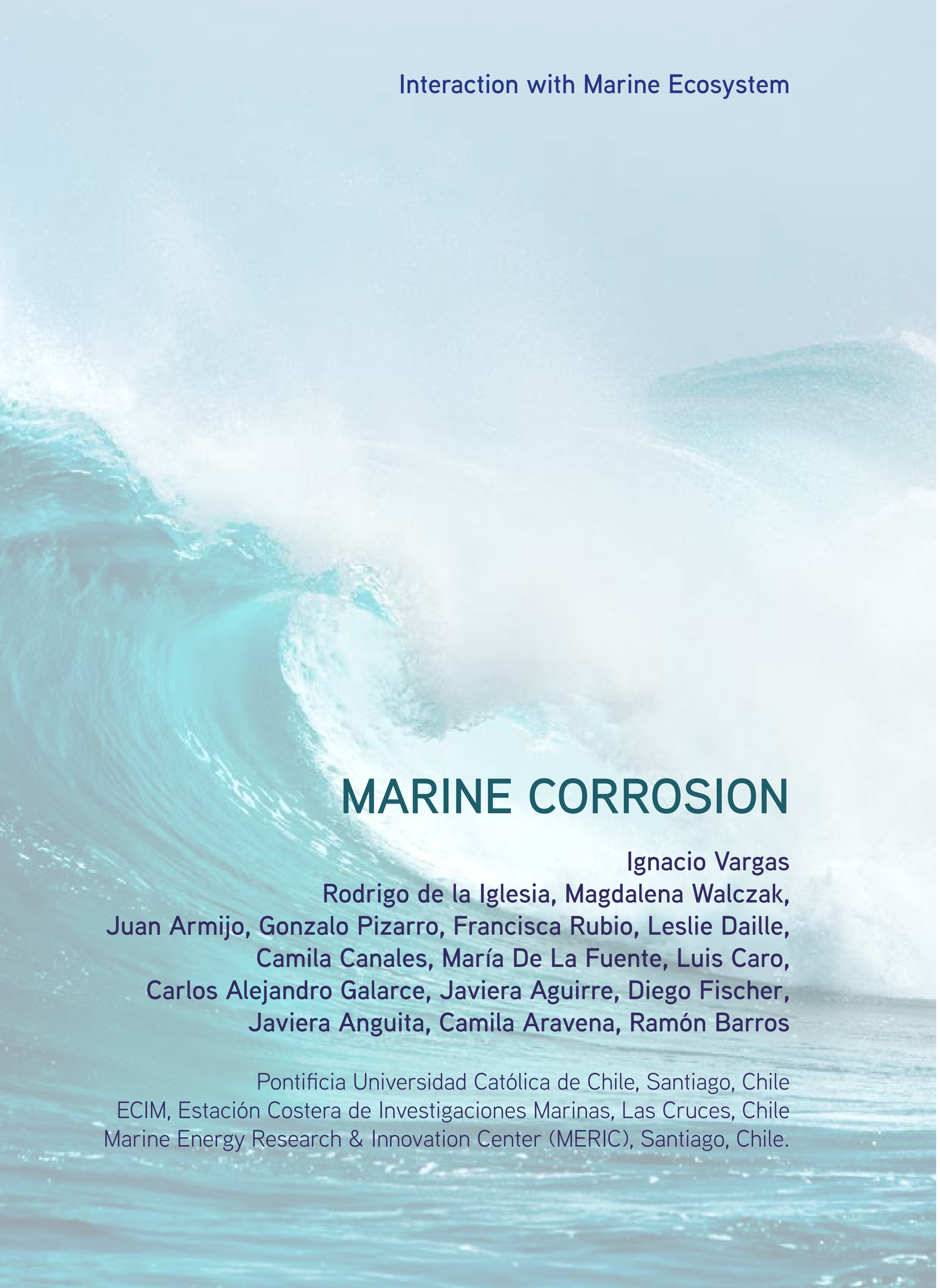


Figure 6: field work of samples installation at four locations and two depths at Cartagena Bay.





MARINE CORROSION

Ignacio Vargas
Rodrigo de la Iglesia, Magdalena Walczak,
Juan Armijo, Gonzalo Pizarro, Francisca Rubio, Leslie Daille,
Camila Canales, María De La Fuente, Luis Caro,
Carlos Alejandro Galarce, Javiera Aguirre, Diego Fischer,
Javiera Anguita, Camila Aravena, Ramón Barros

Pontificia Universidad Católica de Chile, Santiago, Chile
ECIM, Estación Costera de Investigaciones Marinas, Las Cruces, Chile
Marine Energy Research & Innovation Center (MERIC), Santiago, Chile.

INTRODUCTION

Corrosion is an electrochemical phenomenon that affects all metallic materials exposed to an aqueous or humid environment. According to information recently published by the World Corrosion Organisation, the annual cost of corrosion in developed countries is between 3 and 4% of their gross domestic product (Koch et al., 2016). In the marine environment, the wear and tear of structures such as pipes, docks, boats, energy generation devices, among others, generate high costs to industry through losses and maintenance of materials. Corrosion rates for steel in seawater range from 0.1 mm to 4 mm per year (Valdez et al., 2016). For example, corrosion cases are observed in steel breakwaters, which lose their thickness up to the point of perforation and subsequent breakage due to the mechanical stresses of waves. The high costs associated with corrosion have created the need to generate information on how this phenomenon occurs on our shores and how we can predict, control and prevent it.

One of the main aspects researched in this project is the role of marine microorganisms as catalysts of corrosion processes. Stoodley (et al., 2002) showed that microorganisms when adhering to metal surfaces grow and form a community embedded in extracellular compounds such as proteins, sugars and lipids that they produce, that provides them with beneficial conditions to stay adhered to that same surface. This complex and heterogeneous biological structure is what we call a biofilm. In addition, in marine environments larger organisms, such as macroalgae, bivalves, barnacles, among others settle in (Macleod et al., 2016), thereby increasing the complexity of the process. Therefore, preventive and early action strategies are essential to avoid severe and irreparable damage to the structures used in the extraction of marine energy.

Objectives and Work Methodology

Considering the importance of the effects of corrosion on devices for marine energy, this project has proposed the following objectives:

i) characterise the corrosion processes in selected Chilean marine environments,
ii) evaluate the corrosion resistance of different materials studied under marine conditions, and
iii) develop general mathematical models to study and predict marine corrosion.

This project is developed in a parallel and coordinated manner across five laboratories of the Pontificia Universidad Católica de Chile (PUC), namely:

- The Laboratory of Biotechnology and Environmental Microbiology
- The Laboratory of Corrosion and Wear of Materials in the Faculty of Engineering
- The Bioelectrochemistry Laboratory of the Faculty of Chemistry
- The Marine Microbiology Laboratory of the Faculty of Biological Sciences, and
- The Marine Corrosion and Biofouling Laboratory of the Marine Research Station (Estación Costera de Investigaciones Marinas, ECIM) located in Las Cruces (Valparaíso Region).

Currently, the experiments have focused on the study of the corrosion phenomenon of different stainless steels tested with seawater from the Central Coast of Chile (South Pacific Ocean). In these tests we perform an interdisciplinary evaluation of the problem, which involves analysing the following aspects: i) the advance of corrosion through the analysis of the deterioration of the surface of the metal, ii) the development of the microbial community that colonises the surface (microorganisms, how many and when), and iii) the quality of the seawater where the experiments are carried out (pH, conductivity, dissolved oxygen, nutrients, etc.).

To monitor corrosion, we carry out electrochemical analysis, which allows us to analyse the behaviour of the material against exposure to natural sea water, and we also determine the mass loss of the material over time. To characterise the microbial community, we use molecular techniques for the identification of microorganisms, morphological characterisation of the biofilm formed using electronic and epifluorescent microscopy, and atomic force microscopy to analyse the topography of the material after exposure. Finally, water quality is measured by considering physicochemical parameters such us, temperature, pH, conductivity and dissolved oxygen, which is essential in the characterisation of the environment in which our experiments are carried out.

Figure 1: Marine Corrosion and Biofouling Laboratory at Estación Costera de Investigaciones Marinas (ECIM), Las Cruces.

Development of an Interdisciplinary Experimental Platform for the Study of Marine Corrosion

The corrosion process is dependent, among other things, on the composition of the metal surface material that is exposed to seawater. It is for this reason that this project research group has focused its studies on different types of stainless steel and coatings, where the different alloys that make them will determine their resistance to corrosion in marine environments on the Chilean coast.

During the development of this project, we conducted laboratory tests proving the strength of materials, exposing them continuously in seawater, and simulating the effect of the tide and flow. For this reason, the research group has designed tanks, which allow us to simulate these conditions in a controlled way and with natural sea water from the Central Chilean Coast, specifically at the ECIM facilities of the at Las Cruces.

When performing these laboratory experiments, the metal plates are submerged in the water and exposed for defined periods of time based on different research questions. On the other hand, the project has conducted tests directly at sea, evaluating the effect of the depth at which these surfaces are installed on the development of corrosion. To date, 316L stainless steel (marine grade) plates have been exposed to depths of five and 15 meters during different exposure times (approximately two and three months), whose preliminary results show us the possible influence of the incidence of light, nutrients and hydrodynamic conditions across the water column on biofilm development and material degradation. These results were presented at the International Congress on Marine Corrosion and Fouling (Rubio et al., 19th ICMCF, 24-29 June 2018 in Melbourne, FL., USA).

First Steps in the Battle Against Marine Corrosion in Chile

To date the studies carried out by Aguirre et al. (2017), have allowed to determine that the communities of microorganisms that settle on the metal surface are statistically different from the community that is found in the surrounding seawater, therefore, there are specific microorganisms that are naturally found in seawater and that are able to adhere to a metal surface. In addition, it has been determined that the microbial communities that are established on the surface are particular for each material evaluated under laboratory conditions. By exploring the diversity of these biofilms, it has been possible to determine that they are complex communities that comprise both bacterial and eukaryotic microorganisms.

On the other hand, the ECIM Research Station enables us to evaluate the effect of tides on the 316L and 304 steels. For this purpose, larger tanks were used, allowing a complete immersion of the structure where the metal plates were mounted, for periods of 12 hours between tides.

These tests showed us that, in both materials, the treatments with tide simulation showed less mass loss and micro-organisms, greater resistance to adverse conditions, such as those that are not submerged during the simulation phases of low tide (manuscript under review). After 15 weeks, all the plates showed corrosion, however, on those exposed to tidal simulation conditions, the development of corrosion was less aggressive in terms of deterioration, according to Fischer et al. (2016).

Additionally, and within the framework of the search for strategies to control, delay or avoid corrosion, a coating of 304 stainless steel plates with the (3,4-ethylenedioxythiophene) polymer (PEDOT) has been tested. The PEDOT polymer was electrochemically deposited on the steel plates and then these were exposed constantly to natural seawater. The performance against corrosion and the development of the biofilm were evaluated after seven, 35 and 210 days' exposure. The results of this work indicate that the presence of the polymer generates a delay in the colonisation of microorganisms for at least 35 days, and therefore, in the accelerated development of corrosion (Aguirre et al., 2017).

Figure 2: Exposure experiments of stainless steel coupons to seawater. Different types of tanks and configurations are used to simulate the effect of tides and immersion in the corrosion resistance of the tested materials.

Towards the Development of Sustainable Infrastructures to Create Marine Energies in Chile

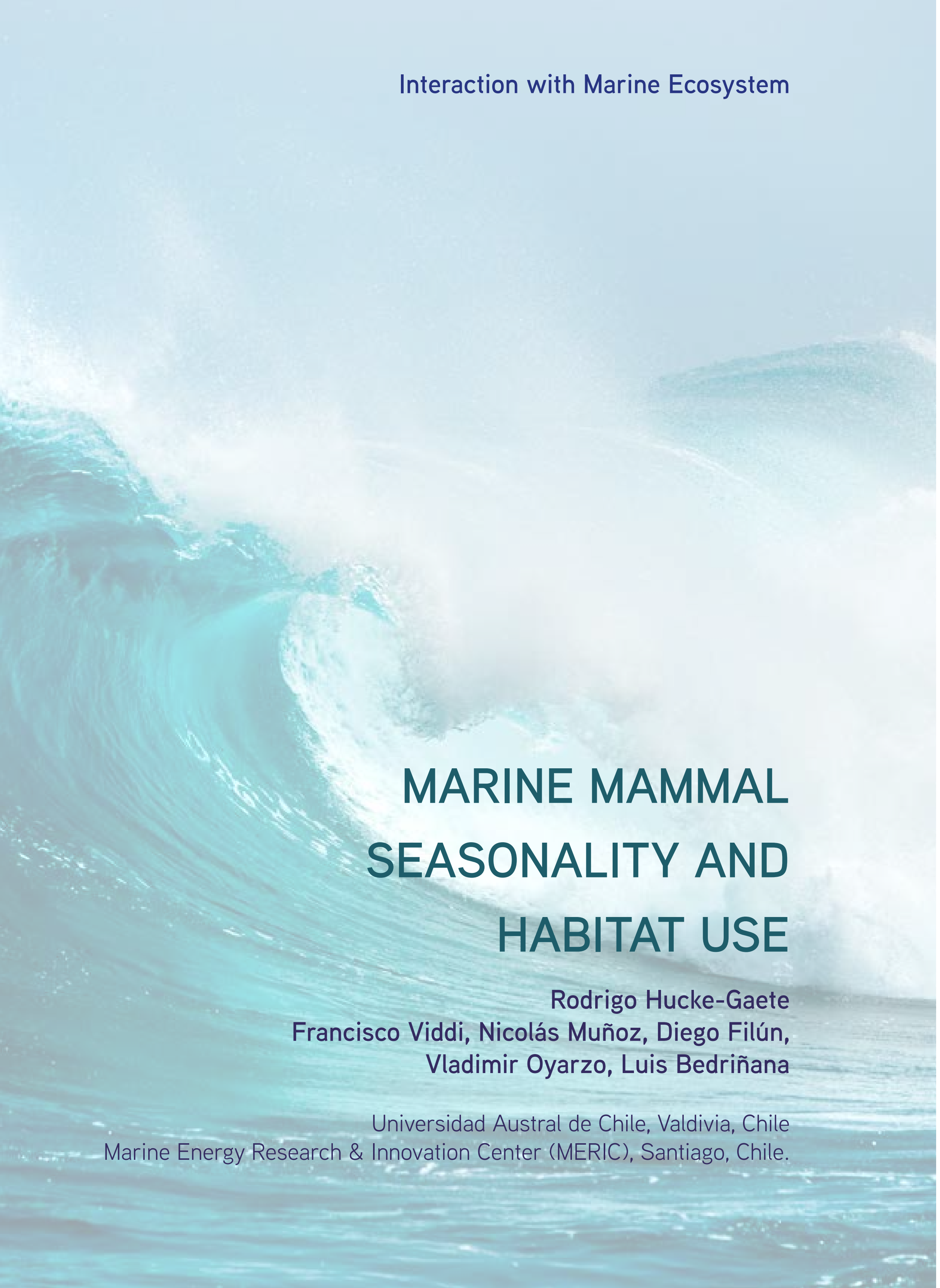
These studies and the consequent results are relevant in several critical aspects for the sustainable development of marine energies. In the first place, this work has allowed us to formulate protocols for the determination of the corrosion rates of diverse materials and the contribution of the associated microorganisms, for the evaluation of corrosion in Chilean coastal systems. This will allow us to have standard and reliable methodologies to understand how different surfaces used in the construction of the structures involved in obtaining energy from the sea are affected by corrosion and biocorrosion phenomena. On the other hand, the results obtained in this project will allow us to establish under which conditions and ideal characteristics should the installation of devices take place to in order to develop marine energies in Chile.

Finally, the results of our research will support the design and validation of predictive mathematical models, with the aim of optimizing anticorrosive strategies for different types of materials relevant to the construction of these complex structures.

Future Challenges and Perspectives

The work in this project has expanded its actions beyond its original aims. This initiative has become the nucleus for the development of additional collaborative projects funded by national and international funding agencies. Examples of the above are: (1) the development of the research project entitled: "Microbial dynamics and its influence on the development of a corrosive biofilm over stainless steel surfaces exposed to marine conditions". This project is led by Professors Ignacio Vargas and Rodrigo de la Iglesia, funded by the United States Office of Naval Research in its Global office; and (2) a project led by Professor Gonzalo Pizarro, funded by the FONDECYT program entitled: "Interdisciplinary evaluation of surface texturing by multi-techniques as sustainable biofilm control in Cu-Ni alloys exposed to seawater". Both projects seek to expand scientific knowledge in both biological aspects, characterisation and modification of surfaces in order to identify solutions to prevent and/or control the formation of microbial biofilms on surfaces exposed to marine environments.

Additionally, owing to the fact that coasts in Chile are diverse in their characteristics, the studies carried out on the central coast are not necessarily comparable with other Chilean areas. For this reason, it is important to project these study methodologies at appropriate places for the development of marine energies. Currently, the project has directed its efforts to the study of corrosion on the shores of the Chacao Channel (Los Lagos Region, southern Chile).



MARINE MAMMAL SEASONALITY AND HABITAT USE

Rodrigo Hucke-Gaete
Francisco Viddi, Nicolás Muñoz, Diego Filún,
Vladimir Oyarzo, Luis Bedriñana

Universidad Austral de Chile, Valdivia, Chile
Marine Energy Research & Innovation Center (MERIC), Santiago, Chile.

INTRODUCTION

The generation of electricity from renewable energy resources is fast becoming a key objective of many countries. The driving force behind this is the link between non-renewable fossil fuels and environmental degradation (Chow, Kopp and Portney, 2003). Climate change is a major concern, leading to predictions of a global temperature rise of 3–5ºC within 50 years and an increase in climatic variability (Houghton et al., 2001). Although the consequences of climate change are currently the subject of much debate, from an ecological standpoint the concern arises from evidence of geographical shifts in the distribution of species (Pounds and Puschendorf, 2004), predictions of a sharp increase in extinction probability for many plant and animal species (Thomas et al., 2004), and wider impacts on ecosystems (Leemans and Eickhout, 2004). Add to this the predicted decline in the amounts of non-renewable resources over the next few decades (Pimentel et al., 2002) and it is clear that alternatives to fossil fuels are needed.

Renewable energy resources may represent one of humankind's best hopes for reducing our substantial contribution to global warming (Krupp and Horn, 2008). Technology to capture the energy from wind, the sun, and biomass are all in various stages of development. Vast and powerful, the ocean probably stores enough energy in the form of heat, currents, waves, and tides to meet total worldwide demand for power many times over (Takahashi and Trenka, 1996). Yet, the challenges facing development of ocean energy technology have been daunting, and to date, ocean energy comprises only a miniscule proportion of worldwide energy supply. As global commitment to renewables increases in the future, more attention is likely to become focused on the immense wealth of energy resources available in the ocean (Pelc and Fujita, 2002).

In many areas of the world, marine renewable energy (MRE) has great promise, but several of the approaches have yet to be developed to commercial standards. Energy from marine wind, tides, currents, waves, and thermal gradients may all hold immense potential for electrical energy generation. The development of the technology, however, is not without environmental and social concerns (Gill, 2005; Inger et al., 2009).

Possible negative effects, specific to marine renewable energy installations, include a number of generic threats, and impacts differ significantly between the construction, operational and decommissioning stages (Gill, 2005). Habitat loss, collision risks, noise and electromagnetic fields are just some factors being posited as having potentially important negative environmental impacts.

Marine mammals are probably the taxonomic group given the greatest attention in environmental assessments in many countries when evaluating the potential impacts of MRE. For many species, past human activities have led to serious negative impacts on marine mammal populations. In addition, they are highly visible, generate greater public interest, and are often protected by laws (e.g., the Marine Mammal Protection Act in the United States; International Union for Conservation of Nature (IUCN) classifications; EU Habitat and Species designations). For these reasons, and as species-based conservation management is currently the focus of our activities when considering human impact on the environment, impacts to marine mammals may have greater consequences for the development of MRE.

Chile has often been identified as a region with great potential for capturing energy from the sea (Scottish Enterprise, 2005; Cornett, 2008; Monárdez et al., 2008; Cruz et al., 2009). In this sense, there is no doubt that unconventional renewable energies will be an important part of our economic development under a more sustainable framework and with less environmental impact. However, it is vitally important to be able to evaluate in advance, with robust information, the possible social impacts and environmental aspects of this industry. Marine mammals (whales, dolphins, sealions, otters) are a particularly important and unique group on the coasts of southern Chile (Hucke et al., 2006, Viddi et al., 2010) that could be affected by the development of these technologies (Carter et al., 2014). These animals can be affected mainly by collisions with the energy generating structures, by disturbances during the construction and during operation due to noise emissions, generating exclusion from their key habitat (Wilson et al., 2014). On the other hand, marine mammals are an ideal group for consideration as environmental indicators, because they are high trophic level predators (Bowen, 1997).

Given the current interest in pursuing MRE in Chilean coastal waters, the general objective of our project is to establish a baseline research to implement a long term monitoring program to determine the potential effects of MRE on marine mammals and provide corresponding recommendations on mitigation procedures. Due to the importance of determining the presence of marine mammals in the area of interest, the specific objectives include evaluating the diversity of species, their seasonality, local distribution and habitat use.

Methods

Study Area

The study has been developed in the Chacao Channel, located in Los Lagos Region (Figure 1). This channel divides the American continent from the north coast of Chiloé Island, linking the Coronados Gulf and Ancud Gulf. It is considered a narrow channel, with stronger tidal current flows reaching more than 4 m/s (Cáceres et al., 2003). The channel is part of the so-called Chiloense ecoregion, characterised by a great diversity of species. The physical conditions and biological diversity patterns of this ecoregion make this area an important habitat for highly emblematic animals, such as marine mammals. Throughout this ecoregion, more than 30 marine mammal species have been recorded, of about 51 existing throughout the country (Hucke-Gaete et al., 2010; Viddi et al., 2010). The area is well known because it is home to one of the most important feeding grounds for blue whales (Balaenoptera musculus) (Hucke-Gaete et al. 2003).

Visual Observations from Vantage Points

Figure 1: Study area. Numbers indicate sites of Passive Acoustic Monitoring (PAM) equipment (see below for details of PAM).

The visual observations from vantage points on land were made by groups of at least three trained observers using a theodolite, located at Punta Falsa Picuta (Figure 2), a strategic point having a wide field of view of the Chacao Channel. Viewing periods were distributed throughout the day, but conditional on weather conditions. Searching for marine mammals was carried out using 7x50 binoculars and the naked eye. Once an individual or group of animals were sighted, the topographic theodolite was used to track and map the animals during sighting.

Passive Acoustic Monitoring (PAM)

Figure 2: Panoramic view of the vantage point for visual monitoring: Punta Falsa Picuta

PAM is the name for a series of techniques to study marine mammal acoustic signals. PAM used in this study included the use of two types of hydrophones: a) C-PODs, which are automatic detectors of high frequency clicks produced by Odontocetes (dolphins and porpoises); and b) Soundtraps, autonomous hydrophones capable of recording high and low frequency sounds.

A. C-POD Detector:

The C-POD detectors (Figure 3) are totally autonomous equipment that are installed statically in the water column, present a positive buoyancy and are capable of detecting sounds produced by Odontocetes when socializing, feeding and travelling. A C-POD records acoustic signals of different species of dolphins and porpoises identifying the click-trains of echolocation that these animals produce to "see" their surroundings and to find prey, to orientate themselves in the aquatic environment, and to communicate. C-PODs can record the time of occurrence, frequency, intensity, duration and variation of the frequency of the echolocation clicks between a range of 20 kHz and 160 kHz. When the C-POD receives the sound produced by an animal, the device translates the pressure changes exerted by the acoustic vibrations to electrical signals and then stores it on a digital card (Secure Digital Card), located inside the equipment together with a battery pack. C-PODs were used with the aim of detecting continuously the sounds produced by Chilean dolphins (Cephalorhynchus eutropia), Peale's dolphins (Lagenorhynchus australis), Burmeister´s porpoises (Phocoena spinipinnis), bottlenose dolphins (Tursiops truncatus), orcas (Orcinus orca), and any other species potentially present in the study area. Data stored in C-PODS are highly specific, and robust hardware and software are needed. Data requires to be filtered (from ambient noise), visualised and further analyzed. Data analysis provides information on temporal and spatial occurrence of dolphins and odontocetes, as well as patterns of habitat use.

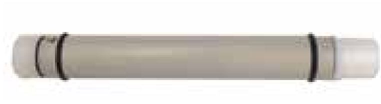


Figure 3: C-Pod.

B. SoundTrap:

The SoundTrap is an autonomous underwater sound recorder used for oceanic research (Figure 4). This equipment, unlike the C-POD, allows us to obtain broadband records between 20 Hz and up to 150 KHz. The SoundTraps used in this study were programmed at a sampling rate of 48 kHz, which allows us to record the presence of vocalisations of Mysticetes cetaceans (great whales), which produce sounds that can even be lower than 10 Hz. Their sampling cycle for this study was set up to record 12 hours a day (15 minutes of recording every half hour). Like C-PODs, highly technological hardware and software are needed. Data analysis form Soundtraps provides information on spatial/temporal occurrence of whales. Soundtraps also are providing important information on environmental noise and anthropogenic influence. Noise maps were generated in order to visualise the sound recorded in each of the equipment location sites.

Figure 4:SoundTrap 300 HF

Results

Visual Observations

More than 140 hours of visual monitoring effort have been accomplished. During our observations four species of cetaceans, an otariid and a mustelid, have been recorded: Peale's dolphin, Chilean dolphin, humpback whale, blue whale, common sealion (Otaria byronia) and chungungo (Lontra felina) (Table 1). The southern sealions are far the most frequently recorded species, moving between their breeding colonies on the exposed rockeries to feeding areas in the Gulf of Ancud and adjacent waters. Additionally and opportunistically, the presence of the southern elephant seal (Mirounga leonina) and a stranding of the southern right whale (Eubalaena australis) were recorded.

Species	Number of sightings	Total number of individuals
Blue whale	1	1
Humpback whale	1	2
Peale's dolphin	22	43
Common sealions	739	1.365
Chungungo	93	144
Chilean dolphin	1	1

Tabla 1: Marine mammal sightings recorded (2016-2018).

Acoustic Presence of Cetaceans

To determine the acoustic presence of the different species of cetaceans in the study area, a manual analysis of the data recorded with the autonomous SoundTrap hydrophones was performed. To qualify as a day with acoustic presence, we used days when at least one characteristic vocalisation was detected and attributable to a species of cetacean previously described within the study area. Blue whales, humpback whales, orcas, Chilean dolphins, Peale's dolphins and Burmeister's porpoise (not yet acoustically distinguishable due to the great similarity with other odontocetes in their high frequency clicks that are capable of emitting) were detected. Indeed, we have the first recordings of orca sounds in Chile.

Environmental Acoustic Map

Using data provided by the Soundtraps, we are evaluating how "noisy" this aquatic environment is, allowing us to identify at which frequencies the greatest sources of noise are found and how they vary, or when they are present over time. Noise maps were made expecting to represent the best possible resolution between time and frequency. For the generation of these noise maps we worked with the frequency values of 1Hz as the size of the "energy bin size" (this means that it will have a resolution of 1Hz in the frequency scale) and in the time scale we worked with an average time of 60 seconds (every 60 seconds an average of the energy (dB) was taken for each 1Hz in the frequency scale). Our results indicate that noise sources are constant over time, but they are also cyclical. This shows us that the monitoring area presents strong tides with a lot of energy. The auroras around these cyclical peaks of high energy can reach up to 40 dB, which infers that these tides are able to remove large amounts of substrate and leave it in suspension in the water column, which generates noise as it collides with our acoustic equipment. Broadband lines that cover the entire frequency range, but for small periods of time ranging between 40 and 60 dB, indicate the possibility of engines on boats as a source of noise.

In Figure 5 we can see an example of detection of humpback whale vocalisation and how it is masked by the noise of the waves and the material in suspension. The reception levels of the humpback whale signal, being a little higher than the energy levels of the environment, allow us to detect it.

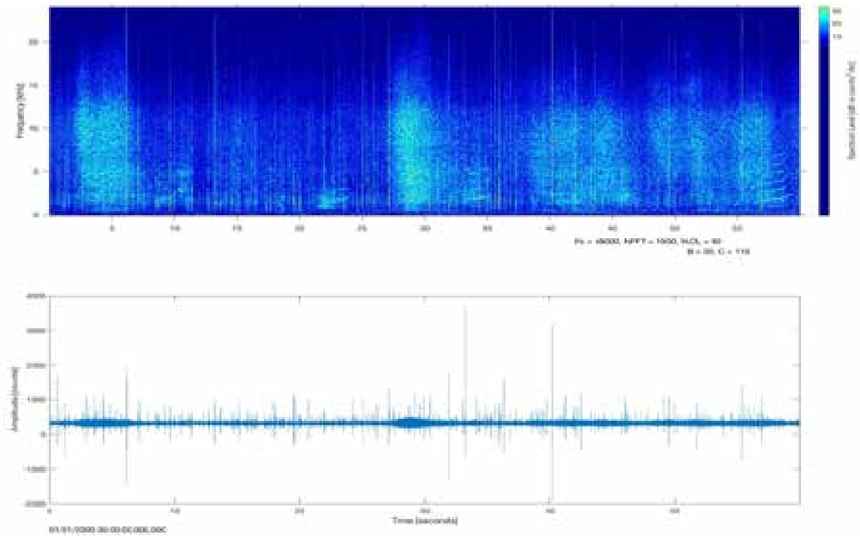


Figure 5: (A) Humpback whale vocalisation (red squares) masked by noise. Y axis: frequency in kHz; X axis: time in s; Z axis: Spectrum Level (dB re counts2 / Hz). (B) Spectrum of signals in A).

Detection of Species

The detection of small cetaceans in the area has been heterogeneous among monitoring sites. Despite this, the presence of these small cetaceans has been detected throughout the study. So far there have been no individual studies of echolocation clicks to identify the possible behavior or action that animals make at each site and whether these sounds are constant or vary over time, between sites or during the day. The largest number of detections of whales have been for blue whales. We have had detections even during the months of August and September.

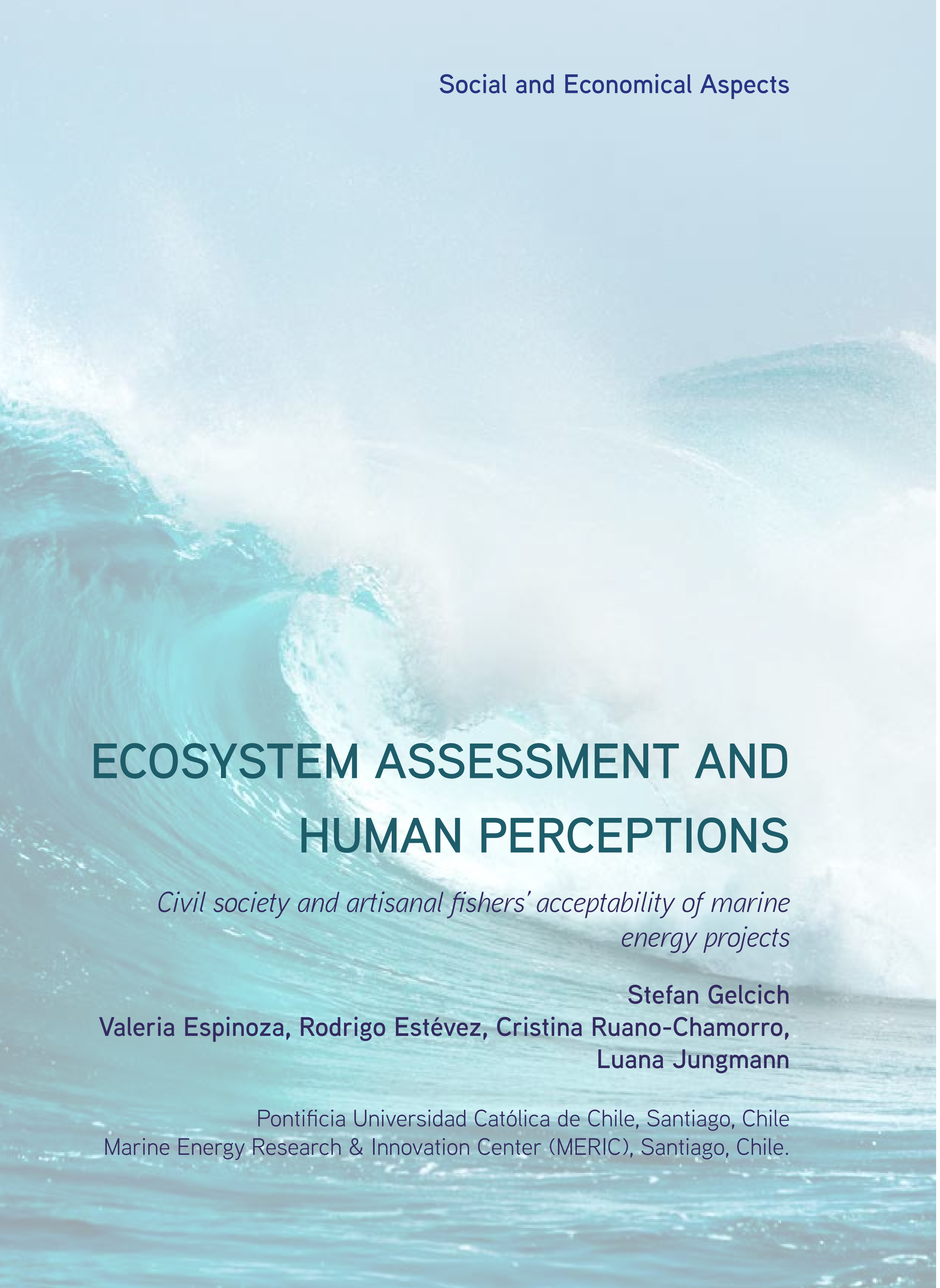
Unlike Mysticetes, odontocetes produce high frequency sounds, but not of such intensity, which do not move or spread over great distances, which gives us information that the detection of orcas was made because these animals were very close to our equipment, in a site which is close to a colony of sealions, the chosen prey for orcas. Although we have been able to identify sounds of different marine mammals that concur within our study area, we must mention that we are not able to detect all the sounds. This is due to the large volume of noise caused by tidal currents.

Discussion

Acoustic study methods nowadays are becoming extremely important and popular in marine mammal studies, particularly as a complementary methodology with traditional techniques (visual methods). Over recent decades, technological advances have sought to automate acoustic monitoring through the use of remote recording units and analytical packages of automated species recognition (Rayment et al., 2009, Elliott et al., 2011). Compared to traditional acoustic sampling methodologies, automated sampling allows the collection of sound environments at different points of a given study area simultaneously and systematically at broad temporal scales, thus increasing the sample size (Tyack and Clark 2000).

PAM allows researchers to obtain information that otherwise could not be acquired in traditional visual censuses, such as high-resolution temporal data, information on the presence or absence of individuals during periods of darkness, and information on species when weather conditions are adverse, and to document behavior not observable on the surface (Nuuttila et al 2013, Verfuß et al 2007, Leeney 2011). In addition, this methodology minimises invasiveness or disturbance towards study animals (Carstensen et al., 2006; W. Rayment et al., 2009). On this regards, it seems reasonable to think that PAM techniques can be one of the best tools to investigate and monitor marine mammals under the scenario of environmental assessment regarding MREs.

Published literature demonstrates a dramatic increase in the number of studies dealing with renewable energy; the percentage that deals with environmental effects, however, is relatively meager (Gill, 2005). It is clear that much work is needed to address the environmental effects of marine renewable energy, and indeed to develop an understanding of potential impacts. Fortunately, MREs are proceeding somewhat more slowly than terrestrial-based renewables such as wind and solar. Environmental effects research, however, is increasingly lagging behind the developing technology; there is thus an urgent need for such research (Inger et al., 2009). In the United States and in many other countries, MRE demonstration projects or pilot-scale facilities are under development. Concurrent environmental research at these sites will help reduce uncertainty of effects and identify impacts for all stressor and receptor groups. This research, in turn, will lead to improvements in the best practices for design of devices and arrays and to better performance standards and monitoring requirements for application to commercial-scale development. Setting environmental standards for MREs is particularly urgent, yet these standards must strike an appropriate balance. If environmental assessments are too lax, we risk severe environmental damage. If the required assessments are overly restrictive, however, there is a risk of inhibiting the development of renewable energy technologies that have the potential to reduce our reliance on fossil fuels (Boehlert and Gill, 2010).



ECOSYSTEM ASSESSMENT AND HUMAN PERCEPTIONS

Civil society and artisanal fishers' acceptability of marine energy projects

Stefan Gelcich
Valeria Espinoza, Rodrigo Estévez, Cristina Ruano-Chamorro, Luana Jungmann

Pontificia Universidad Católica de Chile, Santiago, Chile
Marine Energy Research & Innovation Center (MERIC), Santiago, Chile.

INTRODUCTION

Social acceptability is a vital factor to be considered for long-term development of renewable energy projects. Social acceptance is a vital element for consideration in long-term development of renewable energy projects. Social resistance can constitute a significant barrier, either preventing or delaying the project implementation (Painuly, 2001). Analysis of the human dimension is critical for understanding the factors that influence the acceptability of new energy technologies, projects, and policies (Steg et al., 2015). The factors that determine acceptability are the type of technology, the specific location of a project, its costs, benefits, risks, and perceived trust, among others (Huijts et al., 2012; Bonar et al., 2015).

Marine energies can constitute a fundamental contribution in adaptation for climate change (Paris Secretariat REN21, 2015). Nevertheless, marine energy projects have experienced some scenarios of tension and conflict with fishery systems. Therefore, the perception of fishers and local communities is fundamental for marine energy projects (Ruano-Chamorro et al., 2018).

In the literature, there is a gap in the understanding of values, perceptions and attitudes to co-designing marine energy initiatives. Our research project aims to assess perceptions towards marine energy in Chile in order to inform the co-construction of key governance, environmental and socio-economic requirements to ensure social acceptability. Here, we present the results of a survey about marine energy perceptions and also of artisanal fishers' attitudes towards marine energy projects.

Materials and Methods

Between March and October 2017, we conducted 1,200 surveys in four Chilean regions: Coquimbo, Valparaíso, Los Lagos, and Magallanes. In each region we conducted 300 surveys at coastal localities, divided between 150 urban and 150 rural locations. We selected these regions because of their difference in energy-installed capacity, energy potential and energy projects, representing the different sources of energy available in Chile.

The surveys were carried out among random respondents in public spaces. The questionnaire consisted of open and closed questions and included Likert-type scale responses. We translated the open responses to English and coded them into key categories. At the beginning of the survey, we explained the concept of marine energy to the respondent with an image (Figure 1). We narrowed the concept of marine energy to current, tidal and wave energy. Other energies that can be extracted from the ocean fall outside the scope of this study.

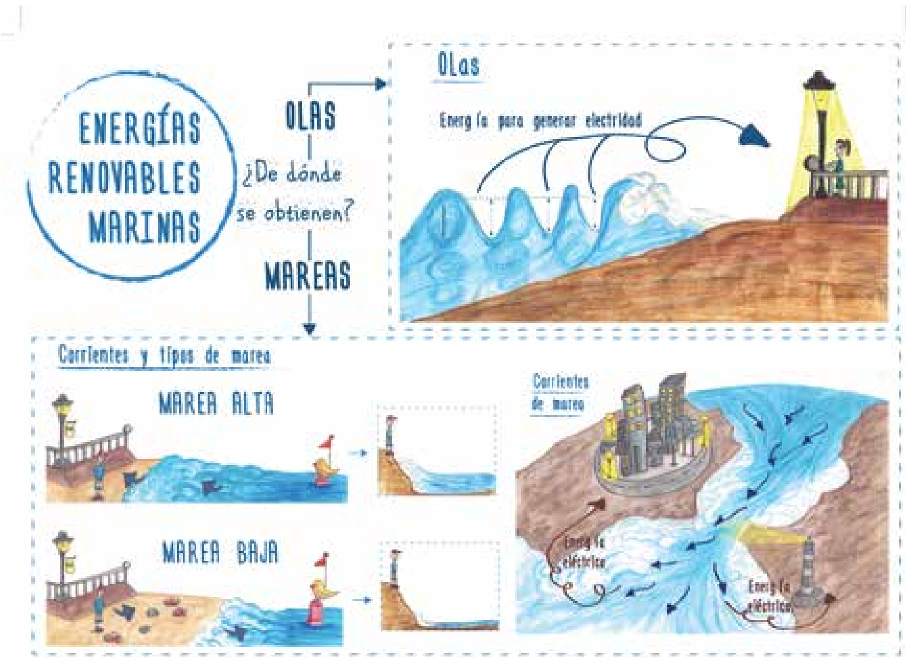


Figure 1: Leaflet used to explain marine (wave and tidal) energy in simple fashion to respondents at the beginning of the survey.

The survey consisted of three parts. In the first, we used open-ended questions to explore perceptions regarding the social and environmental impacts of marine renewable energies. In the second part, we asked 5-point Likert scale questions regarding use and trust associated with sources of information about energy issues, knowledge and perceived level of environmental impact of different sources of energy, and trust in decision-makers. The categories for decision-makers are based on the Participation Guide published by the Chilean Ministry of Energy. Finally, we asked questions about social capital and their socioeconomic characteristics (income, education, gender, age).

Artisanal Fishers and Acceptability

We conducted 97 surveys among fishers from 5 locations in the Region of Valparaíso, at Papudo, Maitencillo, Horcón, Ventanas and El Quisco coves. In these surveys, we repeated some of the questions already asked in the previous survey to civil society, to capture the level of information on types of energies and confidence in decision-makers. In addition, we included questions to understand which aspects are relevant for them to accept a marine energy project close to their coves.

Before starting this questionnaire, we asked them if they would accept a marine energy project. To assess the acceptability of a project by fishers, we asked them about some of the characteristics that a marine energy project would have, and they assigned a score according to their relevance. After they had read through the list of characteristics, we asked them the same question, but considering that the requirements indicated by them would be met. In that way, we can measure the degree of acceptability of a marine energy project.

Additionally, we presented to the fishers a list of nine characteristics that might feature in a marine energy facility, and we asked them to distribute 13 tokens across these nine characteristics, according to their perceived level of importance.

The nine characteristics considered were: i) that instead of installing a large project in an area, small projects would be installed in several areas along the Chilean coast; ii) I would not pay more than what I currently pay in my electricity bill; iii) that the decision-making of the project is made in a fair and participatory manner; iv) that the electricity company compensates the local community; v) that the negative impact on the marine fauna (fish, whales, dolphins, sea lions, crabs, snails, etc.) would be minimised; vi) that the visual impact on the marine and terrestrial landscape be minimised; vii) that the negative impact on other marine activities (surfing, swimming, fishing recreational) is minimised; viii) that the negative impact on fishing activities be minimised; ix) that marine energy facilities be established in non-populated areas.

Compensations

We proposed five types of compensation to the fishers. They then indicated if they would accept any/some/all of them. The compensations proposed were: a) a direct economic payment is offered to the fishers; b) that the community would be co-owner of the project; c) that the project should generate jobs for their community; d) they are offered work on the project itself, and e) their electricity bills will be reduced. The answers were delivered on a Likert scale of (1) totally disagree, to (5) totally agree.

Results - Civil Society Perceptions of Marine Energy

Minimal Requirements

The primary concern of respondents from civil society was to minimise the effect on marine fauna (81%), promote citizen participation (68%), minimise the impacts on activities at sea (57%), maintain or reduce electricity bills (47%), minimise the facilities located in inhabited areas (42%), reduce the magnitude (scale) of the project (35%) and compensate the local community (30%) (Figure 2).

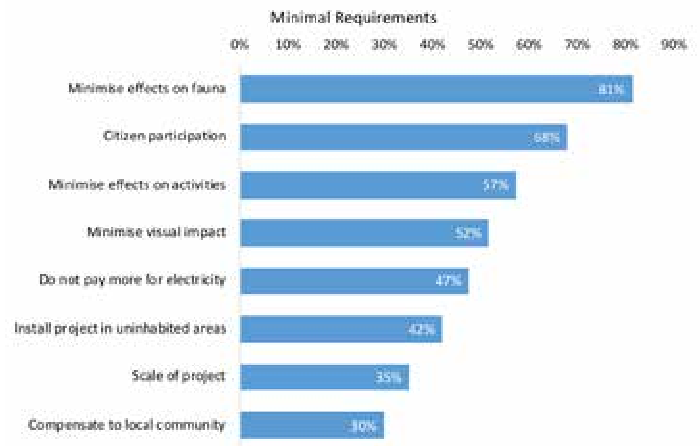


Figure 2: Respondents who identified each of these characteristics proposed as a minimum requirement

Sources of Information

The most important source of information was Internet (I), social networks (SN), television and radio (TVR) and newspapers (N). The less important sources of information were energy companies (EC), Ministry of Energy (ME), and Regional and Local Government (RLG); these are also the sources in which people expressed least trust. Interestingly, although people do not get much information delivered in scientific publications (SP) or by NGOs, these sources are the most trusted (Figure 3).

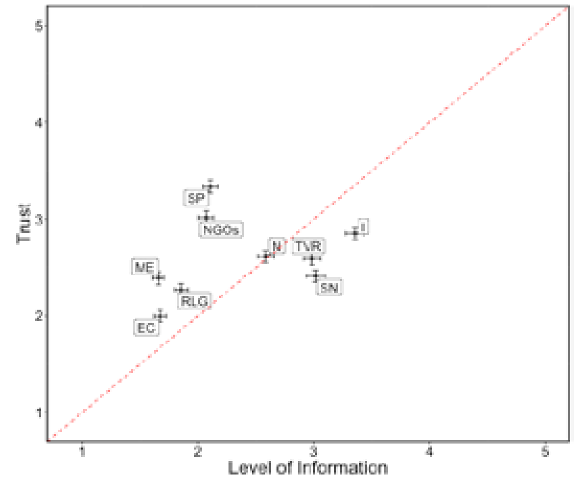


Figure 3: the degree to which respondents use different sources of information (Likert scale (1) never to (5) always), and how much they trust them (Likert scale: (1) very untrustworthy to (5) very trustworthy). (SP: Scientific Publications; ME: Ministry of Energy; EC: Energy Companies; RLG: Regional and Local Government; I: Internet; SN: Social Networks; N: Newspapers; TVR: Television and Radio).

Information About Energy Sources

Respondents indicate that solar energy, wind and hydroelectric power are the sources of energy that they know most about. At the opposite extreme, geothermal, marine and biomass power are the sources of energy they know least about. Interestingly, although respondents informed that their level of information about marine energies is low or very low, they perceived that marine energies have a low environmental impact (Figure 4).

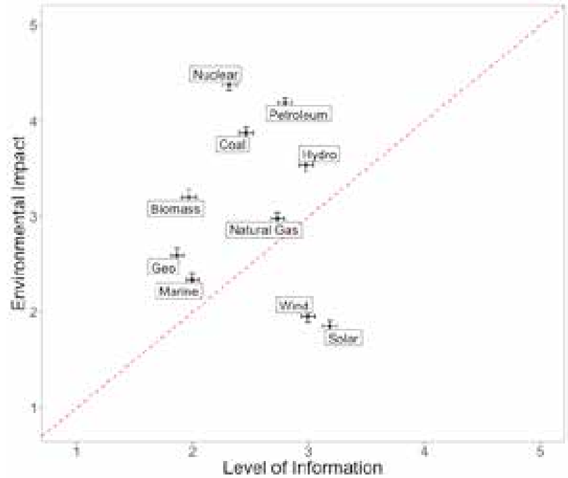


Figure 4: the degree of information of the respondents about different sources of energy and their environmental impact (Likert scale: (1) very low to (5) very high).

Trust in Decision-Makers

Respondents from civil society informed that scientists, communities impacted by a project development and NGOs are the organisations they trust most. Contrarily, electricity companies, central and regional government are the organisations that they trust least (Figure 5).

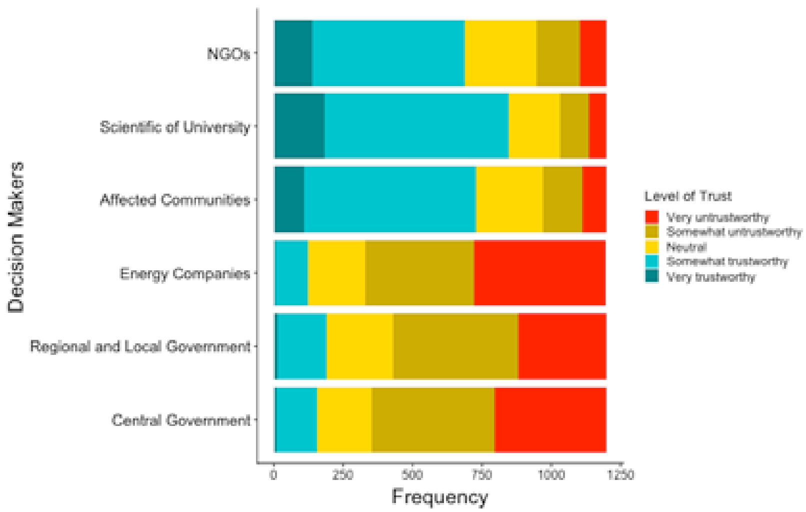


Figure 5: the degree of trust of respondents in decision-makers.

Fishers' Perceptions of Marine Energy

Socio-Demographic Characteristics of Fishers

The 97 fishers who answered the survey were on average 56 years old (standard deviation of 14 years), their household income ranges from CLP$150,000 and CLP$600,000 (US$225 to US$890), and on average they have been fishing for 35 years (s.d. 16.7 years).

Information About Energy Sources

Artisanal fishers indicate that petroleum, solar, hydroelectric and wind are the sources of energy that they know most about. Similar to respondents from civil society, artisanal fishers revealed having very little information about marine energy, nevertheless they consider that its environmental impact is low.

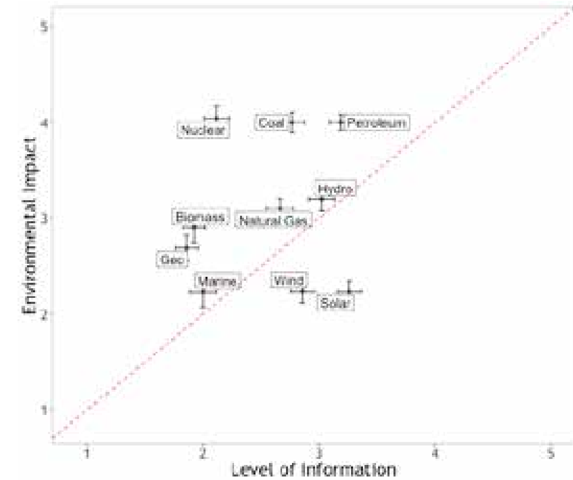


Figure 6: the degree of information of the artisanal fishers about different sources of energy and their environmental impact (Likert scale: (1) very low to (5) very high).

Trust in Decision-Makers

Artisanal fishers expressed that they are more trusting of their fishers' organisation leaders and scientists than other actors, and that they have little trust in energy companies (Figure 7).

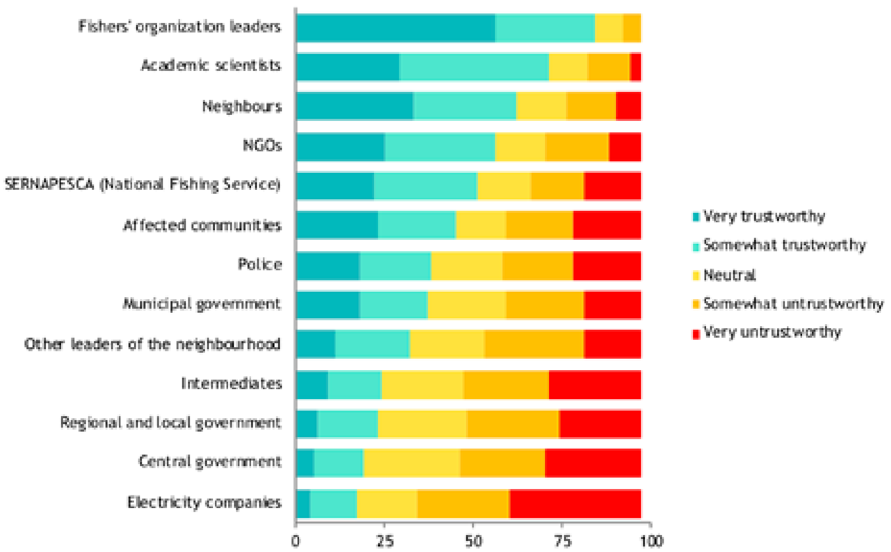


Figure 7: Artisanal fishers' degree of trust in decision-makers.

Minimal Requirements and Acceptability

Artisanal fishers considered that maintaining or reducing energy bills is the most important project benefit. Nevertheless, for fishers it is also essential to minimise the effect on marine wildlife (Figure 8).

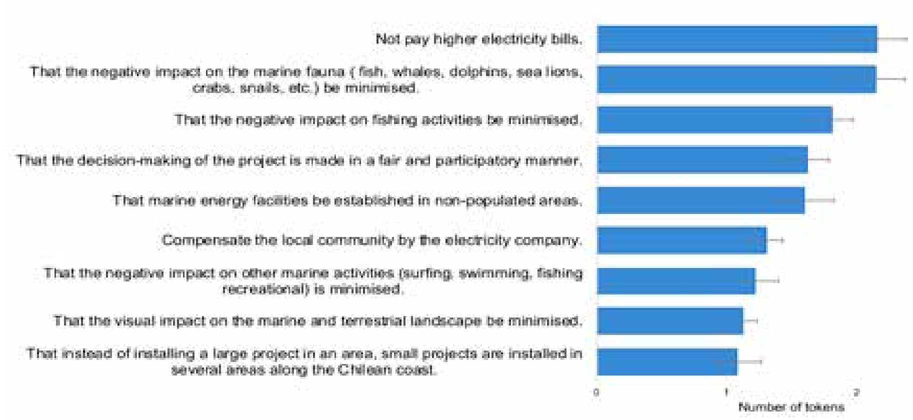


Figure 8: level of importance of the different characteristics of a marine energy project for artisanal fishers.

Most of the fishers would accept a marine energy project on the coast of their community after telling them that their requirements would be met (Figure 9).

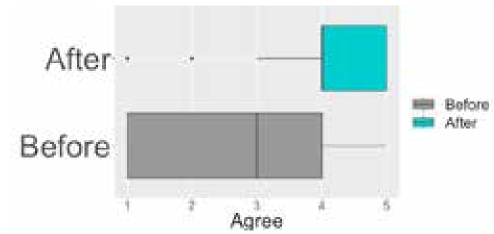


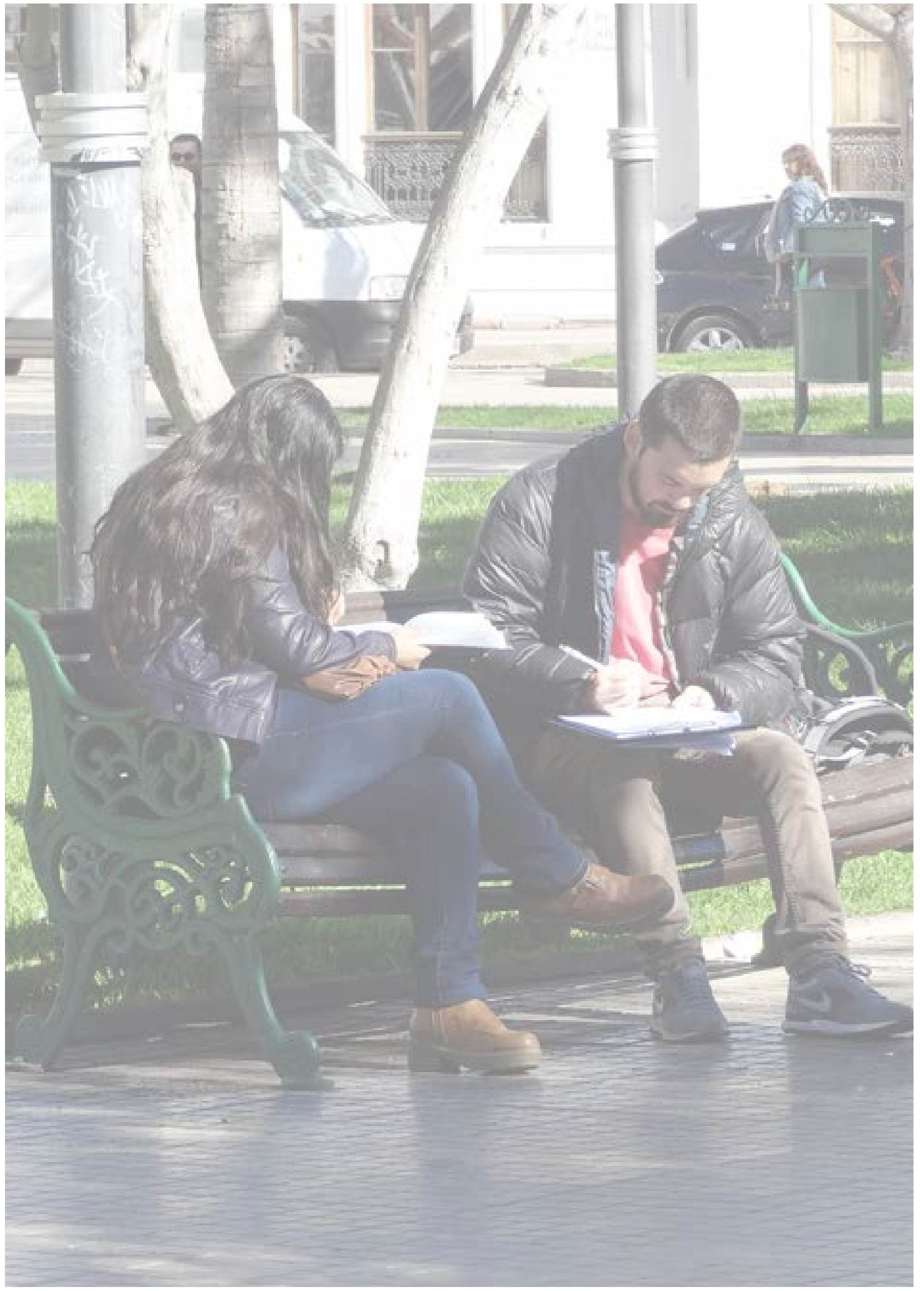
Figure 9: acceptability before and after considering that the most critical requirements considered by fishers would be fulfilled (Likert scale from (1) Definitely not, to (5) Definitely yes).

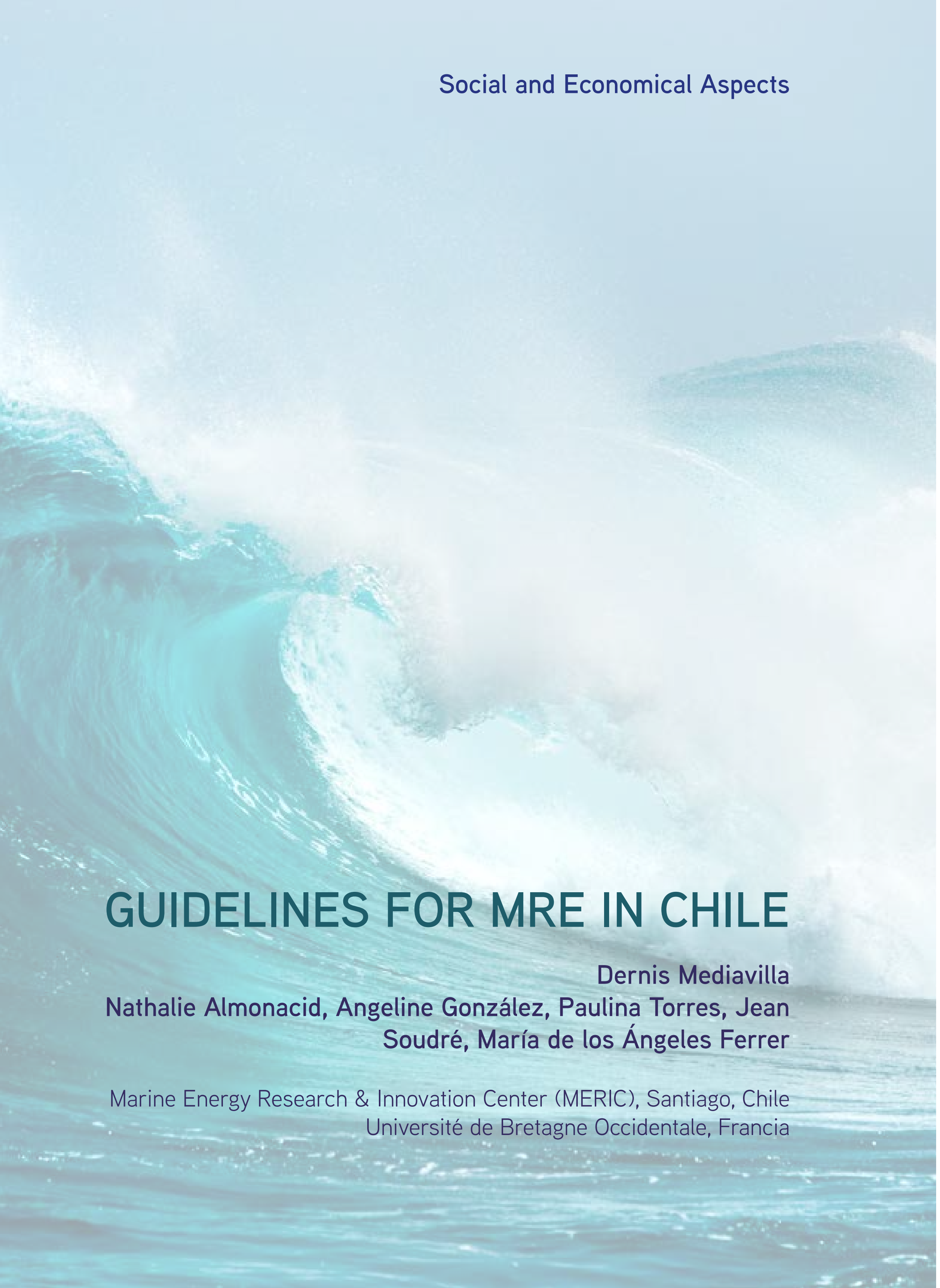
Conclusion

This is the first time that perceptions of people about marine energies have been evaluated in Chile and South America. Knowing the perceptions of people towards marine energy projects is critical to discriminate among the most important attributes, increasing the acceptability of projects. This approach could also avoid or reduce conflicts among stakeholders in a project development. Research should engage in new models of participatory research to understand these dynamics and to design programmes that explicitly integrate a broad range of needs, values, and modes of implementation (Sorice et al., 2018).

Evaluating the degree of information that people have about different types of energy, their perceptions about impacts, and trust among actors, would enable exploring coherent narratives about the role of marine energies. Considering that, on the one hand, people have little information about marine energies, and on the other, people perceived that marine energies have low environmental impact, it would open up opportunities to promote people's participation from the beginning of a project's co-design process. Likewise, identifying which compensations they value most, allows us to design systems with greater possibilities of acceptance by key actors.

The next challenge is to explore models of co-governance for marine energies, and how these models could be implemented in Chile. For this, multicriteria analysis would enable us to determine the critical factors of acceptability. In addition, it is critical for determining the attributes for the design and strategy of compensation measures. All the above with the objective of determining the best way to carry out the co-design of marine energy development for Chile.





GUIDELINES FOR MRE IN CHILE

Dernis Mediavilla
Nathalie Almonacid, Angeline González, Paulina Torres, Jean Soudré, María de los Ángeles Ferrer

Marine Energy Research & Innovation Center (MERIC), Santiago, Chile
Université de Bretagne Occidentale, Francia

INTRODUCTION

In order to enhance energy security and reach Chile's environmental targets, the energetic matrix must be diversified through the development of marine renewable energy. The quest for new sources of energy is essential in the current context of petrol rarefaction and political instability of energy exporting countries. Chile has one of the most energetically wealthy coasts, with 4,200km of linear coastline, significant both for wave and tidal energy extraction.

It becomes attractive to think about sites for installation of MRE projects along the Chilean coast in terms of their energetic resource. Nevertheless, the variables to be taken into consideration for implementing MRE projects are numerous and complex: concessions and permits, social acceptability, seismic risk, tsunami flood areas, marine mammal routes, among others. Unfortunately, sources for this information can be difficult to access, even more in the eyes of international stakeholders, and nor is data centralised in the country. Accessible and useful information for MRE is a gap to be conquered while visualising MRE as a renewable solution for Chile.

The main goal of the Guidelines for MRE in Chile project is to generate tools that facilitate project implementation in the country. This project has three main areas of work: georeferenced information, law and regulation of project implementation and protocols, standards and lessons learnt. Progress on the first two is shown below, while the latter is going to have concrete progress at the end of MERIC Stage 1.

EMMap Energy Marine Map: an interactive tool for MRE

Currently, there are several IDE (Integrated Development Environment) platforms in Chile, focused on different activities. After an exchange with national and international actors in the MRE sector, we identified the need for a joint platform which brings together all the relevant variables for the development of an MRE project in the country, aiming to be a trustworthy source of quality information for the decision-making process of selecting a potential site: Energy Marine Map for Chile. EMMap consists of an interactive map that groups different information layers about Chilean conditions, relevant for the very initial stages of site selection. EMMap's approach is to be a single entry-point to the variety of local IDE platforms with information available, both private and public, meaning that it points towards the platform of origin where data can be accessed if the user needs to, and not allowing for data access directly from EMMap.

The construction of this platform has been an iteration process, that started around November 2016. The first step of this work was a prioritisation exercise, looking for better comprehension of needs at the moment of implementing technology in the open sea. This exercise was performed in the form of a questionnaire distributed among international institutions and companies with hands-on experience in MRE. Once this information was duly processed, we advanced with the collection of different data layers, from existing external platforms and original information from MERIC, in a transversal way: from the physical resource to social and environmental issues, passing through the relevant infrastructure for the implementation of an MRE project in Chile. The information that is going to be seen in EMMap's first release is a balance between the actor's prioritisation and local availability.

Additionally, the platform aims to integrate public results and outputs from the research projects on which MERIC is currently working with internal implementation partners and external collaborators and institutions. The interconnection of the information and a common visualisation aims to support the process of preliminary site selection for a given technology in the country, hoping to facilitate the entry of MRE projects in Chile.

We hope that this interactive tool for MRE in Chile can be seen as an opportunity for MRE development in the country, not only for actors around the globe that could be interested in developing a project on Chilean coasts, but also for national stakeholders to have a deeper comprehension of Chile's capabilities and opportunities related to MRE collection.

Building EMMap

I. First insights

While working on finding the most useful concept for the outputs of the Guidelines for MRE in Chile project, we approached several institutions around the globe, and particularly in Europe, to ask them what type of tools could be useful to guide different actors at the moment of visualising an MRE project in the country. Also, two technological developers and the Chilean Ministry of Energy were involved in this process.

From these conversations, we understood that every country has different mechanisms for showing their resources, mainly in terms of their environmental variables. There is no single standard platform for finding this type of information. In general, they mentioned, the information is scattered according to their thematic areas (environmental, marine regulatory framework, technical protocols, etc.) and displayed in different ways (reports, publications, environmental platforms, maps) making it harder to organise and match the information for final users. Also, they noticed, there is a lack of virtual spaces focussed on marine energy consultation for the public. Language is another limitation: some public reports show very useful information, but local language limits their understanding. Regarding the perception of Chile related to MRE, they are aware of the large energy resource, some even recalling power numbers for wave and tidal energy. However, in terms of technical aspects, supply chain, social or environmental, information is still not clear to them.

After this general view of their needs, we proceeded to ask them in which format they would prefer to access this information. They agreed on some features, like information searching, highlighting the importance of a clear, friendly interface (easy to navigate), ideally a map, with graphics and colouring for fast viewing. This is when we finally decided to start building an interactive map, focused on MRE related georeferenced variables, that we recently named EMMap. This process of first steps of design was supported by a team from Inria Chile.

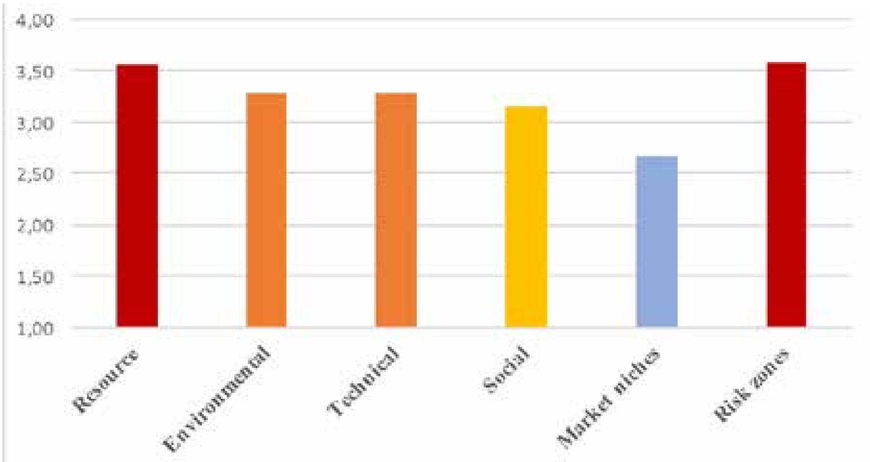
It is worth noting that EMMap is not only useful for technology project developers on MRE (main end-user), but also to sensitise MRE locally, being potentially useful as an information core that can visualise local capacities, supply chain characteristics, research and development work, local institutions and actors, among others.

II. Useful information: questionnaires.

The next step of this process was to ask potential users of this tool which type of variables they would like to see on the map, the uploading of useful information being one of the priorities of EMMap. To ensure a good understanding of their answers, a questionnaire with a list of variables was presented to different institutions and developers from the MRE sector, to be ranked by them.

41 variables were presented, classified into six main areas: resource, environmental, technical, social, market niches and risk zones. Where "resource" referred to parameters considered important when calculating power, "environmental" to protected areas and species, "technical" to the logistical support (such as harbour infrastructure, roads, etc.) that the installation, Operation and Maintenance (O&M) and decommissioning could need, "social" to community perceptions and social conflicts, whereas "market niches" is a first approach to the potential opportunities that a place could offer for MRE to cover a need (for example, mining in the north of the country could need energy or desalinated water, also aquaculture). Finally, "risk zones" referred to the extreme events that the country is affected by: tsunami charts, seismic risk, flooding, etc.

Figure 1 shows that the categories with the highest priority are the resources with the risk zones. These results preliminarily talk about the existing concern associated to the particular conditions of hazards and extreme events in the country. The field with the lowest priority was the one associated to market niches. Additionally, Figure 1 (right) shows the 17 highest priority variables for the users interviewed.



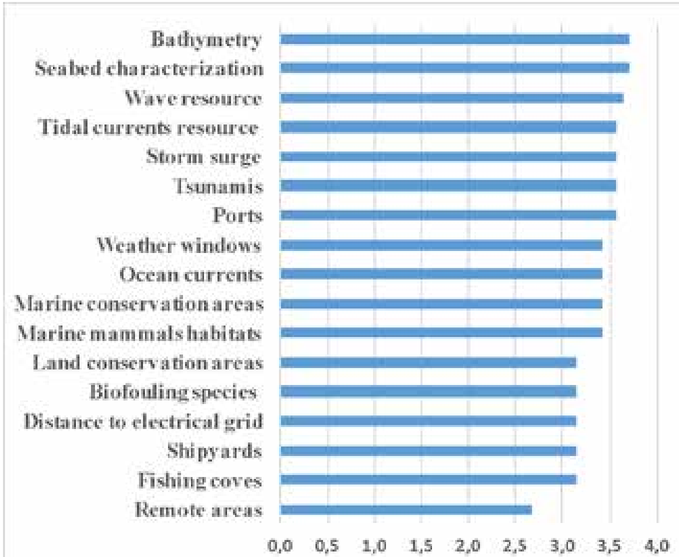


Figure 1: Variable prioritisation process: end-user questionnaires results per area (left) and per variable (right, 17 most relevant).

III. Review of national platforms and data collection

Seeking to avoid duplicating efforts and before starting to construct a first prototype, a comparison with other platforms was performed: the idea was to construct a tool that could fill a gap and not replicate something already created. In Table 1, the list of variables recognised as potentially useful for MRE in Chile and their corresponding platforms can be observed. It is important to mention that their names are substituted by letters. Only one national platform was found to be focused on marine energy, showing the wave resource and providing a report for a specific point previously selected on the map, describing the seasonality of the resource. Despite this, the platform does not incorporate other types of variables. Apart from this platform, there are no other platforms focused on marine energy. The rest displays several variables that potentially could help, but this information is dispersed among them.
In conclusion, variables that could be a priority for developers or users are not found on just one site, but are presented on several sites, making the process of crossing variables and decision-making more complex.

In conclusion, variables that could be a priority for developers or users are not found on just one site, but are presented on several sites, making the process of crossing variables and decision-making more complex.

Platforms	A	B	C	D	E	F	G	H	I	J
Resource										
Wind power			x							
Hydro power			x							
Solar power			x							
Tidal range										x
Wave power									x	x
Salinity										x
Bathymetry										x
Risk Zones										
Tsunami flooding areas	x	x				x				
Historical earthquakes	x									
Volcanic risk	x									
Flooding risks	x					x				
Technical										
Wind farms		x	x							
Hydro power plants		x	x							
Solar plants		x	x							
Thermoelectric plants		x	x							
Biomass plants		x	x							
Transmission line		x	x							
Transmission line projects			x							
Electric substations		x	x							
Power plants		x	x							
Geothermal concessions	x	x				x				
RE project concessions		x								
Marine concessions							x			
Port infrastructure		x								x
Distance to the coast										x
National road network		x								
Basic geology	x	x				x				
Environmental		x								
Environmental protected areas		x		x						
Wetlands		x								
RAMSAR sites		x								
Nature sanctuary	x									
Benthic management areas		x								
Heritage routes		x								
Marine protected areas		x								x
Native forest			x							
Social										
Density population		x								x
Indigenous communities		x		x						
Historical monuments		x								
Touristic atractions		x								
Land use		x								
Socio-environmental conflics					x					
Market niches										
Mining property		x								
Aquaculture								x		

Table 1: Georeferenced mapping platforms and their corresponding variables related to the MRE sector.

IV. Variables selection

From a balance of information availability and the prioritisation made by end-users, we proceeded to collect information and contact institutions. All variables were processed for georeferencing, checking and uniformity before uploading. EMMap's approach is to be a platform for linking other platforms, preserving the original source reference in case the user wishes to download the data itself. We therefore built associated metadata for each variable, and worked on the Disclaimer and Terms of Use of the platform to reflect this.

Around 30 variables are scheduled to be uploaded to the first stable version (to be released at the beginning of 2019, v1), and work on a second upload of around 15 more is to be completed by the end of MERIC's Stage 1. Figure 2 shows the variables to be first uploaded, and Figure 3 the institutions where this information comes from.

Figure 2: Variables to be published on EMMap v1.

Figure 3: Sources of external information for EMMap v1.

V. Prototype building

A first version of EMMap was developed to carry out a series of interviews with end users in order to follow a customer journey map whose feedback could validate the configuration of the final graphic design of the map. This first prototype (Figure 4, below) is just a first approach to a potential map, without considering aesthetic design. As mentioned, it was more focused on functionality with the user, in order to understand their needs during later interviews. We are working now on the final design stage of the map. Through a series of interviews and questionnaires, we expect to capture the different needs that users may have, and, in this way, design an interface that is useful and can support the decision-making process in a friendly, clear and efficient way. For this reason, this new stage considers an iterative process of refining until a minimum viable product is obtained. Currently, a teaser of EMMap is live on the web (www.emmap.cl), but is not fully functional: it has been created as a Beta Version to give a first idea of the potentiality of the tool (Figure 4, below). During this process, we are working together with DESIGNAR.

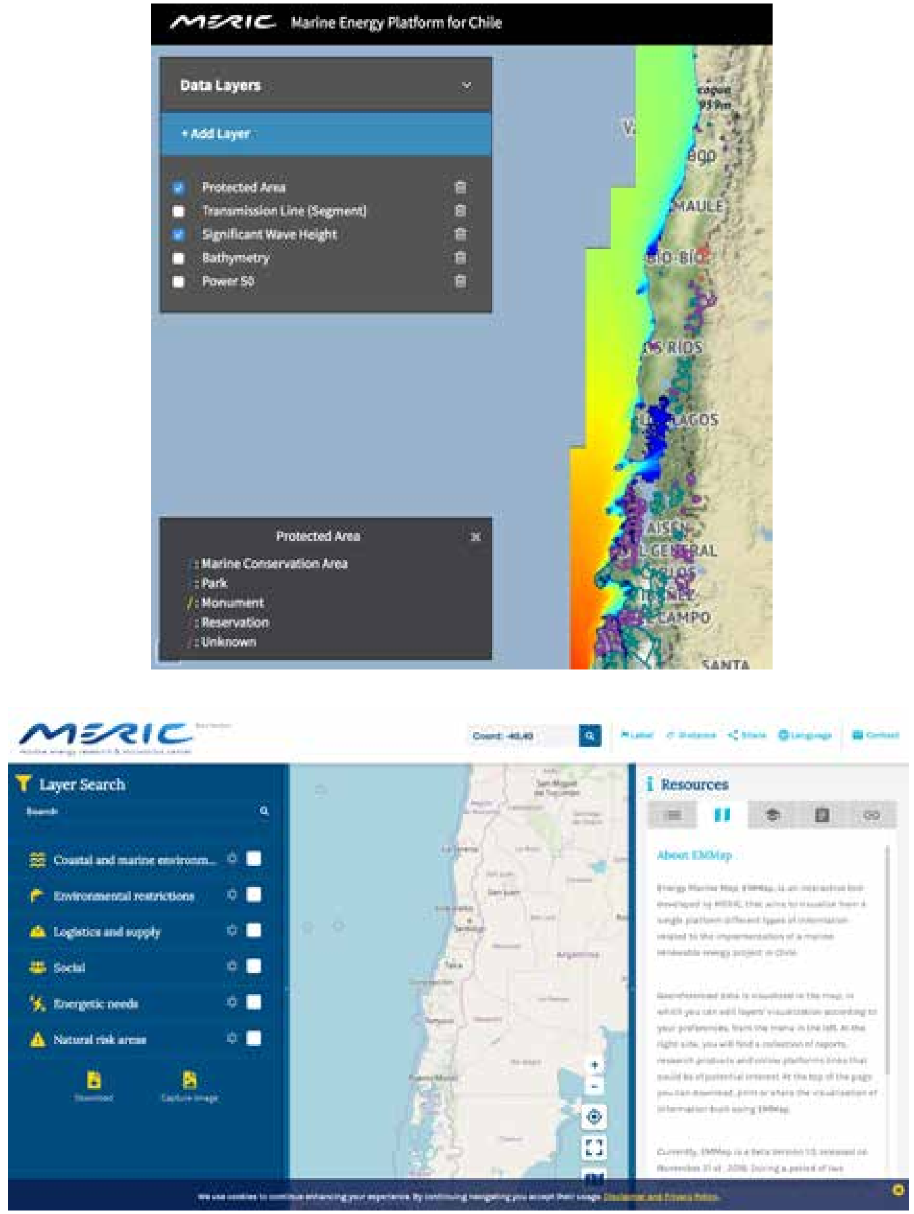


Figure 4: EMMap's first prototype (top) and current Beta Version (bottom).

Until mid-2018, along with the valuable feedback of the Ministry of Energy, EMMap received support from the following national and international institutions:

From the user design process, EMMap has become not only a platform for georeferenced information visualisation and crossing on a map, but also an interface that can collect and present other types of information, such as reports, scientific papers or links to other platforms. This is why the tool has a bar on the right-hand side that will present information related to each variable selected. The development is open for collaboration, from end-user experience support to information sharing. We believe this platform has potential to grow into a real support for MRE in Chile.

What's next

After the release of EMMap v1, we will start working on its projection for MERIC's Stage 2. We have first ideas that we will potentially keep working on:

1. Implementation of a usage tracker (Google Analytics) on EMMap, in order to have a comprehensive idea of how, when and from where the tool is used. This information will feed further user-oriented upgrades.
2. We want to integrate the automatic updating of information to increase the robustness of the displayed information, considering that some of the information is highly variable in time (e.g.., marine concessions, roads, power stations etc.) and therefore a bi-annual update would not be enough.
3. Considering the feedback we have received so far from presenting EMMap to the general public, we would also like to implement user access levels, at least for general, developer, and researcher levels. This will imply the building of a specific tool according to each final user group needs. Also, user access will allow the session and work done with EMMap to be saved.
4. Multi-variable analysis, according to technology specifications entered by the user. The results will be displayed on a heat map along Chile, indicating places where installation could be possible.

Legal framework

One of the sources of uncertainties for MRE installation in the country is the associated permit process, from marine and coast usage to environmental requirements. The aim of the Legal Framework team is to generate a clear guideline to shed some light on this process, which can be complex in terms of timing and paperwork, with multiple institutions involved.

Since 2016, in collaboration with the program Master Droit des Espaces et des Activités Maritimes of the Université de Bretagne Occidentale, France, we have been working on the legal framework regarding installation permits. Also, a comparison with international legal approaches to this subject is performed. We are seeking to give advice on the potential adaptations that the Chilean legal framework could incorporate in order to lighten the legal process for MRE implementation. A first insight to this guideline is presented in the section below, with critical comments on its nature. Also, in parallel to this output, we are working on a condensed version of this information, within a general timeline. The final objectives of this work are:

- Identify other applicable permits and see how they interact with other permits.
- Identify elements that can be improved/suppressed/added, considering the specificities of the marine renewable energies sector.
- Adopt a comparative methodology between Chile and foreign countries in order to identify the deficiencies existing in Chile's marine energy legal framework.

During the end of 2018, we will also start working on environmental legal requirements, to advance in 2019 with community participation and health and safety. The final goal for MERIC Stage 1 is to have a general roadmap for technology insertion in the country, looking into the different stages of the technology lifecycle: installation, O&M and decommissioning. It is worth noting that, so far, this is a snapshot of the legal framework as it is. Taking into account the dimension of this task, further critical analysis and international alignment is expected in MERIC Stage 2.

First insight: guideline for MRE installation permits

How to develop marine renewable energy projects in Chile

What are non-conventional renewable energies (NCREs)?
According to Law 20,257 of 1 April 2008, non-conventional renewable energies can be defined as electric energies generated by renewable energy technologies from renewable resources such as biomass, geothermal, solar, wind and wave, tidal and hydraulic (with a maximum potential of 20,000 kw).

What are NCREs in the sea?
NCREs in the sea include offshore wind and sea energy, which is the mechanical energy produced from the movement of tides, waves and currents or obtained by ocean thermal energy conversion.

An NCRE project in the sea can be initiated by different actors in a variety of ways. If it is initiated by the Government, it is likely that its deployment will result from the application of the public tender procedure for NCRE (or an ad hoc public tender call[1]). Regardless of how the project takes shape, it will be necessary to obtain two compulsory authorisations: a Maritime Concession and a Favourable Environmental Opinion.

What is a public tender?
A public tender refers to a contract which is published by a public sector organisation to invite competing offers from suppliers who can provide goods, services, products, works or utilities that an organisation requires with the decision ultimately being made on the basis of price and quality. In Chile, this notion is defined by the Implementing Regulation 19,886, article 2 (21) of 30 July 2003.

Public tender procedure for non-conventional renewable energy
The public tender procedure for NCRE was created by Law 20,698 of 22 October 2013 to comply with the NCRE obligation whereby 20% of commercialized electricity must be produced from renewable resources (on land or sea) by 2025[2] . To meet this target, the Government is required to make two public tender calls per year.

The Ministry of Energy elaborates the tendering process and defines the eligibility criteria for applicants. In order to be eligible, applicants must obtain a Favourable Environmental Opinion and a Maritime Concession (at least requested). The granting process of these two authorisssations will be explained below. In addition, they have to provide assurance mechanisms to ensure the fulfilling of their obligations throughout the project. Finally, applicants must provide documentation containing technical, commercial, financial and legal information.

Ultimately, the Ministry for Energy chooses the applicant that offers the best ratio in terms of volume of energy and price. Indeed, the prevailing criteria is the **lowest price.**

Obtaining the main authorisations

In order to install renewable energy technologies on the Coastline of Chile and finalise the NCRE procedure, it is essential to obtain a Maritime Concession and (in most cases) a Favourable Environmental Opinion.

Maritime concessions

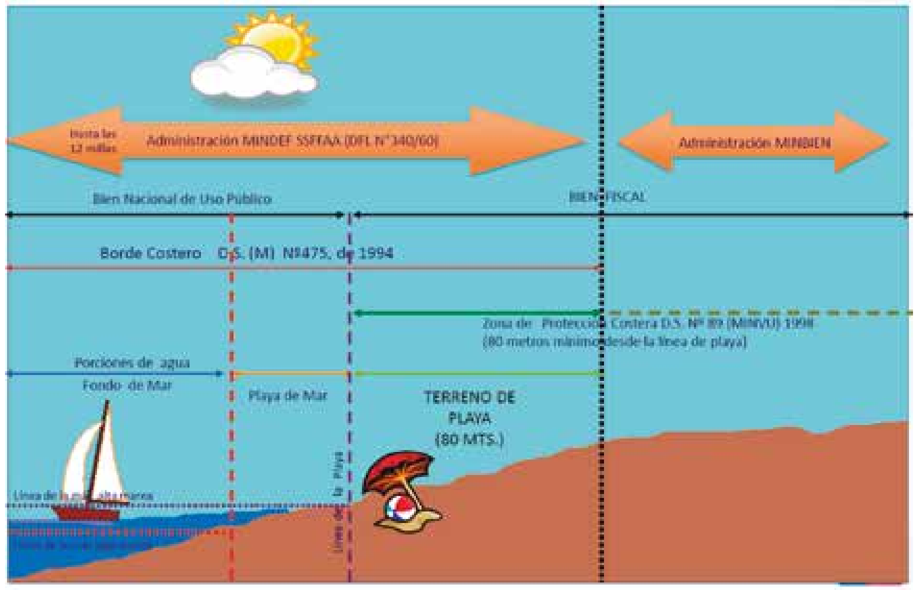
The right to exploit the Coastline and the territorial sea (see diagram below) is granted by a Maritime Concession named *"Concesión Marítima"* under Chilean Law[3] . Applicants must, without exception, obtain this authorisation to install infrastructure in the sea.

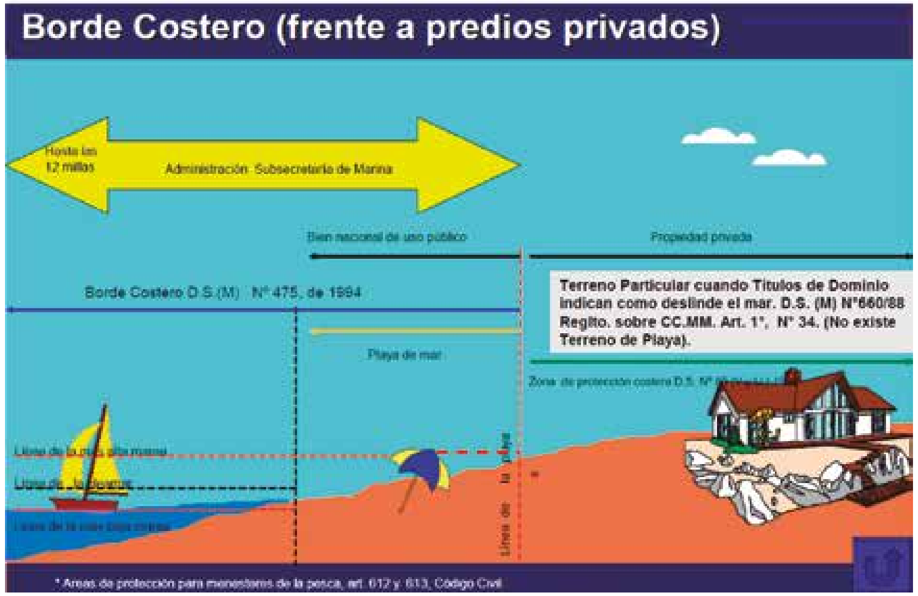
What is a Maritime Concession in Chile?
A Maritime concession is defined as a right by which a part of the maritime domain is partially or totally excluded from general use and granted for a particular use or commercial exploitation to natural and legal persons registered as tradesmen. This administration title is granted by the Secretary of the Armed Forces of Chile ("Subsecretaría para las Fuerzas Armadas").

Definition of the Coastline
The Coastline ("Borde Costero") is defined as the contact zone between sea and land that includes the following areas: an 80-meter stretch of land starting from the highest part of the foreshore (*"terrenos de playa"*), the foreshore (*"playa de mar"*), internal channels (if navigable by ships), bays, gulf and territorial sea. The Coastline is placed under the supervision of Chile's Ministry of National Defence.

1 Ad hoc public tender call refers to a tender call created specifically for a project.
2 Chile announced its target of reaching a minimal quota of 60% of electricity generated from renewable sources by 2035 and 70% by 2050.

3 The Law-Ranking Decree 340 regulates the granting, duration and termination of maritime concessions. It was published on 6 April 1960 and its Regulation fixed by Decree 2 on maritime concessions, was published on 20 April 2006, replacing the regulation fixed by Decree (M) 660 of 1988.





Source: www.asatch.cl

What is the territorial sea?
According to the United Nations Convention on the Law of the Sea of 1982, ratified in Chilean Law, territorial sea refers to the marine zone that extends up to twelve nautical miles from the normal baseline which is the low-water line along the coast as marked on large-scale charts officially recognised by the coastal State.

Maritime concessions are temporary, precarious, revocable, individual, modifiable, renewable, transmissible, onerous and respectful of the rights of third parties.

There are different types of maritime concessions existing in Chilean Law. They are classified according to their duration (**50 years** at most), the amount invested in the project, the associated type of civil service and their intended purpose.

Within the different categories of maritime concessions[4] , the **Major Maritime Concession** is doubtless the most adequate concession for marine energy projects which have an estimated lifespan of 30 years[5] . In effect, this title offers **a 50 year** duration and implies an **invested amount superior to 2,500 MTU.**

What is the Monthly Tax Unit (UTM in Spanish)?
The monthly tax unit was created by Decree-Law 830, article 8 of 31 December 1974. This unit is used for taxation and fines purposes. In May 2018, 1 UTM = 47,396 CLP (Chilean pesos) and 2,500 MTU = 118,490,000 CLP.

A **Transitory Permit** can be requested before the final granting to allow an **anticipated use of the requested sector** and carry out preliminary studies. However, this permit does not bind the Administration to granting the maritime concession. Deadlines for replying to a maritime concession request are not clearly defined by Law-Ranking Decree 340. The whole process lacks transparency, despite the fact that Decree 2 on Maritime Concessions of 2006 sets deadlines for some stages of the procedures.

A Supreme Decree or a Resolution (depending on the type of concession requested) sets the duration and the termination date of the maritime concession. Moreover, concessions can be foreclosed in advance under certain conditions such as a change in the project purpose.

In addition, the Administration retains a unilateral power of revocation to withdraw a title **without obligation to justify** and without engaging its responsibility. Despite

4 Major Maritime Concessions, Minor Maritime Concessions, Authorisations or Permits, Civil Service Authorisation and Aquaculture Concessions.
5 The estimated lifespan of marine turbines is 20 years. Based on the Danish experience, the lifespan of an offshore wind park is approximately 25 years.

compensation mechanisms being set, this possibility underlines the precarious nature of those titles. In practice, the Administration almost never uses this power.

Favourable Environmental Opinion

According to Chilean Environmental Law, any creation or modification of power plants generating more than 3 MW, high voltage lines and electric substations is subject to the granting of a Favourable Environmental Opinion. In this way, applicants have the obligation to submit their project to the Environmental Assessment Service (Servicio de Evaluación Ambiental, SEA). They must carry out an environmental impact study (EIS) or environmental impact declaration (EID) that indicates how their project impacts the environment. If the authority considers that the project meets current environmental rules, a favourable environmental opinion called "Resolución de calificación ambiental (RCA)" is granted. The deadline for granting an EID is 60 days and an EIS is 120 days. Regarding the importance of NCRE projects in the sea, it is likely that developers will have to submit an EIS to the Environmental Assessment Service.

Finally, the Environmental Impact Assessment process includes citizen participation, allowing individuals to formulate observations on the basis of environmental study/ declaration. It is possible to deliver opinions via electronic media throughout the whole project.

Conclusion

An NCRE project in the sea can take shape through three different scenarios:

- A public tender procedure for NCRE is initiated by the Ministry of Energy. If so, the developer needs:
- A Maritime Concession granted, promised or requested.
- A Favourable Environmental Opinion if energy production is to be greater than 3MW.
- A capital base above 20% of the required funds.
- Provide warranty of liability to ensure the fulfilling of their obligations.

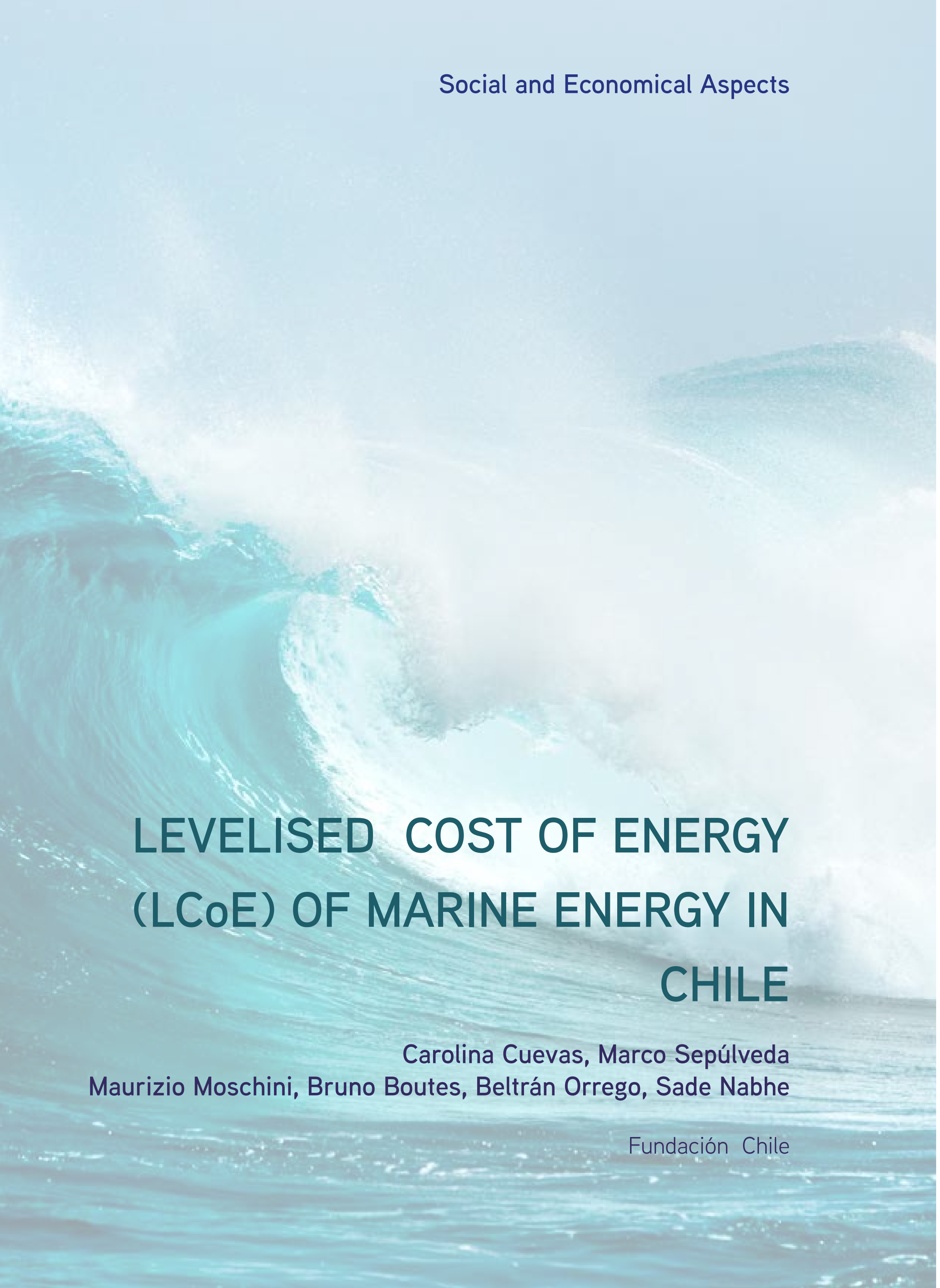
Ministry of Energy makes an ad hoc public tender call. If so, the developer needs:

- A Maritime Concession granted, promised or requested.
- A Favourable Environmental Opinion if energy production is to be greater than 3MW.
- Other conditions might be laid down by the Ministry of Energy.
- This scenario is not defined by law and differs from one project to another.

The developer's own initiative. If so, the developer needs:

- A Maritime Concession granted, promised or requested.
- A Favourable Environmental Opinion if energy production is to be greater than 3MW.

This scenario is not defined by law and may require other conditions.



LEVELISED COST OF ENERGY (LCoE) OF MARINE ENERGY IN CHILE

Carolina Cuevas, Marco Sepúlveda
Maurizio Moschini, Bruno Boutes, Beltrán Orrego, Sade Nabhe

Fundación Chile

SUMMARY

Of the main drivers pushing the development of the energy matrix in Chile, we should mention first: diversification and energy security, decarbonisation and the positioning of Chile as a world leader on this matter; and secondly, looking to the future, the export of green energy to neighbouring countries. Given that Chile has one of the largest marine energy resources in the world, marine energy might play a key role in achieving these goals. Additionally, tidal energy technologies are reaching a more mature development stage, which facilitates performing technical-economic assessments with less uncertainty.

The Levelised Cost of Energy (LCoE) study of wave and tidal technologies aims to identify technical-economic aspects of marine energy projects in Chile. On the other hand, this study comprises the identification of local actors to estimate local value capture and to identify opportunities and challenges in the supply chain. The LCoE tool enables comparisons of different energy projects regardless of technology deployed and project characteristics.

The study is divided into three main phases: first, a comprehensive global literature review of economic assessments and technologies, initial collaboration with technology developers, site and support infrastructure assessment and methodology definition. The second phase comprises supply chain analysis and the estimation of local value capture. The last phase includes the final calculation of the LCoE per site, scale and technology, and the socio-economic study.

During the literature review of studies developed around the world, it was possible to define a breakdown of the items comprised in the LCoE. The first stage also compiled all the information available regarding sites in Chile. This database of site information is the basis for the scenarios' definition of wave and tidal energy projects in the second phase.

During the second phase the scenarios for different sites and technologies were defined, within a framework of collaboration with five international tidal technology developers and three wave energy technology developers. The tidal energy companies are: Sabella, Scotrenewables, Open Hydro, Atlantis and Tocardo. It should be mentioned that Tocardo and Open Hydro suspended their commercial operations during this study. However, Tocardo has restarted, with Dutch government support.

Notwithstanding the above, the assumptions based on these two companies were used to calculate the LCoE. The wave energy companies that have been contacted for this study are: AW Energy, Oceantec, Albatern, Aquanet Power and Biowave.

Technology developers have shared technical and economic information of the several stages of a marine energy project: from equipment and device manufacturing to the operation and maintenance stage. The aspects defined in the scenarios include parameters related to support infrastructure, site characteristics, marine energy farm design, installed capacity and descriptions of the installation procedure.

In addition to the technical analysis of the sites, a community engagement analysis was performed. Restricted areas and special legislation were also identified. The main objective of this complementary study is to ensure the involvement of communities during the whole project life cycle. This process is quantified within the items of the Capital Expenditure (CAPEX) as "social compliance". The value attributed to this item involves significant uncertainty due to the lack of local experience.

The findings and outputs of the first and second stages have been validated by international experts from the University of Edinburgh, Offshore Renewable Energy (ORE) Catapult, Lloyd's Register, BVG Associates and Black & Veatch.

The outputs of the LCoE for different project scales, sites and technologies are given in Table 1. The minimum and maximum values depend on assumptions made for each scenario. The level of uncertainty is based on information quality and other factors of the reference site. However, these levels of uncertainty are discussed and validated during a workshop with national and international experts. The table below shows and summarises final LCoE values for both technologies, tidal and wave.

Project scale	Variable	Wave		Tidal	
		Minimum	Maximum	Minimum	Maximum
Demonstration	Installed capacity (MW)	0,3	0,42	1	2
	LCoE (US$/MWh)	246	1414	228	2139
Medium scale	Installed capacity (MW)	3	4,2	10	10
	LCoE (US$/MWh)	124	884	132	673
Large scale	Installed capacity (MW)	30	42	50	100
	LCoE (US$/MWh)	106	714	71	374

Table 1: outputs of the LCoE for each project scale, sites and technologies.

The following Figures show the results of LCoE for specific technologies (two types of wave energy technology and three types of tidal energy technology), scales (demonstration project, medium scale project and utility scale project) and sites. The final figure shows a comparison between wave and tidal energy in Chile with respect to the LCoE of marine energy in the world in different scales.

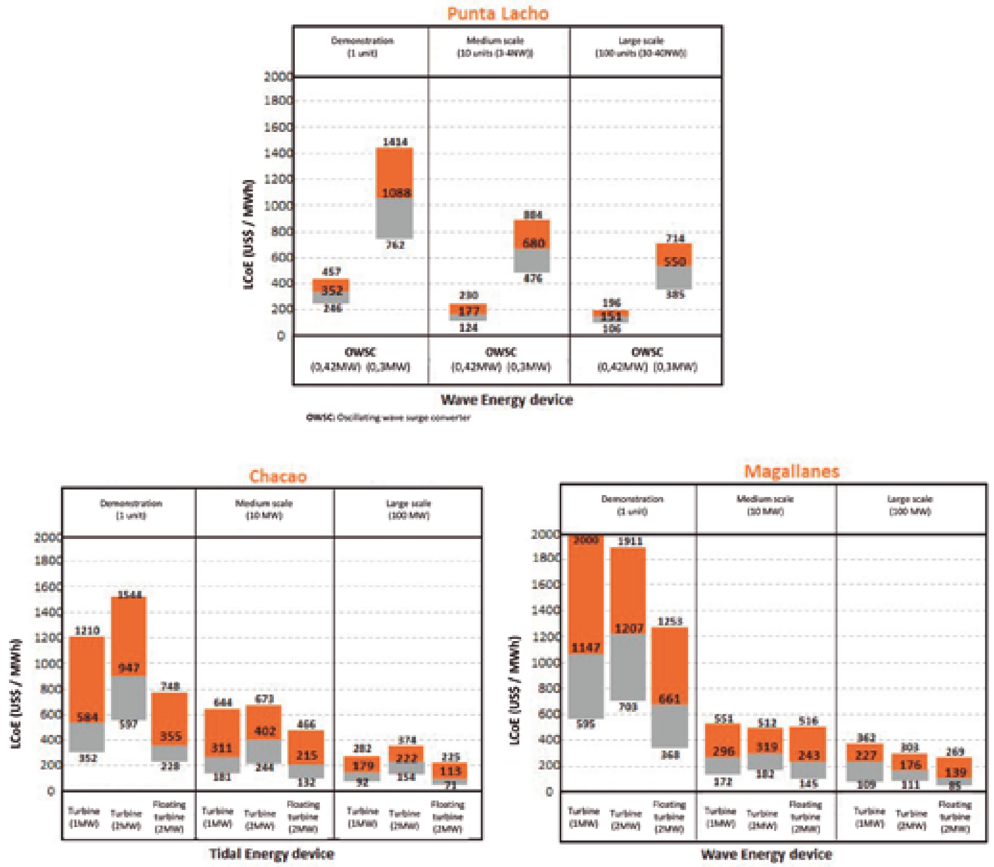


Figure 2: results of LCoE for specific technologies, scales and sites.

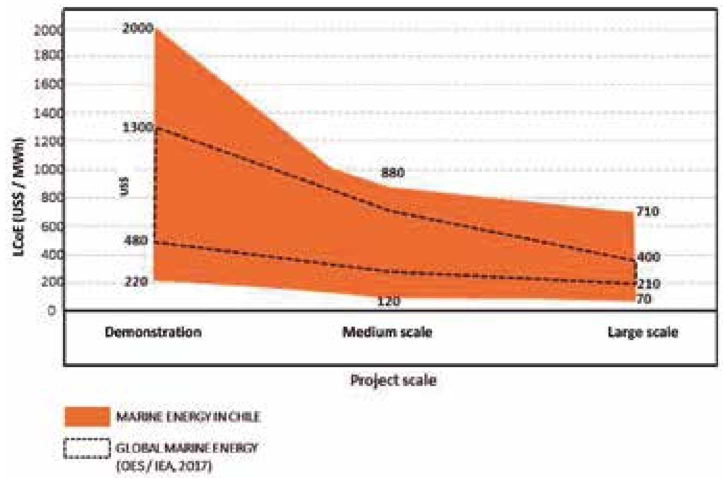


Figure 3: results of LCoE for specific technologies, scales and sites.

Finally, the supply chain analysis was performed in the second phase of this study. During a period of five months, 42 local supply chain actors were interviewed. These local companies are located in the following cities: Punta Arenas, Puerto Montt, Osorno, Valdivia, Concepción, Talcahuano, Valparaíso and Santiago. The main purpose of visiting these actors was to understand capabilities, costs and experience related to marine energy projects. According to the supply chain classification, it is possible to identify services and products with greater local value capture. Likewise, it is possible to recognise the largest challenges for the local supply chain and their impact on CAPEX and Operational Expenditure (OPEX). Using a semi-quantitative analysis, 60% of local value capture is estimated (Figure 3). Capabilities in the following activities can be highlighted: steel structure manufacturing and mooring system installation. Both items have a large impact on the CAPEX and the rest of the operational life of the devices.

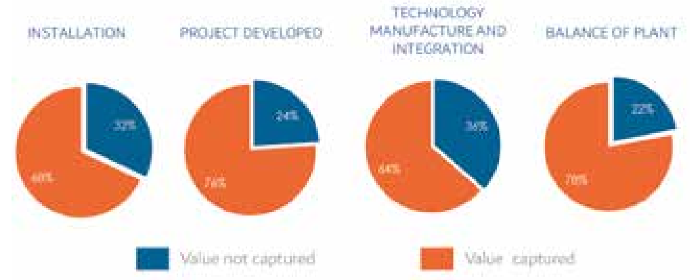


Figure 4: estimation of value captured by the insertion of marine energy in Chile

Parallel to the main objectives of this study, the international consultancy company Black & Veatch developed a socio-economic assessment of marine energy in Chile. The marine energy deployment assumption for 2050 is a range of 65MW to 260MW for pessimistic and optimistic scenarios respectively. Their analysis assessed the potential overall value of the marine energy sector, under the given deployment assumptions in Chile in 2050, to be between 44 billion and 183 billion CLP of Gross Value Added (GVA) with potential for between 1531.2 and 6242.7 full time employment (FTE) jobs to be created in Chile by 2050.

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ACRONYMS LIST

AD - Actuator Disks
ADCIRC - Advanced Circulation Model (coastal numerical model)
ADCP - Acoustic Doppler Current Profiler (oceanographic instrument used to measure water currents at different depths)
ADV - Acoustic Doppler Velocimeter (instrument that measures currents, with higher resolution)
BEM - Boundary Element Method
CAPEX - Capital Expenditure
CERE-UMAG - Centro de Estudios de los Recursos Energéticos, Universidad de Magallanes
CFD - Computational Fluid Dynamics
CLP - Chilean pesos
CPU - Central Processing Unit
CSN - Centro Sismológico Nacional, Universidad de Chile
CTD - Conductivity, Temperature and Depth (oceanographic instrument that measures salinity)
DES - Detached-Eddy Simulations
DIHA - Departamento de Ingeniería Hidráulica
EAM - Eulerian Averaged Model
ECIM - Estación Costera de Investigaciones Marinas
EMMap - Energy Marine Map
FP - Fokker-Planck
FVCOM - Finite Volume Community Ocean Model (coastal ocean circulation model)
FWP - Floating Wind Platforms
GIS - Geographic Information System
GPS - Geographic Positioning System
H/V - Horizontal to Vertical
HDPE - High Density Polyethylene
IDE - Integrated Development Environment
INRIA Chile - Institut National de Recherche en Informatique et en Automatique
IP - Isotropisation of Production
ISC - International Seismological Center
IUCN - International Union for Conservation of Nature
LES - Large-Eddy Simulations
LSM - Lagrangian Stochastic Model
MERIC – Marine Energy Research & Innovation Centre
MHK - Marine HydroKinetic
MRE - Marine Renewable Energy

NCRE - Non-Conventional Renewable Energies
NGO – Non-Governmental Organisation
O&M - Operations and Maintenance
OES/IEA - Ocean Energy Systems / International Energy Agency
OpenFOAM - https://www.openfoam.com
OpenMP - Open Multi-Processing
OPEX - Operating Expenditure
PAM - Passive Acoustic Monitoring
PDF - Probability Density Function
PIC - Particle-in-cell
PUC - Pontificia Universidad Católica de Chile
R&D - Research & Development
RANS - Reynolds-Averaged Navier-Stokes
RCA - Resolución de Calificación Ambiental
RINA - Núcleo de Investigación en Riesgos Naturales y Antropogénicos
SCADA - Supervisory Control and Data Acquisition
SDM-OceaPoS - Stochastic Downscaling Method – Ocean Power Simulation
SEA - Servicio de Evaluación Ambiental
SERNAPESCA - Servicio Nacional de Pesca y Acuicultura
SHOA- Servicio Hidrográfico y Oceanográfico de la Armada
STAR-CCM+: https://mdx.plm.automation.siemens.com/star-ccm-plus
SWAN - Simulating Waves Nearshore (numerical wave model)
TEC - Tidal Energy Converters
TKE - Turbulent Kinetic Energy
TRL - Technology Readiness Levels
TSR - Tip Speed Ratio
UACh - Universidad Austral de Chile
UC - Pontificia Universidad Católica de Chile
URANS - Unsteady Reynolds-Averaged Navier-Stokes
USGS - United States Geological Survey
UTM - Monthly Tax Unit (Chile)
WEC - Wave Energy Converter
WTB - Wave Test Bench

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Energía Marina SpA
Apoquindo Avenue 2827, 12th floor
Las Condes, Santiago, Chile
contacto@meric.cl