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Wave energy in Europe: current status and perspectives

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Abstract

The progress in wave energy conversion in Europe during the past ten years is reviewed and current activities and initiatives in the wave energy sector at National and Union level are described. Other important activities worldwide are summarized. The technical and econ-

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omical status in wave energy conversion is outlined and important wave energy developments are presented.

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1. Introduction

The world energy consumption is estimated to rise considerably over the next decades, and in the same period the energy consumption in the European Union will increase by almost a similar rate. Being constantly reminded that traditional methods of energy production are contributing to serious environmental problems the governments of the Member States have seen the urgent need for pollution-free power generation. The energy sector was forced through a renovating process, which sees an opening towards renewable energy. In the dynamic evolution of the renewable energy industry a wave energy industry is emerging. Although the technology is relatively new, and currently not economically competitive with more mature technologies such as wind energy, the interest from governments and industry is steadily increasing. An important feature of sea waves is their high energy density, which is the *highest* among renewable energy sources.

The idea of converting the energy of ocean surface waves into useful energy forms is not new. There are techniques that were first patented as early as 1799 (Girard & Son, France), and, in addition, references in the technical literature to ideas that prescribe these techniques. Leishman & Scobie [29] have carefully documented the development of wave-powered devices from the first British patent in 1855 up to 1973, when there were already 340 patents. Several configurations of wave energy converters have been designed and tested at model scale in this period, and some have been operated in the sea [46,34,73,56].

In Europe intensive research and development study of wave energy conversion began, however, after the dramatic increase in oil prices in 1973. Different European countries with exploitable wave power resources considered wave energy as a possible source of power supply and introduced support measures and related programmes for wave energy. Several research programmes with government and private support started thenceforth, mainly in the United Kingdom, Portugal, Ireland, Norway, Sweden and Denmark, aiming at developing industrially exploitable wave power conversion technologies in the medium and long term. The amount of this work is very large and extensive reviews have been made by Shaw [58], Lewis [30], Salter [54], Ross [52], Petroncini [48], Thorpe [68,69,70] and others.

The efforts in research and development in wave energy conversion have gained the support of the European Commission, which has, since 1986, been observing the evolution in the wave energy field. The research programmes of the Commission on wave energy effectively started with the fourth Framework Programme in 1994 following successful completion of related studies and preparatory RTD work. Starting in 1993, the Commission supported a series of international conferences in wave energy (Edinburgh, UK, 1993, Lisbon, Portugal, 1995, Patras, Greece, 1998 and Aalborg, Denmark, 2000), which significantly contributed to the stimulation and coordination of the activities carried out throughout Europe within universities, national research centres and industry.

In the last 25 years wave energy has gone through a cyclic process of phases of enthusiasm, disappointment and reconsideration. However, the persistent efforts in R&D, and the experience accumulated during the past years, have constantly improved the performance of wave power techniques and have led today to bringing wave energy closer to commercial exploitation than ever before. Different schemes have proven their applicability on a large scale, under hard operational conditions, and a number of commercial plants are currently being built in Europe, Australia, Israel and elsewhere. Other devices are in the final stage of their R&D phase with certain prospects for successful implementation. Nevertheless, extensive R&D work is continuously required, at both fundamental and application level, in order to improve steadily the performance of the particular technologies and to establish their competitiveness in the global energy market.

2. General aspects of the utilization of wave energy

Wave energy is derived from the winds as they blow across the oceans, and this energy transfer provides a convenient and natural concentration of wind energy in the water near the free surface. Once created, waves can travel thousands of kilometres with little energy loss. Hence, waves created e.g. on the American side of the Atlantic will travel to the western coast of Europe, supported by the prevailing west winds. The energy fluxes occurring in deep water sea waves can be very large. The power in a wave is proportional to the square of the amplitude and to the period of the motion. Therefore, long period (~7–10 s), large amplitude (~2 m) waves have energy fluxes commonly averaging between 40 and 70 kW per m width of oncoming wave. Nearer the coastline the average energy intensity of a wave decreases due to interaction with the seabed. Energy dissipation in near shore areas can be compensated for by natural phenomena such as refraction or reflection, leading to energy concentration ('hot spots').

Situated at the end of the long, stormy fetch of the Atlantic, the wave climate along the western coast of Europe is characterized by particularly high energy. Only the southern parts of South America and the Antipodes have a more energetic wave climate, due to circumpolar storms near the Atlantic [69]. Recent studies [49] assign for the area of the north-eastern Atlantic (including the North Sea) available wave power resources of about 290 GW. The long-term annual wave power level increases from about 25 kW/m off the southernmost part of Europe's Atlantic coastline (Canary islands) up to 75 kW/m off Ireland and Scotland. When moving further north it decreases to 30 kW/m off the northern part of the Norwegian coast. In the North Sea, the resource changes significantly, varying from 21 kW/m in the most exposed (northern) area to about half of that value in the more sheltered (southern) area. In the Mediterranean basin, the annual power level off the coasts of the European countries varies between 4 and 11 kW/m, the highest values occurring in the area of the south-western Aegean Sea. This area is characterized by a relatively long fetch and high wind energy potential. The entire annual deep-water resource along the European coasts in the Mediterranean is of the order of 30 GW, the total wave energy resource for Europe resulting thus to 320 GW.

It is important to appreciate the difficulties facing wave power developments, the most important of which are:

- Irregularity in wave amplitude, phase and direction; it is difficult to obtain maximum efficiency of a device over the entire range of excitation frequencies
- The structural loading in the event of extreme weather conditions, such as hurricanes, may be as high as 100 times the average loading
- The coupling of the irregular, slow motion (frequency ~0.1 Hz) of a wave to electrical generators requires typically ~500 times greater frequency.

It becomes apparent, that the design of a wave energy converter has to be highly sophisticated to be operationally efficient and reliable on the one hand, and economically feasible on the other. As with all renewable energy sources, the available resource and variability at the installation site has to be determined first. Present trends support devices of moderate power generation levels up to 1.5–2 MW, or small, modular devices of 5–20 kW rated power, which may meet multi-Megawatt demands when installed in arrays.

Wave energy is generally considered to provide a clean source of renewable energy, with limited negative environmental impacts. In particular, wave power is seen as a large source of energy not involving large CO_2 emissions. The limited experience with wave power schemes makes it possible to form only an incomplete picture of possible environmental effects caused by wave power devices. Thorpe

[68] summarizes the environmental impacts of wave energy conversion technologies as follows:

Environmental Effects	Shoreline	Nearshore	Offshore
Land use/sterilization	W		
Construction/maintenance sites	W		
Recreation	W	W	
Coastal erosion	W	W–M	W–M
Sedimentary flow patterns		W	W
Navigation hazard		W	W
Fish & marine biota	W	W	W
Acoustic noise	W		
Working fluid losses		W	W
Endangered species	W	W	
Device/mooring damage		W–M	W–M

W: Weak effect; M: Medium effect

The main wave energy barriers result from the energy carrier itself, the sea. As stated previously, the peak-to-average load ratio in the sea is very high, and difficult to predict. It is, for example, difficult to define accurately the 50-years return period wave for a particular site, when the systematic, in situ recording of wave properties started just a few years ago. The result is either underestimation or overestimation of the design loads for a device. In the first case the total or partial destruction of the facilities is to be expected, with mathematical accuracy. In the latter case, the high construction costs induce high power generation costs, thus making the technology uncompetitive. These constraints, together with misinformation and lack of understanding of wave technology by the industry, government and public, have often slowed down wave energy development.

On the other hand, the advantages of wave energy are obvious, the development of which is sustainable, as it combines crucial economic, environmental, ethical and social factors. The abundant resource and the high-energy fluxes in the sea prescribe—at appropriate design of the devices—economically viable energy production. Particular advantages of wave energy are the limited environmental impact, the natural seasonal variability of wave energy, which follows the electricity demand in temperate climates, and the introduction of synchronous generators for reactive power control. The negligible demand on land use is an important aspect, followed by the current trends of offshore wind energy exploitation. As for most forms of renewable energy, the in situ exploitation of wave energy implies diversification of employment, and security of energy supply in remote regions. Furthermore, it is anticipated that the large-scale implementation of wave power technologies will stimulate declining industries, as e.g. shipbuilding, and job creation in SME-sized industries.

3. Initiatives and programmes in Europe

3.1. National activities

Research and development on wave energy is underway in several European countries. The engagement in wave energy utilization depends strongly on the available wave energy resource. In countries with high resources, wave power could cover a significant part of the energy demand in the country and even become a primary source of energy. Countries with moderate, though feasible resources, could utilize wave energy supplementary to other available renewable and/or conventional sources of energy.

Denmark, Ireland, Norway[1], **Portugal, Sweden** and the **United Kingdom** considered wave power a long time ago as a feasible energy source. These countries have significant wave power resources and have been actively engaged in wave energy utilization under governmental support for many years. This has led over the past 25 years to a large amount of RTD work and considerable progress in wave power conversion.

Denmark lies in a sheltered area in the southern part of the North Sea, however, in the North-western regions the wave energy resource is relatively favourable for potential developments. The annual wave energy resource of Denmark has been estimated to be about 30 TWh with an annual wave power between 7 and 24 kW/m coming from a westerly direction.

The Danish Wave Energy Programme started in 1996 with Energy 21, by assigning 5.3 MECU for a period between 1998–2002. The objective is to promote wave energy technology following the successful Danish experience of wind energy [42]. In 1997, a Danish Wave Energy Association was formed to disseminate information and arrange meetings for its members and for those interested in wave energy. The Danish Energy Agency established an Advisory Panel of experts representing the Danish Hydraulic Institute—DHI, The Danish Maritime Institute-DMI, the Folkecenter for Renewable Energy, the University of Aalborg, the Technical University of Denmark and the Danish Wave Energy Association. Their function is to advise on appropriate wave energy testing and research.

Ireland has considerable potential for generating electricity from wave power. According to Lewis [31], the wave energy resource of Ireland is 375 MWh/m at the 20 m contour location, while the total incident wave energy is around 187.5 TWh.

The policy of the Minister for Marine and Natural Resources is to encourage offshore electricity generation resources. A Foreshore Act for Licences and Leases for offshore development, such as wave energy and offshore wind, was published

[1] Norway is not a Member State of the European Union.

in July 2000. In 1997, wave energy was supported under AER-3. One project was selected for the offer of a Power Purchase Agreement (with the ESB) and an EU grant-aid. However, the offer of the grant-aid was withdrawn by the EU on the basis that wave technology had not advanced sufficiently beyond the research stage to justify assistance under the European Infrastructure Operational Programme and the project did not proceed.

At present, a partnership of the Hydraulic & Maritime Research Centre, University College Cork, Irish Hydrodata Ltd, Ove Arup & Partners Ltd, the Department of Mechanical and Aeronautical Engineering, University of Limerick and the Marine Institute are finalising a Strategic Study on Wave Energy in Ireland. The objective of the study is to provide a scaled selection of wave energy sites and to investigate a wave climate prediction methodology.

Norway has a long coastline facing the Eastern Atlantic with prevailing west winds and high wave energy resources of the order of 400 TWh/year. Even though there is high wave energy availability, due to the economics and the uncertainties of the available technology, the conclusion of Energy and Electricity Balance towards 2020 are that 0.5 MWh will be the wave energy contribution to the Norwegian electricity supply, mainly from small-scale developments.

All of Norway's electricity supply has traditionally been renewable hydropower, but the increased electricity demand of recent years has not been met by an equal increase in power plants, due to public opposition to large hydropower developments. The government is promoting land based wind and biomass, with particular focus on hydrogen as an energy carrier and gas fuel cell pilot projects. The environmental concern of high CO_2 emission from power generation for oil and gas offshore installations could create the basis for a potential wave energy market.

Norway started its involvement in wave energy in 1973 at the Department of Physics in the Norwegian University of Science and Technology—NTNU, and had official governmental support from 1978. In the 1980s two shoreline wave converters were developed, the Multi-Resonant Oscillating Water Column—OWC and the Tapered Channel—Tapchan of 500 and 350 kW respectively. In 1985, the OWC was built by Kvaener Brug A/S and the Tapchan by Norwave A/S in Toftestallen about 35 km north-west of Bergen. The plants were seriously damaged during storms in 1988 and 1991, but there are plans for re-opening the TAPCHAN plant.

Portugal is characterised by an annual wave power of between 30 and 40 kW/m. The highest wave power is found off the northwestern coast of Portugal and in the archipelago of the Azores. It has been estimated that the overall resource of wave energy on continental Portugal is about 10 GW mean, and half of it can be potentially exploited [41].

The Portuguese government supports wave energy, as other renewable energy technologies, through different financial mechanisms. The Ministry of Science and Technology provides funding for R&D and Demonstration (led by companies) projects through different programmes. However, most of the funding for energy demonstration projects is provided by the Ministry of Economy using national funding, in addition to European money.

In Portugal, wave energy research started in 1978 at the Instituto Superior Tecnico

(IST) in Lisbon and it was joined in 1983 by the Instituto Nacional de Engenharia e Tecnologia Industrial (INETI). Since 1986, Portugal has been successfully involved in the planning and construction of the shoreline wave energy converter Oscillating Water Column in Pico of the Azores, supported by the government, the EU Programme Joule and the utility companies in the Azores and mainland.

Sweden has a few good areas for utilising wave energy. The north parts of the west coast facing the North Sea and the Baltic Sea around the islands of Öland and Gotland. The technically available resource is approx. 5–10 TWh per annum. This is to be compared with the annual electricity demand of 150 TWh in Sweden.

Wave Energy research started in Sweden in 1976, and in 1979 a Wave Energy Research Group was founded, which consisted of four departments at Chalmers University of Technology, and the private consultant company Technocean. In 1980 the first full scale point absorber buoy in the world was installed outside Göteborg. It was 'Elskling' the project was funded by the private company Interproject Service AB (IPS) [17]. The trials were successful, and after modification during the winter the buoy was launched once again in the summer of 1981. Another large project was the Hose-Pump project. It was also full scale tested at sea, 1983–1986. This project was run by Technocean [59] and funded by Swedyards later Celsius Industries. Technocean has also evaluated a large number of wave energy converters as part of the Swedish National Wave Energy Programme (1980–1986) and participated in the CEC project OWEC-1. Technocean has also participated in several other proposals to the JOULE programme. There was a small research programme 1989–1996 [4]. Today apart from the Swedish involvement in the Wave Energy Network, there is only IPS and Sea Power International [27] active on the Wave Energy Market in Sweden. Sweden has no national research programme at the moment.

The **United Kingdom** is located at the eastern end of the long fetch of the Atlantic Ocean with the prevailing wind direction from the west, and it is surrounded by stormy waters. The available wave energy resource is estimated to be 120 GW [71].

Wave energy RTD started in the UK at the University of Edinburgh when the oil crisis in 1973 hit the whole world. In 1974, S. Salter published his initial research work on wave power [53] and the research on the offshore wave energy converter, the Salter Ducks, was started. In the meantime at least another ten wave energy projects were initiated in the UK [54]. The government supported and funded extensively wave energy research until 1983, and in 1999 the UK government declared a renewed favourable position in supporting R&D on wave energy with a budget of about £3 (EUR 4.92) million over the next three years 2000–2003. Furthermore, the success of the initial LIMPET OWC project and its full decommissioning in 1999 has created the basis for including three wave energy projects in the third Scottish Renewable Obligation (SRO-3). Three wave energy projects of a total of 2 MW capacity have been awarded with a 15 year purchase contract in Scotland: by 2003, the Limpet, the Pelamis and the Floating Wave Power Vessel—FWPV (see also Section 5) will supply electricity to the island of Islay on the west cost of Scotland and to Shetland.

'The Energy from the Sea' by the Marine Foresight Panel outlines the 'roadmap' (OST, 1999) for the development of wave energy in Scotland towards 2020. A Commission for Wave Power in Scotland was launched in 1999, which involved representatives from the government, the industry and the utility company. The Commission will work to create the basis for the development and success of wave energy in Scotland.

Two organisations involved with wave energy are going to be formed in the near future. One is the Marine Energy Technology Network that will be a virtual network incorporating Universities and companies, consultants etc. The other is the ‘Sea Power Association’ which will work closely with METN and the British Wind Energy Association (BWEA).

Due to political reasons, mainly the focalisation to other energy sources, or lack of feasible resources, wave energy conversion has not undergone significant development in **Belgium, Finland, France, Germany, Greece, Italy,** the **Netherlands** and **Spain** in the past years.

Belgium, Germany and the **Netherlands** are characterized by a relatively limited length of coastline, shallow coastal water and high offshore traffic density. All these factors militate against significant interest in wave energy development. In spite of these limitations, R&D work has taken place in Universities, research centres and private companies. Teamwork Technology BV, Netherlands, is developing a promising wave power conversion device, the Archimedes Wave Swing [50], a pilot scheme of which is currently being finalised (see also Section 5). In Germany, different companies and research institutions from the fields of offshore engineering, power engineering and other engineering sectors that are closely related to wave power conversion, are currently involved in European wave power developments [18,24].

France has a long coastline on the Atlantic and the Mediterranean Seas. The most significant resource is in the area of the Gulf of Gascoigne, with annual power levels up to 40 kW/m and a total resource in this area of approx. 28 GW. On the Mediterranean side the annual power level is of the order of 4–5 kW/m.

Although a number of successful wave energy projects were operated in France during the early part of the last century, wave energy conversion has not undergone significant development in the recent past. A number of projects were carried out in the 1980s under the supervision of IFREMER (Institut Francais de Recherche pour 1’Exploitation de la Mer) but funding was stopped after the initial development phase. ECN (Ecole Centrale de Nantes) has been following a programme of fundamental research, which has been reoriented since 1995 towards the dynamic absorption problem, namely the development of wave absorbing devices (paddles) for the equipment of wave basins [33]. The same research group is participating in the development of the European wave power pilot plant on Pico island (Azores), mainly involved on (sub)-optimal control strategies for wave energy OWC devices [5,6,7,9,10,13].

Greece has a coastline of over 16,000 km in the Aegean and Ionian Seas. The large wind potential over the Aegean Sea in a prevailing North-South direction induces a relatively intense wave climate of 4–11 kW/m annual average power [3,49]. There is certainty of the presence of ‘hot spots’, caused by the complex island terrain, and recent measurement campaigns and theoretical studies [8,61] provide more detailed information about the wave climate in the Aegean. Wave power plants are particularly suitable for delivering electricity to the large number of islands, which are mainly supplied by diesel stations. The high cost of electricity on the islands will make wave energy competitive against conventional power producers; however, wind energy has already proven its feasibility in this region, and it is heavily supported by the government and private investors.

Wave energy underlies legislation regarding the implementation of renewable energies and the deregulation of the energy market, R&D mainly being conducted in Universities [3,38] and the Centre for Renewable Energy Sources [11].

Italy has a long coastline in relation to its land area and would appear suitable for utilisation of ocean energy. Wave studies around the coastline, however, show that, in general, the wave energy annual average is less than 5 kW/m. There are a number of offshore islands and specific locations, such as Sicily or Sardinia, where the mean wave energy is higher, up to approx. 10 kW/m.

R&D on ocean energy exploitation is conducted mainly in the 'La Sapienza' University of Rome and by Ponte di Archimede nello Stretto di Messina S.p.A. In the University of Rome a novel wave energy device is developed, which is particularly suitable for closed seas of moderate wave power [14]. The system utilizes a floating gyroscopic converter, which is excited to oscillations by the waves and provides mechanical power to an electrical machine. Ponte di Archimede nello Stretto di Messina S.p.A. is developing the ENERMAR plant, utilizing marine currents (A. Fiorentino, private communication). It consists of a floating Kobold turbine, which drives an alternator. A 130 kW prototype with a 6 m diameter turbine is currently being constructed and will be deployed 1.50 m offshore Messina.

3.2. The role of the European Commission and the European Thematic Network on Wave Energy

The European Commission has been supporting projects in this area since 1992, from the start of the Joule Programmes. There have been 22 projects in total. It represents now nine years of R&D in the area of wave energy converters and of tidal and marine currents for a total amount of 9.5 M€. Fig. 1 shows the evolution

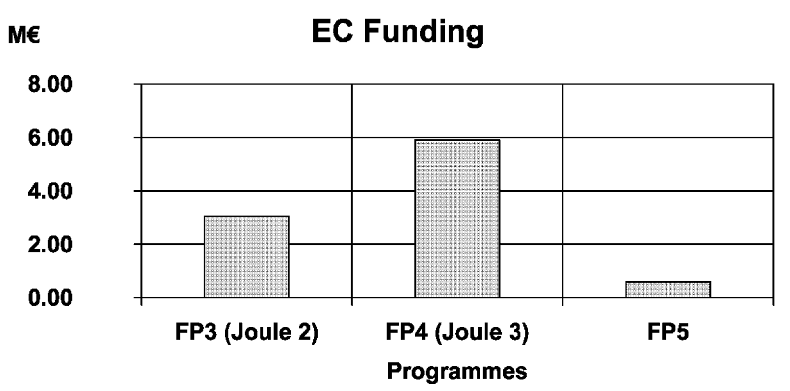

Fig. 1. Funding of wave energy projects by the European Commission.

of the funding through the programmes. The information concerning project funding under the fifth Framework Programme (FP5) is not complete, as the programme will finish in 2002 and there are still two calls opened.

The potential to extract energy from the waves and the currents was recognised early. Two studies have set the basis on this potential in two documents the 'Atlas of Wave Energy Resource in Europe' (1996) and the 'Exploitation of Tidal and Marine Currents' (1996). It has been clear also, from the start, that extracting power from the sea will be difficult. Experiences around the world have shown it. The Commission has therefore considered helping the development of the technology by financing projects making steps towards proving the technical feasibility of this energy extraction. Their selection was done on the basis on the evaluation criteria and also in the demonstration by the consortium of their understanding of the difficulties. This approach provided two outstanding results, the Pico and the Limpet Pilot Plants, now in operation.

Because of its rough locations, the area has still, however, to prove its reliability, its durability and its practicability before demonstrating its importance to Europe. More successes are therefore needed.

An important step to co-ordinate collaboration between European countries in the wave energy sector has been taken in the formation of the 'European Thematic Network on Wave Energy'. In 1999, the European Commission invited 14 wave energy representatives from various European countries to co-operate in such a Network.

The Network was launched in 2000 and anticipated the finding of the Ove Arup report with regard to the lack of co-ordination and the lack of investor confidence [71]. The tasks address important scientific, technical and economic aspects of wave energy conversion and will produce a variety of outputs, as:

- **Standards,** e.g. wave & current load design criteria, standardised design methods for wave and tidal current power plants;
- **Recommendations,** e.g. on connection to local grids, the use, selection and design of energy storage units, reliability improvements;
- **Guidance,** e.g. on minimising environmental impacts, satisfying planning requirements;
- **Software,** e.g. on plant control and monitoring;
- **R&D,** e.g. promoting a better exchange of information, publishing collated reports, and helping to identify the best devices and technology to develop;
- **Supporting Material,** e.g. promotional material and a web site for increasing public awareness, more technical material for planners and would-be investors, independent assessments to overcome credibility problems, articles in renewable energy journals to raise the technology's profile;
- **Workshops and conference,** to foster information exchange, gain publicity and help promote synergistic activities/partnerships.

These outputs will be made available to the relevant target groups: developers, operators, public bodies, financiers, planners, etc. Most of these outputs would be produced in 18–34 months' time, although useful outputs (such as the web site) will appear within 12 months of starting.

4. Activities in other countries

R&D on wave power utilization is conducted in a number of countries outside Europe, as **Australia, Canada, China, India, Indonesia, Iran, Israel, Japan, Korea, Mexico, Russia, Sri-Lanka,** the **U.S.A.** and others.

Australia has a large wave power resource of about 100 GW, however the energy demand in many of the regions of Australia is quite low compared to the available resource. Recently, the federal government has awarded to Energetech Australia Pty Ltd and to Ocean Power Technologies grants for commercial wave energy projects at Port Kembla and Bass Strait (see also Section 5).

In **Canada,** traditionally a net energy exporting country, wave energy is given low priority in R&D programmes. Feasibility and resource assessment studies are conducted at the University of British Columbia and Powertech Labs Inc.

In China R&D is performed mainly at the Guangzhou Institute of Energy Conversion and the Guangdong University of Technology, in co-operation with other national institutions and institutions from Denmark, India, Japan and the United Kingdom. The main R&D efforts are concentrated on the development of OWCs, a 100 kW demonstration device operating in Zhelang, southern China [75, 78] and BBDB converters, currently being tested in scale [32].

India initiated a national wave energy programme at the Indian Institute of Technology Madras in 1983. R&D is performed at the National Institute of Ocean Technology, established by the government and the Indian Institute of Technology Madras [51]. The Institution is co-operating with other national and international research centres. A 100 kW demonstration plant was built in 1991 at Vizhinjam in south India, while other WECs of the OWC, the BBDB and the overtopping types are currently being developed [67,57,12,23,55,36].

S.D.E. Ltd. in **Israel** has developed an innovative wave power device of the floating type, which uses a novel method to convert wave energy into hydraulic pressure and subsequently produce electricity. A number of models have been built and tested and a 40 kW demonstration device has operated successfully. Recently, the company has been granted a governmental concession for commercial electricity production.

Japan, an island with total coastline of 35,000 km which is almost wholly dependent on imported fuel, is considering wave energy as a feasible power supply. R& D on wave energy is conducted in different research institutions and by a number of industrial companies [2,21,35,37,44,62,64,72]. At the present time, the only large-scale project in open sea is the Mighty Whale, carried out by JAMSTEC of the Ministry of Education, Culture, Sports, Science and Technology (see Section 5). Other projects concern small-scale systems for port and harbour facilities and for unmanned lighthouses.

In Sri Lanka R&D on wave and thermal energy conversion is conducted at the National Aquatic Resource Agency in Colombo. A 150 kW demonstration OWC device has been built, funded by the Ministry of Science & Technology, which follows on from the success of the prototype tested in 2000.

In the **U.S.A.** R&D started quite early, in the 1950s [47,39,40]. However, the interest in wave energy in the USA is limited. Although annual average power levels of up to 235 kW/m have been recorded off the northern west coast, the potential contribution to the national energy supply is considered to be small. Currently, two major projects are implemented with participation from the U.S., the McCabe Wave pump and the OPT WEC (see section 5).

In other countries such as **Indonesia, Iran, Korea, Mexico** and **Russia**, basic R&D on wave energy is conducted in Universities and research Institutes under governmental support, often in co-operation with institutions from Europe and Asia [19,22,28,45,63,66,76,79].

5. The current economical and technological status of wave energy

Wave power developments must face several difficulties, as a corrosive environment, immense loading in extreme weather conditions, randomness in power input or low transmission frequencies. To be competitive, the design of a wave energy converter has to cope with these difficulties efficiently; this has to be done in an environmentally beneficial and economically reasonable scheme. Starting at the initial idea, the development of a wave energy device undergoes a long-lasting evolution. Beginning with theoretical analyses, extensive experiments in the wave tank at a small and an intermediate scale are required before the first prototypes can be deployed in open sea. This evolution is often restrained by the power of nature, being both a friend and an enemy. The freak loads in the sea may exceed the rated values by several orders of magnitude and are difficult to predict. Therefore, the design of a wave energy converter requires a high degree of sophistication to provide sufficient operational safety in extreme conditions on the one hand, but also be economically competitive on the other.

In contrast to other renewable energy resource utilization there are a large number of concepts for wave energy conversion. Although over 1000 wave energy conversion techniques are patented in Japan, North America and Europe, the apparently large number of concepts for wave energy converters can be classified within a few basic generic types. The main types of wave energy converters are:

- The oscillating water column, which consists of a partially submerged, hollow structure open to the sea below the water line.
- Overtopping devices that collect the water of incident waves to drive one or more low head turbines.
- Point absorbers (floating or mounted on the sea bed), which usually provide a heave motion that is converted by mechanical and/or hydraulic systems in linear or rotational motion for driving electrical generators.
- Surging devices that exploit the horizontal particle velocity in a wave to drive a deflector or to generate pumping effect of a flexible bag facing the wave front.

There are important developments that do not fall under the above categories, such as the *Salter Duck*, the *Cockerell raft* and the *McCabe Wave Pump*.

In the last five years there has been a resurgent interest in wave energy. Nascent wave energy companies have been highly involved in the development of new wave energy technologies such as the Pelamis, the Archimedes Wave Swing and the Limpet. There is a plan to increase the world-wide wave energy capacity to 6 MW in the next few years between 2002–2005 [70]. At present the world-installed capacity is about 1 MW, mainly from demonstration projects.

The potential world-wide wave energy economic contribution in the electricity market is estimated of the order of 2,000 TWh/year, about 10% of the world electricity consumption, and with an investment cost of EUR 820 billion [71]. The predicted electricity generating costs from a wave energy converter have shown a significant improvement in the last twenty years, which has reached an average price of approx. 0.08 EUR/kWh at a discount rate of 8%. Compared to the average electricity price in the EU, which is approx. 0.04 EUR/kWh, the electricity price produced from wave energy is still high, but is forecasted to decrease with the development of the technology. This can be speeded up with initial financial and market support as it has been made in the past for preceding technologies such as wind, nuclear and oil.

The amount of ongoing work on wave energy schemes is large, and we cannot do it justice in a single presentation. Here, the most promising technologies will be presented. For ease of presentation, these activities will be divided between the technologies suitable for deployment on the shoreline, near the shore and offshore. This categorization is so far appropriate as the available resource and the operating conditions, and thus the design architecture, are strongly dependent on the local water depth.

5.1. Shoreline devices

Shoreline devices are fixed to, or embedded in, the shoreline itself, which has the advantage of easier maintenance and/or installation. In addition these would not require deep-water moorings or long lengths of underwater electrical cable. However, they would experience a much less powerful wave regime. This could be partially compensated by natural energy concentration ('hot spots'). Furthermore, the deployment of such schemes could be limited by requirements for shoreline geology, tidal range, preservation of coastal scenery, etc.

The **European Pilot Plant** (Fig. 2) on the Pico Island in the Azores is an OWC-type WEC developed by the Instituto Superior Tecnico of Lisbon, Portugal. This 400 kW plant was designed as a full scale testing facility, but it is also used to supply, on a permanent basis, a sizable part of the island's energy demand [15,16].

The **LIMPET OWC** (Fig. 3) is an OWC-type WEC developed by Wavegen Ltd in Ireland and the Queen's University of Belfast in the UK. The Queen's University of Belfast developed a 75 kW prototype shoreline OWC constructed on the island of Islay, Scotland in 1991. The successor of this prototype, the 500 kW LIMPET

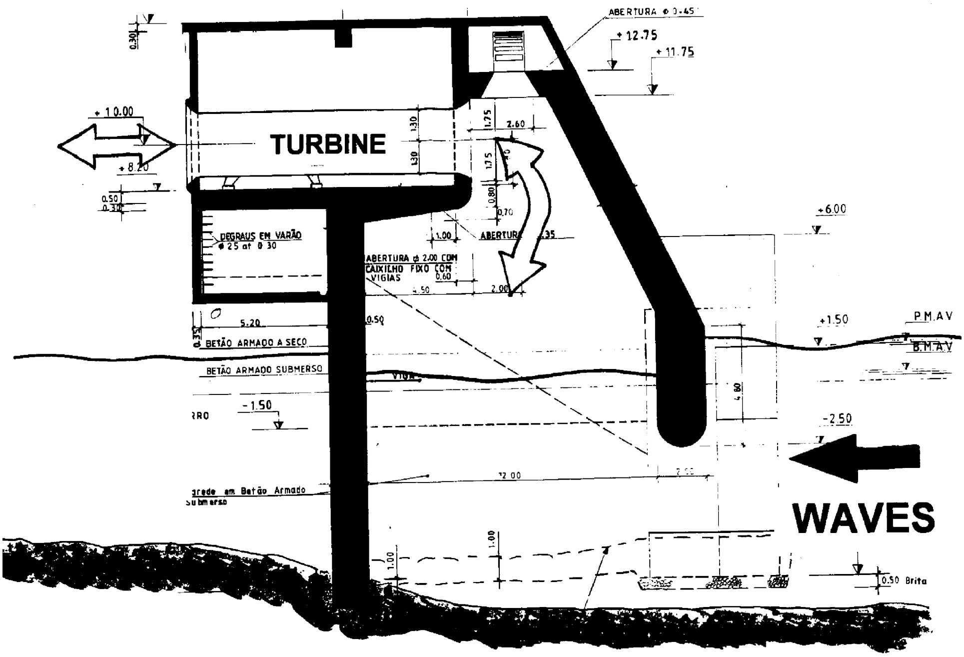

Fig. 2. The European Pilot Plant.

Fig. 3. The Limpet OWC.

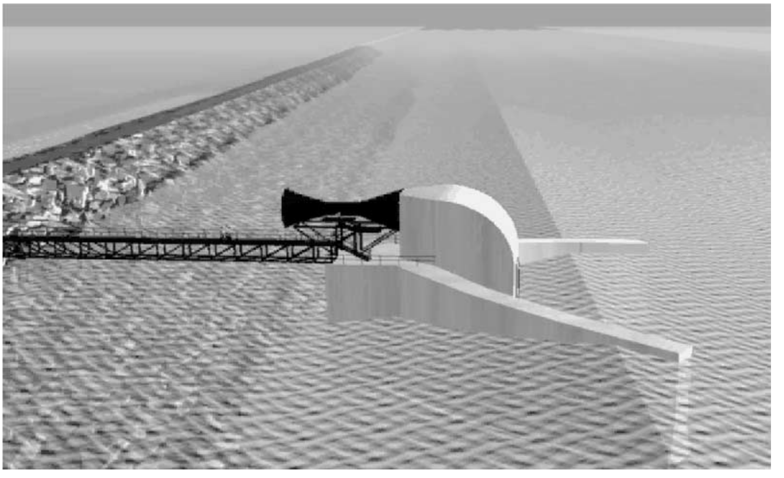

Fig. 4. The Energetech OWC.

OWC is intended to address many of the issues that currently hinder the full-scale commercial deployment of OWC devices [1,20].

The **Energetech OWC** (Fig. 4) is developed by Energetech in Australia (Fig. 1). This uses a novel, variable, pitch turbine and a parabolic wall behind the OWC to focus the wave energy on the collector. This scheme already has a power purchase agreement with the local utility at Port Kembla, 80 km south of Sydney, for a 500 kW plant, the construction of which is about to begin.

The **Pendulor** (Fig. 5) is a surging type WEC, consisting of a rectangular box, which is open to the sea at one end. A pendulum flap is hinged over this opening, so that the actions of the waves cause it to swing back and forth. This motion is then used to power a hydraulic pump and generator. Several schemes (>5kW) have been built in Japan and there are plans to develop a larger plant [25].

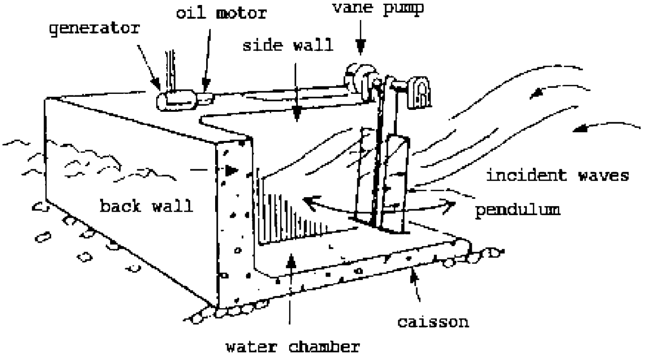

Fig. 5. The Pendulor.

The **TAPCHAN** (Fig. 6) is a shoreline WEC of the overtopping type developed by Norwave AS. It consists of a gradually narrowing channel with wall height equal to the filling level of the reservoir (typical heights 3–7 m). The waves are amplified in a narrowing collector until the wave-crests spill over the walls. A demonstration device was built in 1985 at Toftesfallen, Norway but was seriously damaged in 1991.

5.2. Near-shore devices

The main prototype device for moderate water depths (i.e. <20 m) is the **OSPREY** (Fig. 7) developed by Wavegen in the UK. It is an OWC-type WEC designed for deployment on the seabed. The first prototype (Osprey I), with a steel body, failed during problem in installation near Dounreay, Scotland (1996). The new Osprey 2000 will be a composite construction with installation procedures designed to minimise the time required to install in open waters. It is designed to operate in 15 m of water within 1 km of the shore, generating up to 2 MW of power for coastal consumers.

5.3. Offshore devices

This class of device exploits the more powerful wave regimes available in deep water (>40 m depth). More recent designs for offshore devices concentrate on small, modular devices, yielding high power output when deployed in arrays. Some of the promising offshore WECs are the following.

The **Archimedes Wave Swing** (AWS, Fig. 8), developed by Teamwork Technology BV, Netherlands, resembles an underwater buoy of which the upper part (floater) moves up and down in the wave while the lower part (basement) stays in position [50]. The periodic changing of hydrostatic pressure beneath a wave initiates

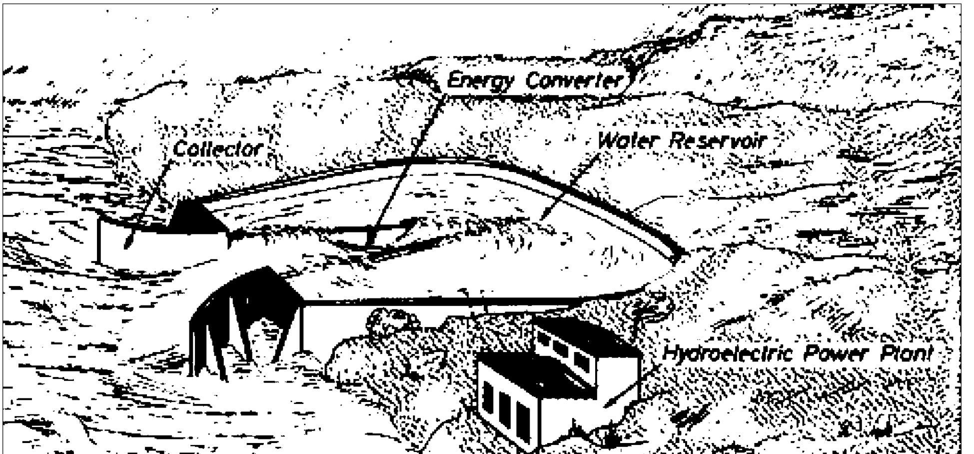

Fig. 6. The TAPCHAN.

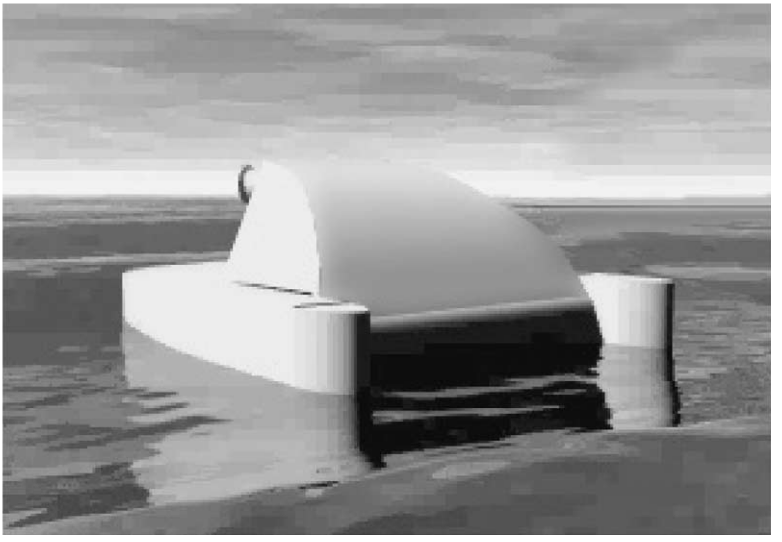

Fig. 7. The OSPREY.

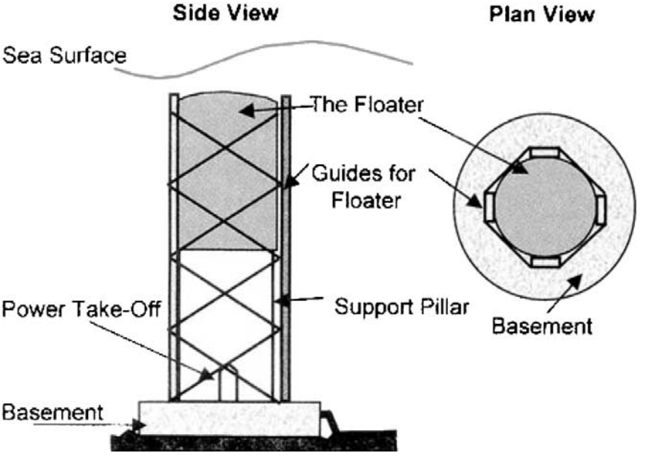

Fig. 8. The Archimedes Wave Swing.

the movement of the upper part. The design of a 2 MW pilot scheme is currently being finalised.

The **Floating Wave Power Vessel** (Fig. 9) is an overtopping device for offshore operation developed by Sea Power International, Sweden. It consists of a floating basin supported by ballast tanks in four sections. A patented anchor system allows the orientation of the vessel to the most energetic wave direction. A pilot plant was developed and deployed in the 1980s near Stockholm, Sweden while a 1.5 MW vessel is planned to be deployed in Spring 2002 at 50–80 m depth 500 m offshore Mu Mess, Shetland [27].

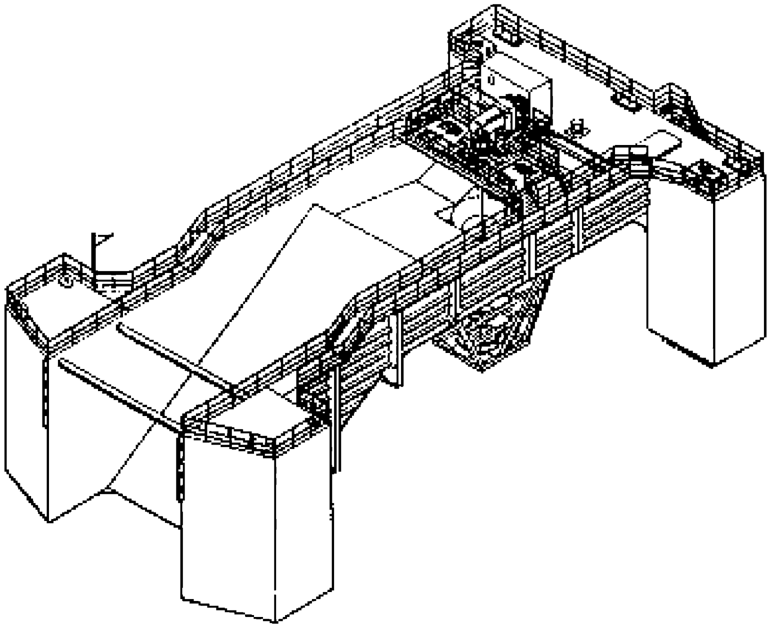

Fig. 9. The Floating Wave Power Vessel.

The **McCabe Wave Pump** (Fig. 10) was conceived by Peter McCabe in 1980, after which it was studied both theoretically and experimentally [26,43]. The device consists of three rectangular steel pontoons, which are hinged together across their beam. The bow of the fore pontoon is slack-moored and two more slack moorings are attached part way down the aft pontoon. This allows the system to vary its alignment in order to head into the oncoming seas. A 40 m long prototype was deployed in 1996 off the coast of Kilbaha, County Clare, Ireland and a new demonstration device is currently being constructed.

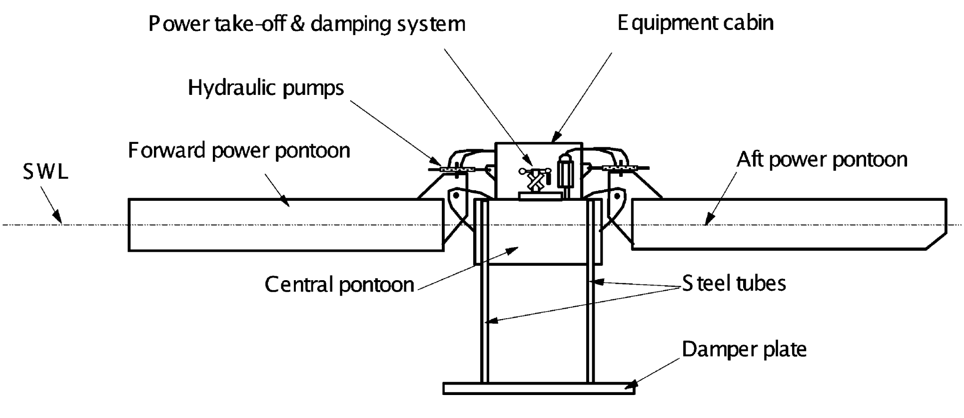

Fig. 10. The McCabe Wave Pump.

The **Mighty Whale** (Fig. 11) is an OWC based device for offshore operation, developed by the Japan Marine Science & Technology Center [74]. A 120 kW prototype with 3 OWCs in a row has been operating since 1998 1.5 km off Nansei Town at 40 m depth. The mooring system is designed to withstand wind-wave conditions resulting from a 50 year storm.

The OPT **WEC** developed by Ocean Power Technology in the USA consists of a 2–5 m diameter buoy type cylinder closed at the top and open to the sea at the bottom. A hydraulic ram is positioned between the top of the shell and a highly buoyant steel float contained within the shell. The relative motion of the shell to the buoyant float activates a hydraulic system to pump oil at high pressure to a generator. Extensive tests on a large scale in the eastern Atlantic have been concluded and the first commercial schemes are about to be built in Australia and in the Pacific. The individual WECs are rated at between 20 and 50 kW, intended to meet multi-megawatt demands using arrays [65].

The **Pelamis** (Fig. 12) device is a semi-submerged articulated structure composed of cylindrical sections linked by hinged joints. The wave induced motion of these joints is resisted by hydraulic rams which pump high pressure oil through hydraulic motors via smoothing accumulators. A 130 m long and 3.5 m diameter device rated at 375 kW is being developed by Ocean Power Delivery Ltd—OPD, Scotland [77].

The **Point Absorber Wave Energy Converter** (Fig. 13), developed by Rambøll in Denmark, consists of a float connected to a suction cup anchor by a polyester rope. The relative motion between the wave-activated float on the sea surface and the seabed structure activates a piston pump (actuator) inserted between the rope and the float. A 1:10 scale model was tested at sea at the Danish test site 'Nisum Bredning' over a period of three months, and a 1:4 scale model 2.5 m in diameter, is currently being developed for open sea testing [42].

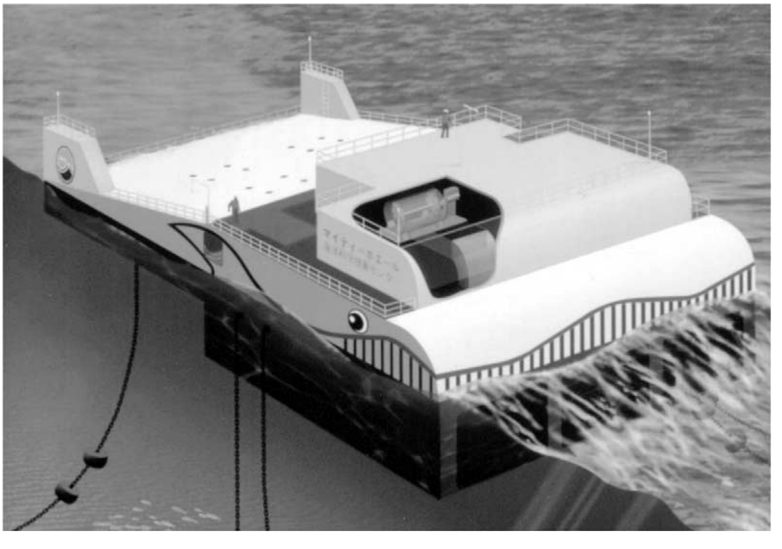

Fig. 11. The Mighty Whale.

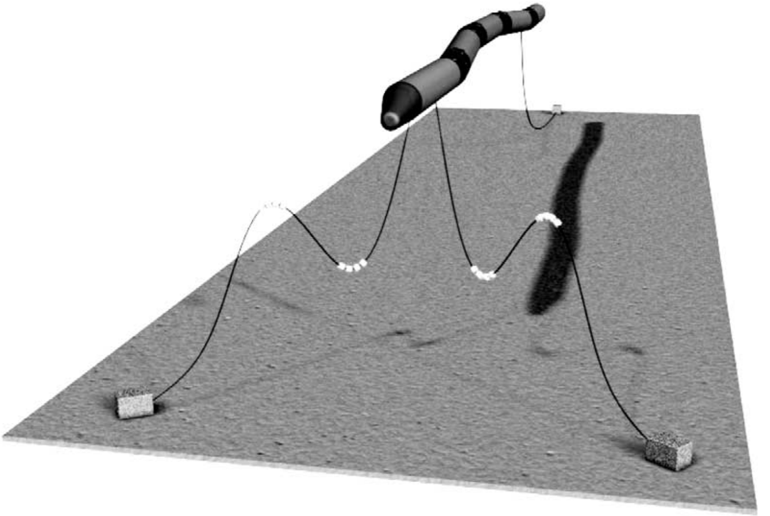

Fig. 12. The Pelamis.

The concept of the **Salter Duck** (Fig. 14) was introduced in 1974 by S. Salter [53]. An important feature of this device is its capability of converting both the kinetic and potential energies of the wave to mechanical energy, achieving thus very high absorption efficiencies (theoretically over 90%). The system has undergone considerable development since 1983. It was redesigned in 1993, and the present design is characterized by high availability and overall efficiency and energy production costs between 5.7 and 8 p/kWh [70].

The **SDE** wave power device (Fig. 15) is an offshore wave energy converter of the floating type, developed by S.D.E. Ltd in Israel. The device takes advantage of both as the kinetic and potential energy of a wave to generate hydraulic pressure, which is then transformed into electricity. A number of models have been built and tested, and a 40 kW model is in operation. The company has been granted a governmental concession for commercial power production in Israel.

The **Wave Dragon** (Fig. 16) is an offshore wave energy converter of the overtopping type, developed by a group of companies led by Loewenmark F.R.I., Denmark. It utilizes a patented wave reflector design to focus the wave towards a ramp and fill a higher-level reservoir. Electricity is produced by a set of low-head Kaplan turbines. The scheme has been tested in the laboratory at 1:50 scale and on a 1:3.5 scale model turbine [60]. A 1:4.5 scale model will be tested in open sea from autumn 2002.

6. Conclusion & perspectives

The sea is a colossal reservoir of energy of particularly high density—the highest among the renewables. The utilization of this energy could cover a significant part

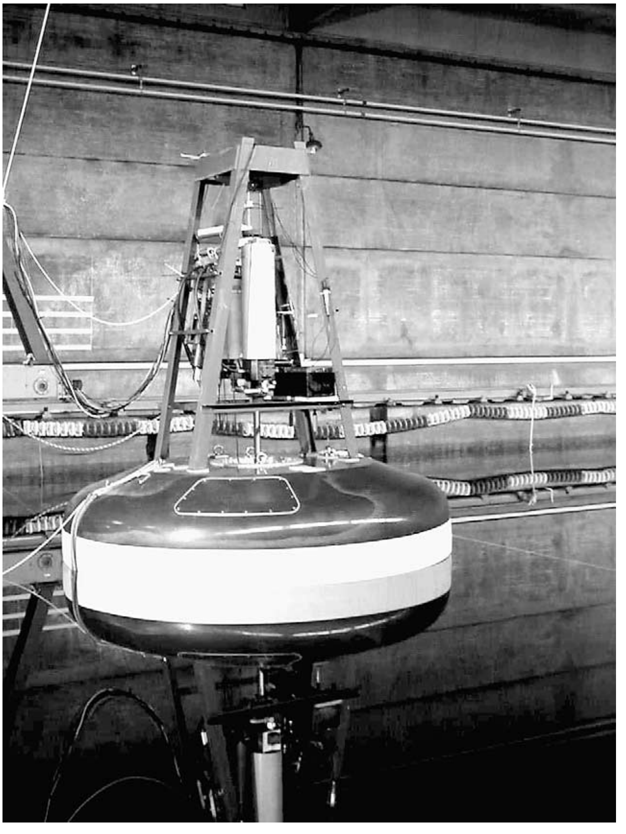

Fig. 13. The Point Absorber Wave Energy Converter.

of the energy demand in Europe, and, moreover, it could make a substantial contribution to a wide range of the objectives of environmental, social and economic policies of the European Union.

Europe is exposed to one of the most energetic sea areas on the planet, the eastern Atlantic, the importance for Europe in the development of reliable wave power conversion technologies becoming thus evident straightaway. Different European countries scheduled specific R&D programmes on wave energy in the 1980s and 1990s, and others are promoting it through national R&D programmes for RES. The European Commission has supported these activities since 1992, from the start of the Joule Programmes.

As a result of these efforts wave energy conversion technologies have significantly advanced in Europe during recent years. Some wave energy devices are at the end of their R&D phase and several others are currently being deployed. There is also continuous progress in wave energy in other countries with feasible wave power resources, such as China, India and Japan.

A review of the economics of wave energy devices indicates that specific techno-

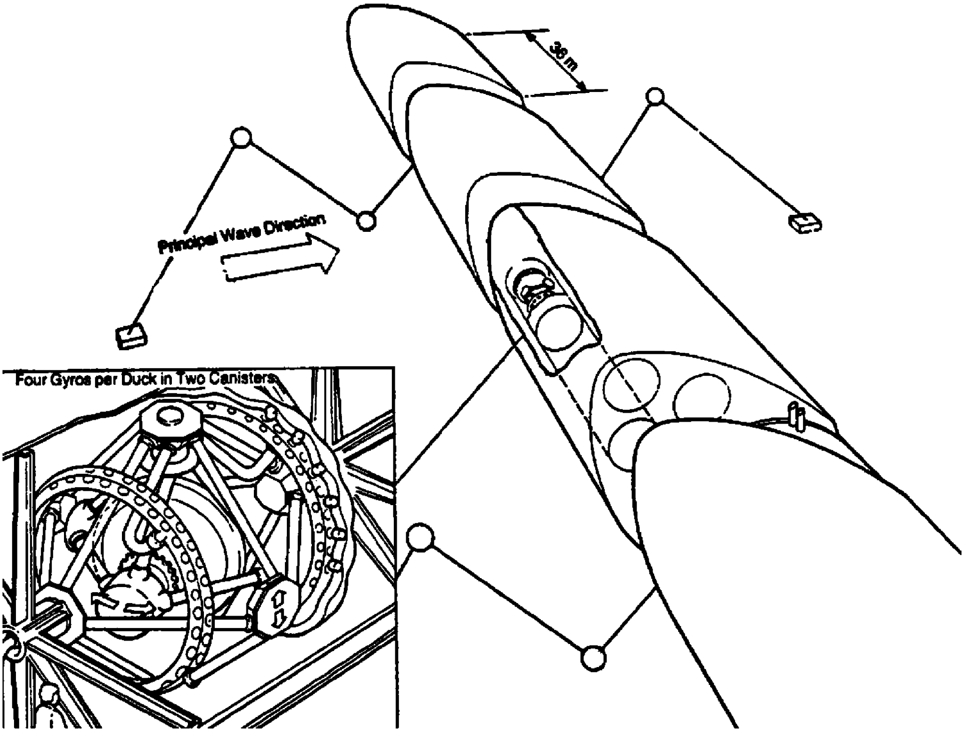

Fig. 14. The Salter Duck.

logies are already competitive in niche markets, and different wave power companies have already been granted governmental concessions in Israel, Australia, the UK, and elsewhere, for commercial power production from the sea. Other promising schemes require further R&D to achieve this. The potential market for several wave power technologies is large, but initial political and financial support is needed for their breakthrough.

An important aspect of the evolution of wave power conversion and its supporting industry in Europe lies in the close co-operation between the Member States of the European Union. Following previous success and experience, this co-operation will accelerate the technological development and avoid work overlapping within Europe. The role of the European Commission in this progress is substantial and the contribution of the Commission's supporting mechanisms is catalytic.

Certainly, wave energy technologies are still to a lesser or greater extent far from maturity. The potential for improvement of the techno-economical indicators of wave power conversion technologies is very large, while the survivability and the reliability of many devices, particularly for offshore operation, has still to be demonstrated. The approach of technological and economic viability, and the sustaining of a vital position for Europe's industry in this sector presupposes a consistent and comprehensive strategy for wave energy at national and Union level.

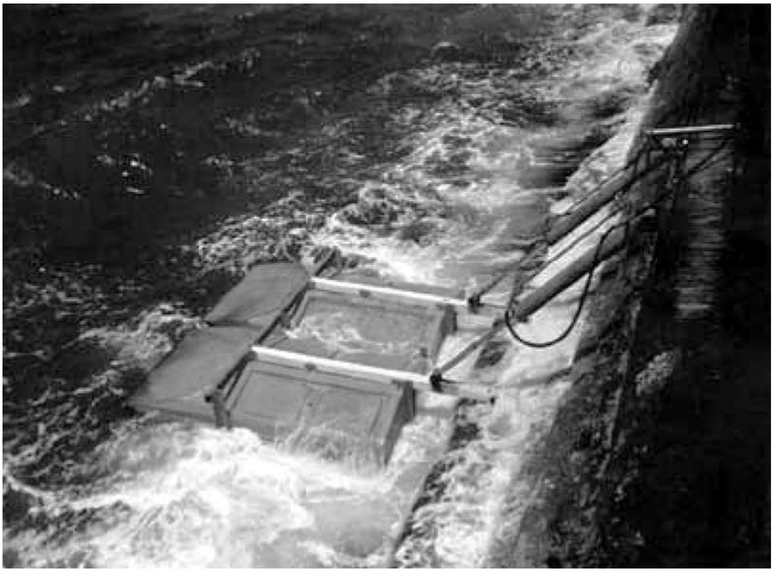

Fig. 15. The SDE Wave Power Device.

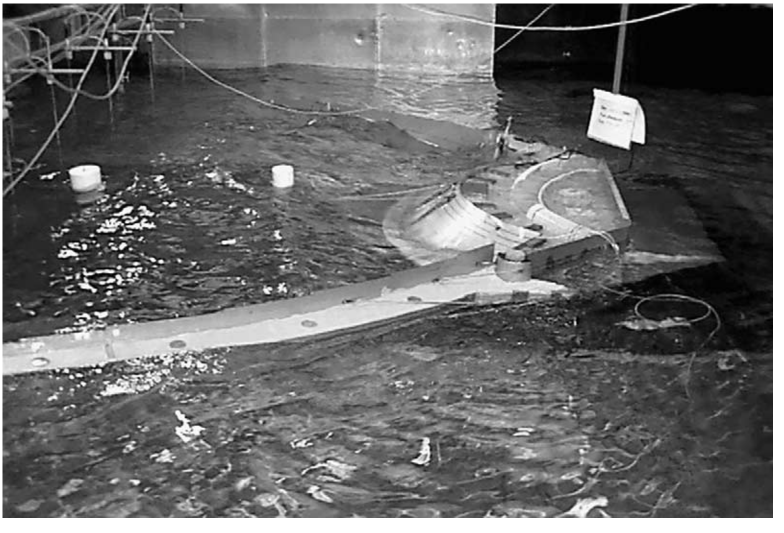

Fig. 16. The Wave Dragon.

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