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(PUBLISHABLE PART)

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ACRONYM : LABBUOY

TITLE : ECONOMICALLY EFFICIENT FLOATING DEVICE FOR WAVE POWER CONVERSION INTO ELECTRICITY; PHASE I: MATHEMATICAL & PHYSICAL MODEL TESTING

PROJECT CO-ORDINATOR :
CENTRE FOR RENEWABLE ENERGY SOURCES (GR)

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TABLE OF CONTENTS

1 Project Summary

The LabBuoy project concerned model testing of a novel, on shore operating wave power converter. The converter is of the floating type, the power transmission and power conversion systems being mounted above still water level on solid fundament (breakwater or pier), Fig. 1. This architecture yields increased power production due to wave reflection on the breakwater frontage, and high reliability and operational safety.

The central objectives of the project have been:

1) development of reliable numerical simulation models to be used for system design and loads prediction, valid for various representative wave climates met along the European coast line;

2) validation of the mathematical models and verification of the applicability of the technology by experiments in small scale in a wave tank;

3) elaboration of sophisticated system configuration for maximum power absorption, production and reliability;

4) assessment of feasibility, socio-economic and environmental impact of the technology for representative sea states in Europe.

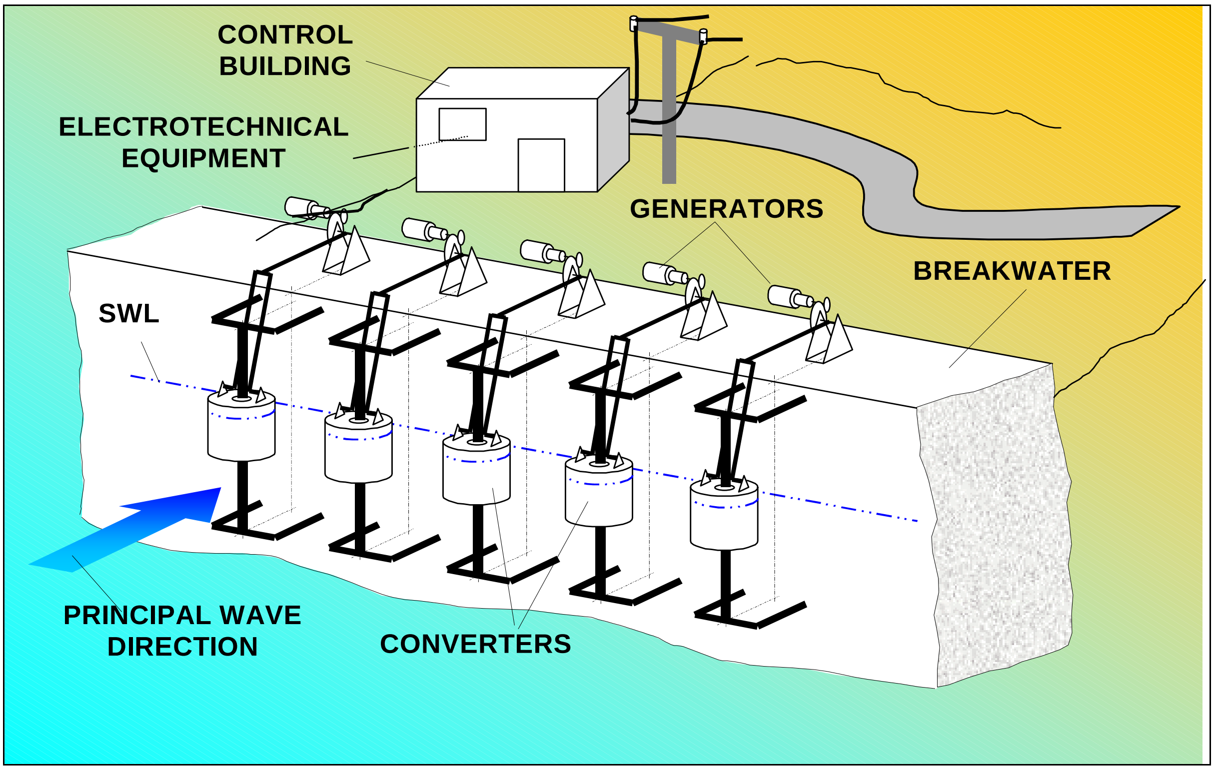

Fig. 1: *Sketch of a Labbuoy-power plant*

The project objectives have been attained through different research and validation tasks. Two approaches have been made: mathematical modelling and physical model testing.

In the first approach the development of numerical models has been conducted, simulating the device operation under various wave conditions as met along the European coastline. The models provide non-linear, time-domain simulation of the device. Approximate linear modelling has also been conducted which enables prediction of the device performance in the frequency domain. The main model features are: modelling of the hydrodynamic interactions between the converters and the adjacent breakwater; loads prediction; transient response assessment; latching/anti-latching simulation; linear, non-linear and exponential power control.

In the second approach a model of a row of five converters in front of a vertical plan wall was designed and manufactured. The electrical machines attached to the converters were simulated by computer controlled electro-mechanical speed control devices. The experiments, which included diffraction measurements, free and forced buoy oscillations, were performed under various wave conditions, simulating representative wave climates met along the European coastline. For the validation of the electrical systems simulation model a special laboratory model has been constructed and deployed in a narrow wave tank, with which various linear and non-linear control strategies have been tested. A “virtual instrument” in the Labview s/w environment was developed, which controls interactively the data acquisition and motor control system. This “virtual instrument” has been appended specific networking features, which allow internet-based experimental monitoring, data transfer and partner communication. This “network-platform” is expandable to remote control and monitoring functions for larger and full scale plants, intended to be developed for future deployment in open sea.

In parallel, the standards environment and certification regulations applying to the present technology have been investigated, and a number of studies were conducted, which combine the theoretical and experimental findings to assess the economic, environmental and social indices of the technology.

The project results confirm the validity of the simulation models developed and demonstrate the applicability and the feasibility of the proposed technology. The development and experimental validation of the mathematical system model yield a reliable tool for realistic design of converter systems for field-testing at larger and full scales, which is planned to be performed in subsequent, follow-on projects.

The project consortium consisted of 6 organizations from 4 European countries, which assumed the following main responsibilities:

- **Centre for Renewable Energy Sources (GR):** project co-ordination; set-up of measurement equipment; environmental impact assessment, life cycle analysis and feasibility studies
- **National Technical University Athens (GR):** hydrodynamic analysis, device modelling, experiments, data analysis & evaluation
- **Athena SA (GR):** physical model manufacturing; technology substantiation studies
- **Rambøll (DK):** Device modelling; physical model design
- **Queen’s University College (UK):** numerical and experimental modelling of electrical systems
- **University College Cork (IE):** wave power resource assessment and modelling, socio-economic studies.

2 Progress and Results

2.1 Numerical Device Modelling

The numerical simulation model of the device developed in the course of the LabBuoy project consists of two modules, a hydrodynamic-kinematical and an electrical module. The hydrodynamic-kinematical model was developed in the Mathlab and Fortran environment. This describes the heave motion of each converter in the array. A non–linear system of coupled equations of floaters' motions has been established and solved both approximately in a linearized version, as well as and in its complete non–linear form using time–domain techniques. The hydrodynamic interactions between the converters themselves and the adjacent breakwater have been properly taken into account by solving the exact first–order hydrodynamic diffraction and radiation problems.

Of particular importance for the solution of the governing equations of motion, is the evaluation of the exciting wave forces and of the hydrodynamic coefficients for each cylinder in the array by considering their hydrodynamic interactions among each other and to the adjacent breakwater. The latter is considered vertical and fully reflecting the incident wave train. A row of N truncated circular cylinders placed in front of a breakwater at constant water depth h is considered. The cylinders are exposed to the action of a plane incident wave train of frequency ω and amplitude A propagating at an angle θ with respect to the positive x-axis. The problem under investigation is equivalent to the one of an array of cylindrical bodies consisting of the initial and their image virtual cylinders with respect to the breakwater that are exposed to the action of surface waves without the presence of the breakwater. For the solution of the diffraction problem, however, the equivalent array of cylinders should be considered exposed to the action of two incident wave trains; one propagating at angle θ and a second one at the angle $180 - \theta$. The corresponding results are then properly added to produce relevant hydrodynamics.

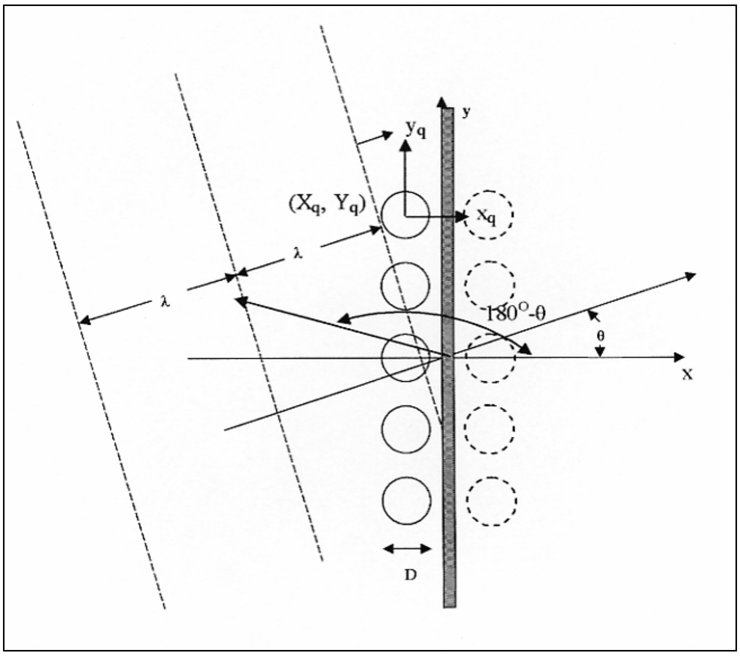

Fig. 2: *Plan view of the cylinder array in front of the breakwater (image cylinders denoted dashed)*

The electrical machine model consists of a Simulink model of the beam arm, freewheel and electrical machine and a MatLab script file called by Simulink to solve the induction machine equations. The model is comprised of several blocks, a schematic of which is shown in the next figure. The elements of interest are the free wheel and the induction machine model. The arm model is a simplistic model, which can be replaced by a more complex one.

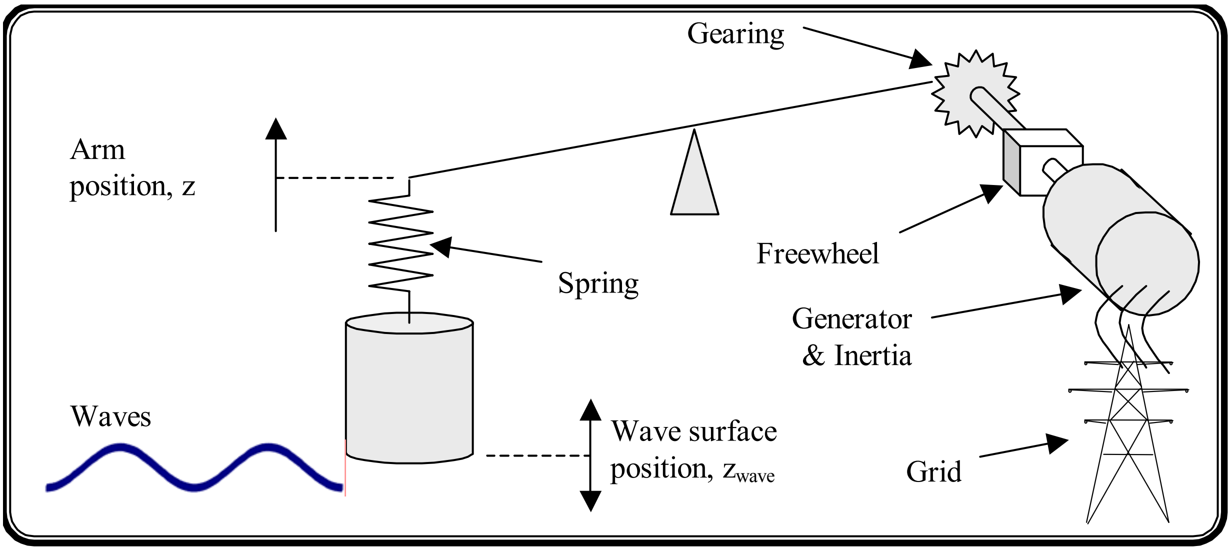

Fig. 3: *Arm Freewheel Machine Schematic*

To verify PTO simulation it was considered necessary to build a laboratory model of part of the device to investigate further the different aspects of design. Construction of this model raises additional issues of instrumentation (how does one measure what is happening) and control (how does one control what is happening). The construction of this prototype model was not in the initial plan but provided an essential building block in examining the control strategy and in assessing the critical features of the final design.

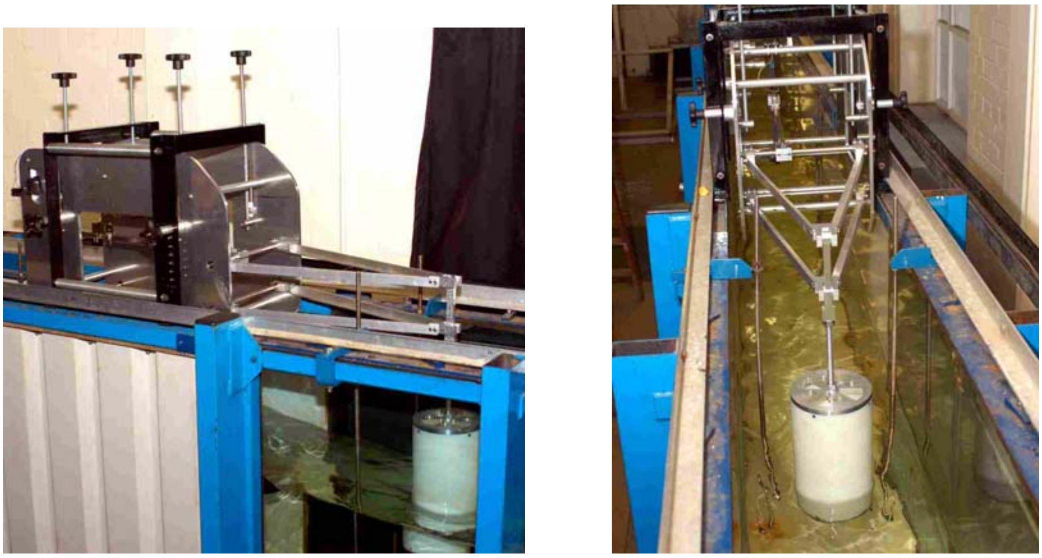

Fig. 4: *Laboratory model for validation of the PTO simulation in a narrow wave tank*

2.2 Physical Model Testing

A 1:15 scale model consisting of 5 converters in row was manufactured and deployed in the wave tank of the National Technical University of Athens (Fig. 5), and a number of experiments under various wave conditions of interest were conducted. Central aim of the scale experiments was the validation of the numerical simulation models of the device.

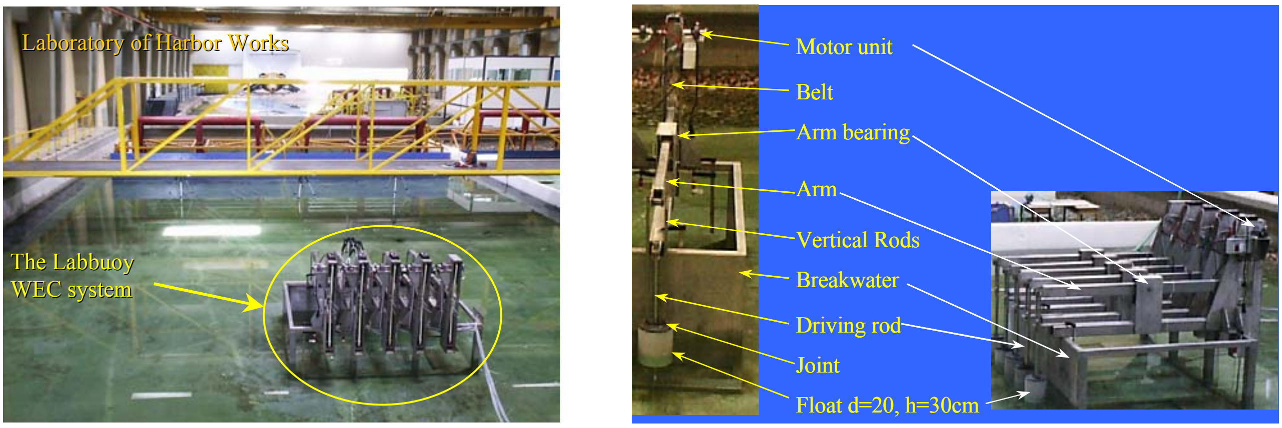

***Fig. 5:** 1:15 scale model of five converters in front of breakwater in a wide wave tank*

A DC-motor is attached to the rear end of the arm of each model which provides a controllable resistance torque to the arm motion via a toothed belt. Each motor is controlled by a controller with encoder feedback. The motors can be controlled to excite the floats to specific motions, as e.g. forced sinusoidal oscillations.

Each model converter is equipped with the following sensors:

- force sensor for the measurement of the vertical buoy force
- angular position sensor for the measurement of the instantaneous position of the model arm
- optical encoder for the measurement of the instantaneous rotational speed of the model arm

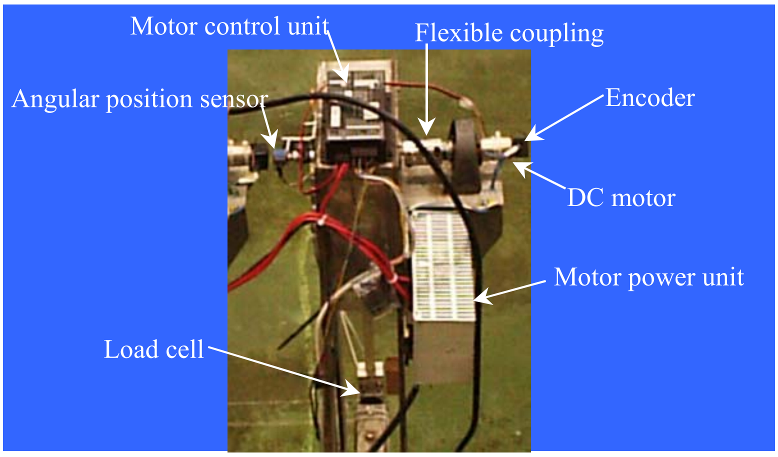

***Fig. 6:** Model sensors and PTO simulation details*

In addition, simultaneously to the model properties, the instantaneous wave height was sensed by wave sensors in 6 significant locations

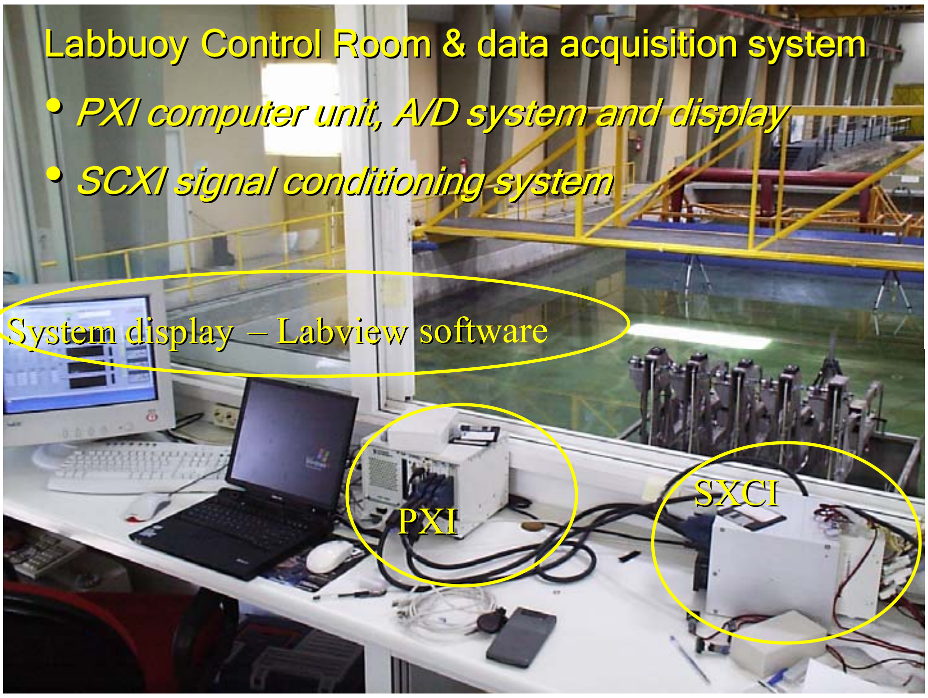

Fig. 7: *DAQ system*

The data acquisition and data management system is capable of real-time measurements, i.e. it works independently of the operating system of the host computer, being thus not affected by limitations regarding data transfer rate. The system consists of a controller, a D/A converter, an analogue signal conditioner, a strain gauge signal conditioner, an A/D converter and a counter card.

A “virtual instrument” (vi) has been developed in the LabView s/w environment to control several functions of the data acquisition and data management system, in particular:

- Sensor calibration
- Adjustment of the hardware profile (scan rate, channel identification, amplification and filtering, etc.)
- Adjustment of the profile of the PTO control system (operational mode, PID parameters etc.)
- Calibration and zero adjustment of the sensors; data conversion to physical units
- On-line data display
- Data storage

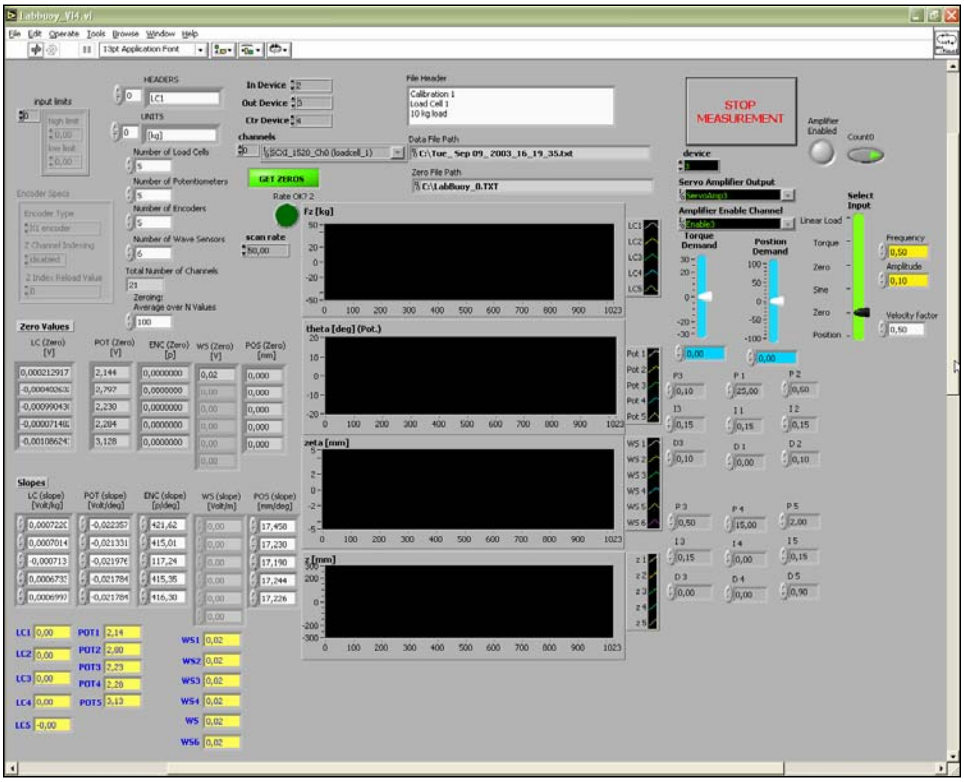

Fig. 8: DAQ and control vi

The vi can be made available on the internet to remote partners, allowing monitoring and operation. Data transfer to a remote location is also possible with an additional ftp-module, also developed in the course of the project.

With the equipment described above a number of experiments were conducted, in particular:

- *Diffraction measurements* with fixed buoys under various wave conditions of interest. This series of experiments includes measurements of the vertical forces acting on the buoys at regular waves of various heights H and periods T, as well as irregular waves of various significant wave heights H_s and energy periods T_e. The experiments were conducted at two different wave incident angles (0^o and 30^o).
- *Free oscillation measurements*; this series of experiments includes measurement of the buoy motion and forces during the free oscillation of the buoy after its release from a submerged position, and parallel measurements of the waves radiated by the buoys. This experimental series provides information about the system inertia and the radiation coefficients of the buoys.
- *Forced oscillation measurements*; in this experimental series the buoys are forced to harmonic oscillations about their state of equilibrium. The motion is driven by the DC-motors. The experimental series includes measurement of motion, forces and radiated waves at various oscillation frequencies and amplitudes.

2.3 Experimental Results and Numerical Model Validation

The experimental results confirm the numerical model reliability and its ability to predict the device behaviour, and its performance and power output under various wave conditions of interest. Some representative results are shown in the figures below. Fig. 9 shows comparison between theoretical and experimental values from diffraction measurements. Based on the excellent agreement between experimental data and numerical predictions, the validation of the developed software, which is suitable for solving the linearized body – wave interaction problem between a row of WEC placed in front of a vertical breakwater and incident waves, is fully justified.

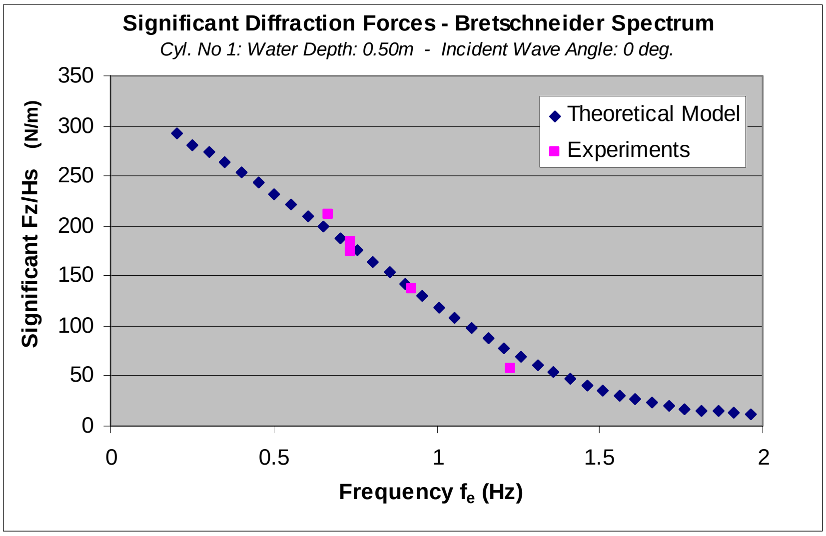

Fig. 9: *Diffraction forces: comparison between experiments and simulation*

Fig. 10 shows a comparison between experimental and theoretical results for a free oscillation test. Good agreement between them can be observed. The discrepancies towards the end of the motion may be influenced by the frictional non linear forced inherent to mechanical systems, which were unavoidably present during the experiments, and which were not possible to be included in the theoretical model, apart from an increase in the system damping value. The frequency content and shape of the decaying oscillations are sufficiently predicted by the theoretical model.

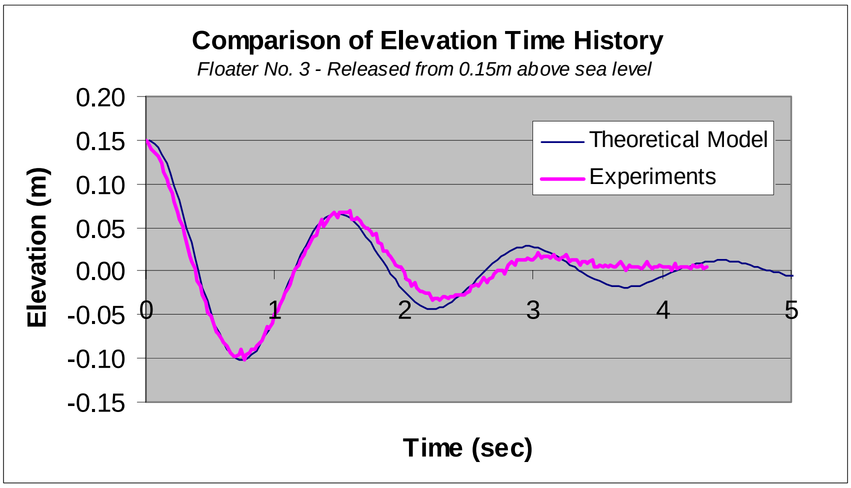

Fig. 10: *Free oscillation tests: comparison between experiments and simulation*

2.4 Environmental Issues, Feasibility and Market Prospects

Additional studies conducted in the project concerned the technical and economical feasibility of the device, the perspectives of the large scale implementation of the technology in Europe and its expected economic and environmental impact. Some general conclusions are summarized below:

- With some modifications in the original design, the LabBuoy technology is forecasted to provide an efficient, economic, safe and environmental friendly source of energy. The main areas of environmental concern of the Labbuoy technology are typical for on/near-shore operating wave power devices: optical and acoustic intrusion, shore alteration and impact on fauna.
- Optical and acoustic intrusion is expected to be easy manageable (Fig. 11). As with most wave power conversion technologies, the latter two impacts have to be studied carefully in subsequent projects. "Labbuoy-breakwaters", as e.g. in Fig. 11, are likely to find easy acceptance in built-up, coastal industrial areas, such as harbors, ports, shipyards, refineries etc. The noise level created in the energy conversion phase might also become a low priority consideration in this case.

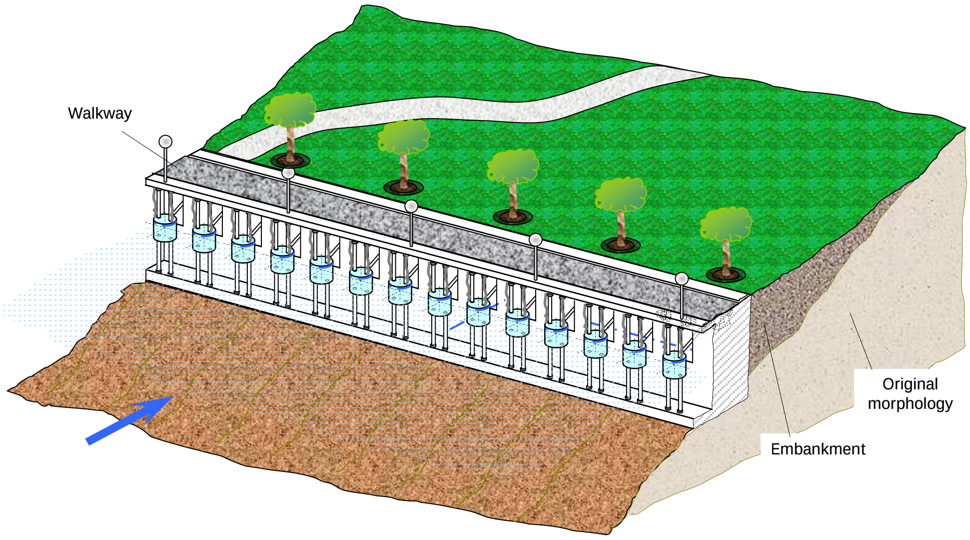

Fig. 11: *An optically acceptable LabBuoy-breakwater*

- The LCA analysis conducted has shown that the most severe impact on the environment results from the breakwater in the form of emissions of respiratory inorganic substances (Fig. 12). The next important impact was found to be the depletion of minerals resulting from the manufacturing of the converters.
- The use of aluminium for the manufacturing of the converters would increase, both, its cost and its environmental impact. Steel is more economical and also friendlier to the environment. However, use of recycled materials, incl. aluminium, would drastically reduce any impact, and should be taken under consideration in the design of the system.
- Depending on the incident wave power level, the generating costs of the technology have been predicted to range from ~9 c€/kWh (at 15 kW/m) to ~7 c€/kWh (at 45 kW/m). Hence, the generating costs of the Labbuoy device, as predicted at the current stage of development, are higher than conventional electricity (~4 c€/kWh), they are however significantly lower than for other ocean energy technologies or "expensive" RES technologies such as the photovoltaics. The capital costs have been predicted to range

typically from ~2000 €/kW(rated) to ~4000 €/kW(rated). Capital and generating costs are expected to reduce with the refinement of the technology, as, both, the device efficiency and the construction costs will improve in the subsequent phases of device development.

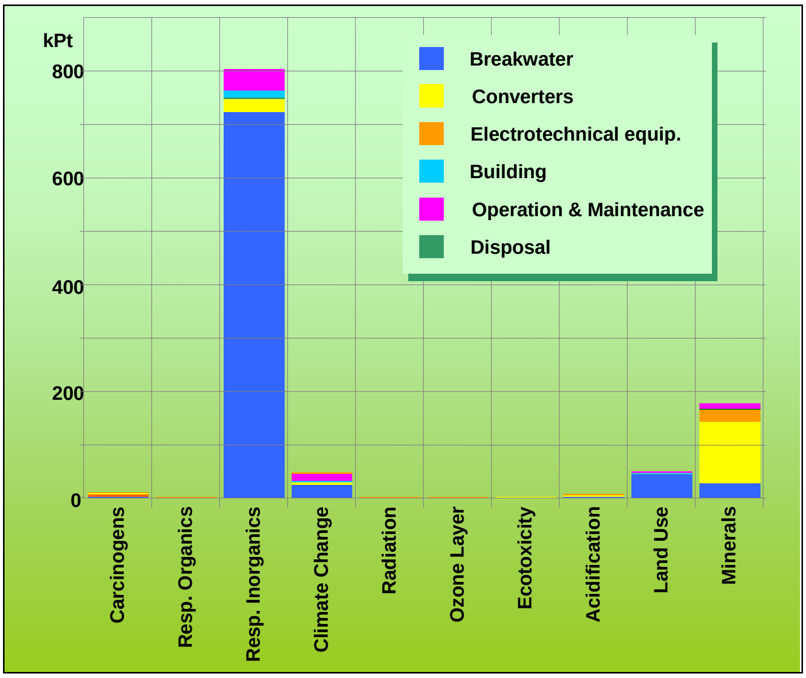

Fig. 12: *Categorized impact of major components of the Labbuoy converter*

- The highest cost in the construction of the system was found to result from the breakwater. The design of the breakwater should be reconsidered, so as to reduce its cost, on the one hand, and its environmental impact, on the other. Alternative foundations, e.g. pylons or girder structures, could eventually be more economical and environmentally more friendly, and should have to be investigated in subsequent projects.
- Fig. 13 shows the European coastline exposed to exploitable wave power climate (dotted lines). The total length of this coastline is estimated to be at least ~30,000 km. Assuming an initially available coastline in the EU (incl. Iceland and Norway) of 180 km in total for device deployment, this would correspond to a market of ~23,500 devices with floater diameters of 2-4 m. This market corresponds to a job-market of ~19,200 man-years of skilled technical personnel, not including operation, maintenance and repair. The labour effort for project development would be approx. 700-1000 man-years of engineers/administrators.

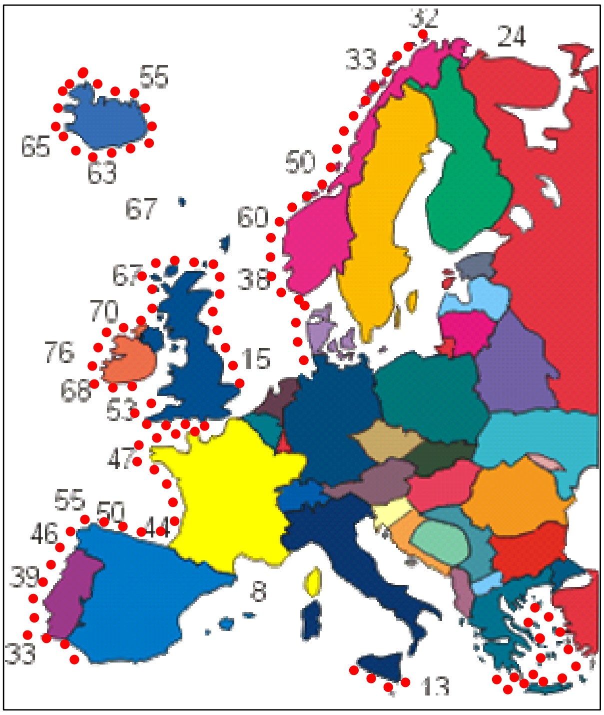

Fig. 13: *Potential European market; candidate areas (dotted lines) of device deployment*

3 Conclusions and Outlook

The LabBuoy (Phase I) project concerned numerical modelling and experimental testing at small scale of a novel on/near-shore operating wave power converter. Furthermore, the techno-economical feasibility, the market prospects and potential environmental impacts of the technology have been investigated.

The numerical models developed describe the dynamic response of the device to various incident wave conditions of interest. The models have been validated with experiments in small scale in wave tanks in regular and irregular waves. The comparison between modelling and measurement is satisfactory and verifies the reliability of the numerical model. This model enables now the exact configuration of the device to specific wave conditions, so as to maximize power production and achieve sufficient operational safety.

The predicted generation costs of the device of ~7-9 c€/kWh are still higher than for conventional electricity. They remain however significantly lower than for other ocean energy technologies or “expensive” RES such as the photovoltaics and are expected to reduce with the refinement of the technology.

The present project has provided the basic knowledge and tools for subsequent large scale testing and prototyping of the technology. Currently, device testing at intermediate scale (~1:3…1:5) in the open sea is planned. The immediate implementation of this project would enable prototype installations in 2-3 sites in Europe with local wave power levels ranging from ~15 kW/m to ~45 kW/m before 2009.