Ocean Energy

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Tide and Tidal Power

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1.1 Energy From The Ocean

The first sources of ocean energy that come to mind are the hydrocarbons. From timid extraction operations hugging the coastline and shallow depth wells, not too difficult to cap, giant steps have been made, to the point that platforms have been erected, far out at sea, and oil is obtained from ever-greater depths. The value of methane has become more apparent during the last half-century and gaso-ducts—gas-pipelines—cross ever longer water and land expanses, just as oleo-ducts, the oil carrying pipelines, do. However, with the urgent need to reduce greenhouse gas emissions, the love affair with gas and oil has considerably tapered down.

The ocean bottom has also yielded coal from mines accessible from land or at sea: Scotland, Taiwan and Japan, for instance, continued ocean coal mining operations. But coal too is not any longer being courted, for the same polluting and global warming causing reasons. Futuristic thoughts go to sophisticated extraction of hydrogen, deuterium, tritium. While these can technically be retrieved, costs are high, prohibitive for many, and technological refinement is still needed. The same is true about the non-renewable sub-marine geothermal energy.

But there are other sources of energy which can and should be put to work, which are non-polluting, and minimally environment impacting. Unfortunately their extraction is often expensive.[1,2] Of these some have been tapped, with unequal success though, such as the tides, the waves, the marine winds, others remain more engineers' dreams like marine currents, salinity differential. As for OTEC, ocean thermal differences, it is technically possible to put it to work, but economically it remains unattractive. To use a French expression, let us have a *tour d'horizon* of the fields.

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[1] Hislop, D. (ed.), 1992, *Energy Options. An introduction to small-scale energy technologies:* Rugby, Intermediate Technology Publications.

[2] Kristoferson, L.A. and Bokalders, V., 1991, *Renewable energy technologies. Their applications in developing countries:* Rugby, Intermediate Technology Publications.

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1.1.1 Tidal Power

Anyone who has ever watched tides roll in on the coasts of Normandy or Brittany, on the estuary of the Severn River or in the Bay of Fundy, cannot help but be awed by the force that is unleashed. The phenomenon had, of course, already been observed in Classical Times and this power was put to work on rivers such as the Tiber River in Rome, the joint estuary of the Tigris and Euphrates rivers even much earlier. Tide mills on the Danube may date from later periods. Mechanical power was sought to grind grain, to power sawmills, to lift heavy loads.[3]

These tide mills are of course not different from run-of-the-river mills, except that they include an impounding basin where the water brought in by the incoming (flood) tide is stored: At ebb tide the water is released but has to pass through a channel wherein the mill wheel is set. Some more sophisticated mills even captured power from both ebb and flood tides. And still others captured the energy of the horizontal movement of tides. The tide mills' demise in man's industrial arsenal was slow but their numbers declined rapidly and abruptly, as newer technology unfolded.

The tide mill may appropriately be considered the forerunner of the tidal power plant that generates electricity and, in France for instance, has brought a sleepy region into the twentieth century. The Rance River plant (Brittany) has successfully provided power for more than forty years.[4,5] It has also provided the dismal Russian North with the electricity needed to develop a rather desolate region.[6] The Canadian plant, in Nova Scotia, is more a trial run than a badly needed plant.[7,8] Originally geographically limited to coasts with large tidal ranges, the development of very small head turbines permits the implantation of tidal power plants[9] in many more locations. The development of the tidal power plant went hand-in-hand with, or at least was boosted by that of the bulb turbine (France, Russia)[10] and later of the Straflo turbine (Canada).[11]

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[3] Charlier, R.H. and Ménanteau, L., 1999, The saga of the tide mill: *Renew. Sustain. En. Rev.*

[4] Charlier, R.H., 1982, *Tidal energy:* New York, Van Nostrand-Rheinhold.

[5] Barreau, M., 1997, 30th anniversary of the Rance tidal power station: *La Houille Blanche-Rev. Int. de l'Eau* **52,** 3, 13.

[6] Bernshtein, L.B. and Usachev, I.N., 1957, Utilization of tidal power in Russia in overcoming the global and ecological crisis: *La Houille Blanche-Rev. Int. de l'Eau* **52,** 3, 96–102.

[7] Anonymous, 1982, *Fundy tidal power update '82*: Halifax, Nova Scotia, Tidal Power Corporation.

[8] Delory, M.P., 1986, The Annapolis tidal generating station: *Int. Symp. Wave, Tidal, OTEC and Small Scale Energy* III, 125–132.

[9] Henceforth referred to by the acronym TPP.

[10] Charlier, R.H., 1982, *op.cit.* fn. 4.

[11] Charlier, R.H. and Justus, J.R., 1993, *Ocean energies*: Amsterdam-New York, Elsevier pp. 316–320.

The first major hydroelectric plant to use the energy of the tides was put into operation in 1967. It produces approximately 540,000 kW of electrical power[12]. A modest amount in view of heralded plans to produce over a million kilowatts. The dam crosses the estuary of the Rance River at its narrowest point and accommodates a four-lane highway. Bulb turbines permit reversible operation and pumping. The flow of the waters amounts to some $24,000\,\mathrm{m}^3/\mathrm{sec}$. The station was linked to France's national electricity grid; this allows to raise the reservoir's level by pumping, thus at high tide the reservoir is overfilled by taking power out of the system, and, at minimal power loss, the reservoir's level is raised 1 m.

The high capital investment required has certainly acted as a principal deterrent to the construction of more tidal plants, and has laid to rest plans for mammoth schemes for the Severn River (Great Britain),[13,14] Chausey Islands (France) and Passamaquoddy Bay–Bay of Fundy. The Chinese government, taking a more down-to-earth view, has constructed over a hundred small plants, using earthen dams, some of which were pre-existing.[15] Government figures disclosed in 1999 at a Qingdao (PRC) conference on the history of oceanography, announced that China's electricity production from tidal energy would reach 50 MW by 2000 and climb to 310 MW by 2010.[16] This would permit electrification of large, but distant, areas. Initial costs were further brought down when it proved possible to construct plants using modules and dispensing with the costly cofferdams. Argentina and Australia, who conducted major feasibility studies, have now been silent for more than ten years on the topic. On the other hand Korea (ROK) had announced serious plans for a large tidal power station, e.g. Garolim Bay, Inchon Bay, and fostered economic studies.[17] A contract with Sogreah, the French company active in hydrological constructions, was canceled for political motives: France's ill-timed diplomatic recognition of North Korea.

It seems that tidal energy could be put to work for poorer nations and regions by using [modernized versions of] tidal mills and modest plants, as did the Chinese.[18,19,20] Furthermore, end of last century studies found that the cost of a

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[12] The labeling of this plant as "first" requires some caution, as small facilities were installed elsewhere before. The matter is discussed in a later chapter.

[13] Shaw, T.H. (ed.), 1979, *Environmental effects study of a Severn Estuary tidal power station*: Strathclyde UK, The University.

[14] Severn Barrage Committee, 1981, *Tidal power from the Severn Estuary*: London, H.M. Stationary Office.

[15] Cf. fn. 15.

[16] The authors have not been able to ascertain whether this figure was indeed reached by that date.

[17] Chang, Y.T., 1996, Korean experiences in estimating the non-market benefits of the development of coastal resources: the case of a tidal plant: *Book of Extended Abstr. Ocean Canada '96 (Rimouski, Quebec) 40–44.*

[18] Charlier, R.H., 2001, Ocean alternative energy. The view from China—"small is beautiful": *Renew. Sustain. En. Rev.* **5,** 3, 403–409.

[19] Fay, J.A. and Smachlo, M.A., 1982, *Small scale tidal power plants:* Cambridge, MA, Massachusetts Institute of Technology (MIT Sea-Grant College Program).

[20] Cave, P.R. and Evans, E.M., 1984, Tidal energy systems for isolated communities. In: West, E. (ed.), *Alternative energy systems:* New York, Pergamon pp. 9–14.

tidal plant kilowatt is today hardly higher—if indeed it is—than that produced by a conventional central or even a nuclear plant.[21] The longevity of a tidal power plant is between two and three times longer than the lifespan of those.[22]

More modestly even, reintroduction of tide mills in appropriate and selected sites may prove to be a profitable very low cost investment. As proof one may cite several such mills that have been restored and are working musea, or simply an artisanal revival.

Man-made currents can interact with tidal currents to deflect, redirect, modify sediment transport. To the chagrin of dredgers, this would reduce the costs of navigation channel maintenance and control formation of sandbanks hampering ship traffic.

1.1.2 Marine Winds

Of all the ocean energies, marine winds have known the most important development during the last decades. They are a "renewable" which was easy to harness and which required only relatively modest capital investments. Sites are abundant, and a judicious choice permits to dampen the objections voiced because of the noise they cause. Marine wind "farms" have been implanted in numerous locations particularly in Northern and Western Europe. However environmental-linked objections are being raised, spurring engineers to devise new approaches.

Most of the ocean energies require engineering developments to be harnessed and produce electricity, except the marine winds and the tides. The WECS, as they were designated a quarter of a century ago, made first a timid appearance, but they were spurred on by ever climbing prices of fossil fuels and the need to reduce carbon dioxide emanations. The technical problems were rather rapidly solved and the first energy captors were erected on land, mountaintops, away from human habitat. The towering structures were not free from environmental impact, particularly noise and aesthetics.

Pylones have become taller and turbines larger. Everyone applauded the harnessing of marine winds but nobody wanted the pylones in his "backyard". There is also concern that the machines may cause hecatombs of birds particularly during migration seasons An answer to noise, migrating birds routes, aesthetics has perhaps been found, at least *in partim:* siting of the marine wind turbines on floating—and movable—platforms. The design is ready and the construction on the books.

It did not stem the determination of some countries to replace by wind, centrals burning coal, oil, or nuclear products. Locations on the coast were favored and even better, offshore sites. From installations involving a few wind turbines,

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[21] Gorlov, A.M., 1979, Some new conceptions in the approach to harnessing tidal energy: *Proc. Miami Int. Conf. Altern. En. Sources* II, 1711–1795; Gorlov, A.M., 1982, *idem: Proc. Conf. Tidal Power (New Bedford, NS, Inst. Oceanog.).*

[22] Charlier, R.H., 2003, Sustainable co-generation from the tides: *Renew. Sustain. En. Rev.* 7, 187–213; 215–247.

builders passed to sites where large numbers of turbines were installed. Utgrunden in the Baltic was inaugurated as one of the first "wind farms". The proliferation of marine wind turbines occurred especially in Northern and Western Europe: Sweden, Denmark, Germany, Scotland, The Netherlands, to name a few countries. The success so impressed the Americans that they talked about placing turbines on Georges Bank off the coast of Maine, but it looks like that it is off the coast of Texas that a wind farm will be implanted.

Aeolian energy has been on the foreground for quite some time. The windmill of yesteryear is the undisputed ancestor of today's aero-generator. Wind turbines can of course be installed inland, near-shore or even at sea. Twenty years ago proponents of wind power were derided as a new breed of Don Quichottes.[23] Today even combinations of wind energy parks with coastal defense are being considered. Some thought is being given on capturing offshore winds energy through wind turbines placed along an artificial reef implanted as a recreational beach protection device against waves.[24]

The high population concentration in European countries, their trend to move towards the coasts and the ensuing conurbation restrict the available area. Yet, various studies established that offshore wind resources are far higher than those on land. As water depth increases only slowly with distance from shore along many European coasts this favors mounting of offshore turbines.[25]

Thirteen countries participated in the 2-year assessment project "Concerted Action on Offshore Wind Energy in Europe" (CA-OWEE)[26]; at its issue the view was held that by 2011 the wind parks installed in the coastal seas of Europe[27] might be able to furnish the energy needed by the Union.[28] Some interest has been also voiced in the United States East Coast regions and in Tasmania. All aspects of the problem were considered, including grid integration, but particular focusing was on economics. On-shore-placed turbines are definitely less expensive, so only multi-megawatts centrals would be cost-effective.[29] Higher initial expenses are due to foundations, but also for maintenance and operation.[30] The lion's share of costing is

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[23] Heronemus, W.E., 1972, Pollution free energy from off-shore winds: *8th Ann. Conf. Expo. Mar. Tech. Soc. (Washington).*

[24] For further information contacts can be made through (1) owner-coastal.list@udel.edu; (2) www.esru.strath.ac.uk/projects/E and E98-9/offshore/wind/wintr.htm; (3) www.coastal.udel.edu/coastal/coastal.list.html

[25] Garrad, M.H., 1994, *Study of offshore wind energy in the EC. Co-funded by the CEC, Joule I Programme:* Brekendorf, Germany, Natürliche EnergieVerlag.

[26] Anonymous, 2001, *Offshore wind energy: ready to power a sustainable Europe*: Brussels, CA-OWEE, The European Commission (Final Report).

[27] Belgian, British, Danish, Dutch, German, Irish, Swedish, possibly French, waters.

[28] Belgium, Denmark, Finland, France, Germany, Great Britain, Greece, Italy, Ireland, Netherlands, Poland., Spain, Sweden.

[29] Cockerill, T.T., Harrison, R., Kuhn, M., et al., 1998, *Opti-OWECS final report.* III: *Comparison of off-shore wind energy at European sites:* Delft NL, Instituut voor Windtechnologie, Technische Universiteit Delft.

[30] Van Brussel, G. and Schöntag, C., 1998, Operation and maintenance aspects of successful large offshore windfarms*:Proc. Europ. Wind En. Conf. Dublin, Ireland* no pp.nbrs

for the turbine (on-shore 71%, off-shore at least 50%), grid connections (on-shore 7.5 %, off-shore 18%) and foundations (on-shore 5.5%, off-shore about 16%). Land turbines cost considerably less than those used with marine installations. The moral of the story is that to reduce costs, the larger the turbine, the better; with rotor diameters of about 70 m a North Sea sited wind-turbine can produce annually between five and six million kilowatt/hour. There being no neighbors to complain of the noise, windmills at sea can safely turn 10–20 % faster than on land.

A park was built eight years ago on the IJsselmeer, in The Netherlands[31]; a second park was inaugurated in 1996 (Medemblik and Dronten). Denmark built parks in 1991 and 1995, but the most recent is at Middelgrunden and is only two years old, and is the largest producer with 89,000 MWh/year.[32] Sweden's installations date from 1990, 1997–1998, and the newest completed recently. The Utgrunden (marine wind-) park (2000) is Sweden's largest with 38,000 MWh/year. The only British facility in operation is located near Blyth and is a relatively small producer with 12,000 MWh/year. Interestingly the Danish Middelgrunden facility is owned jointly by a 3,000+ members wind-energy cooperative and a local electricity utility.

The development of offshore wind farms may however be slowed as the market is liberalized; the cost of the kilowatt must be reasonable at production time or a project's viability will unavoidably be put in jeopardy. It was thus pointed out that Europe may be left in the odd position of disposing of an environment-friendly and abundant energy resource, supported by public and governments alike, but without the market framework to foster its development.

Nine offshore wind farms are planned: five by Denmark (two in 2002,[33] then one each in 2003, 2004 and 2006), one by France (in 2002 near Brest[34]), a near-shore one by The Netherlands (2003), another by Belgium (2003), and one by Ireland[35] on Arklow Bank. Plans in Belgium include, as marine and fluvial installations an additional farm near Zeebrugge and another one along the Scheldt-Rhine canal, north of Antwerp.

A Danish company's subsidiary—Vestas Mediterranean East—will sell some 47 wind turbines (850 kW) to Sicily for three wind projects to Asja Ambiente Italia; the total installed capacity will reach 40 MW and operations started early in 2007. They are dwarfed by the 52 turbine wind farm of Hadyard Hills (South Ayrshire). Thus far 171 MW of electricity generating wind turbines came on line in 2006, providing current for 80,000 household and over 665 MW were added to normal electricity production.

Danish and Dutch projects would produce a kWh for $0.049–0.067 compared to on-shore prices of $0.027–0.07. Production costs vary of course with the speed of

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[31] Formerly Zuiderzee, prior to the damming and polderization of a major portion of the water body.

[32] Giebel, G., 2001, *On the benefits of distributed generation of wind energy in Europe:* Copenhagen, Fortschritt Berichtte (VDI). DEA/CADETT, 2000, *Electricity from offshore wind:* Copenhagen, Danish Energy Agency.

[33] Two facilities scheduled for that year.

[34] But not built at this writing.

[35] No date set at this writing.

the prevailing winds, turbine size, and plant dimensions, while technological refinements allow expecting one kWh to cost between \$0.04 and 4.6. The Dutch estimate that on their sector of the continental shelf they could erect sufficient wind turbines to satisfy, by 2030 180% of the country's electricity needs. This figure may have to be scaled down, however, as a study conducted in 1995 on behalf of the European Union; indeed, there are several sites where turbines cannot be placed, for instance because depths are too great or the distance to shore is. The same rather simplistic calculation ventured of the possibility that the British could capture at sea four times their electricity needs, the Irish fourteen and the Danes even seventeen.

At Zeebrugge, Belgium, a small park has been installed on the sea harbor breakwaters. Production amounts to 4.8 MW, a drop in the bucket for a country needing 15,000 MZ. Belgian authorities gave recently the green light for positioning fifty air turbines on an artificial island at 15 km (8.10 nautical miles) off-shore from the city-resort of Knokke-Heist.[36] The contractor is *Seanergy*. The 1,000 MW produced are to provide electricity to 85,000 families. Construction is scheduled to start in 2003 and placing into service in 2004. Notwithstanding reports from similar projects concluding to benign influence on the marine environment, an impact study will be conducted. The installation is deemed to have a life span of 20 years and the contractors are held, by the contract, to remove all wastes. However, claiming aesthetic pollution (view cluttering from shore), the city of Knokke-Heist filed an objection with the Council of State to block the construction, even though, to minimize their visibility, the turbines will be painted gray to match the North Sea waters' local color. Coming from a city that has, for many years, notoriously failed to provide adequate water purification facilities, one may raise a somewhat surprised eyebrow. . . .Granted, the marine wind parks are not exactly attractive, yet they are not really objectionable, the more so that they are visible at best as specks on the horizon.

The endless procedures came finally to a close in 2007 and the wind-park will be built. The delay has had one advantage: technology has progressed and the latest and largest turbines will be installed.

Tunǿ Knob, on the Kattegat (Denmark) towers 40 m above the million kilograms concrete foundation placed at a depth of 3–5 m. Its wings spread about 15 m. But, on the positive side, the sea-turbines are 150% effective compared to their land-placed cousins.

And objections are raised in The Netherlands also, claiming deterioration of the polders' landscape. Yet, the Dutch researchers, buttressed by loud Greenpeace endorsement, estimated already at the end of 1998 that 10,000 MW would be extracted from the North Sea by 2030, or 40% of the current electricity consumption. The government promised that by 2020 the energy used in the country would be generated by sustainable sources.

Wind power from the ocean has also been considered for providing the energy needed by pumps and desalination plants.

Marine winds are providing energy to 24 turbines in Zeebrugge; they have a total capacity of 5.2 MW. An isolated one in Middelkerke is rated at 660 kW, and

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[36] Federal Minister of the Environment Magda Algoet's decision of June 25, 2002.

five turbines, placed along the Baldwin (Boudewijn) Canal in Bruges have a total capacity of 3 MW.

The German DEWI (Deutsches Windenergie-Institut) conducted an in-depth study which concluded in 2000 that Belgium, The Netherlands, Denmark, Germany, and Great Britain could cover their entire 923 million MWh needs (1999 estimate) from offshore wind-energy. This would, however, require placing 100,000 2-MW turbines in North Sea sites.

Amongst plans often mentioned for Belgium are a wind-farm of 50 2-MW turbines off-shore Wenduine, upgrading of the Zeebrugge “windmills” and addition of two more, the new total of 26 would bring production up from 5.2 to 13 MW.

Such projects, understandably, distress tourism-conscious resort municipalities such as Knokke-Heist and Wenduine-Klemskerke-De Haan.

1.1.3 Wave Power

The number of patents taken out on wave power activated machines is stunning, and they go back well over two hundred years. Probably the first to be taken out was by Girard, father and son in 1799 and proposed to take out mechanical energy using a raft. In the twentieth century buoys and lighthouses used wave-generated electricity. In the USA several attempts were made in California (San Francisco, Capitola, Pacifica). The power is provided by the onslaught of a breaking wave, which can be captured in a reservoir, accessible by way of a converging ramp, and connected with a return channel at the exit of a low pressure turbine. Power can also be generated by means of devices set directly in motion by the wave itself.[37]

Though diffuse, available power is impressive: there is more power represented in the potential energy of a heaving ship than there is present in the thrust of its engines. Summed up the total available power of ocean wind waves amounts to 2.7×10^{12} watts. It is conceivable to use similar waves from land-locked seas or even lakes; power of such waves is $2\frac{1}{2}\%$ less than that of seawater waves.

Waves are a concentrated form of wind energy. The very nature of wind waves requires a large number of small devices for its energy extraction. Waves have the distinction of making more energy available as energy is extracted, due to the inefficiency at which energy is transferred from the wind to the sea at highly developed sea states.

Engineers and designers have been repeatedly discouraged in their attempts to capture wave energy because the occasionally unleashed fury of the sea destroys stations. The force is such that a 25-ton block of concrete has been found inland, after a storm, at about 5 km from shore. To protect against installations’ destruction, special constructions are needed, both quite expensive and return limiting.

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[37] Wave-harnessing systems can use flaps and paddles, focuses, heaving bodies, pitching and rolling bodies, pneumatic or cavity resonators, pressure, rotating outriggers, surges, a combination of several of the above.

Research has been pursued on finding appropriate and affordable approaches e.g. in China.[38]

Wave extraction systems utilize either the vertical rise and fall of successive waves, in order to build-up water- or air-pressure to activate turbines, or take advantage of the to-and-fro, or rolling motions of waves by vanes or cams which rotate turbines; or still use the concentrations of incoming waves in a converging channel allowing the build-up of a head of water, which then makes it possible to operate a turbine.

Conversion of energy devices can provide propulsion, buoy power supply, be offshore or shore-based plants. A physics classification would recognize devices that intervene in wave orbits, utilize the pressure field, are accelerative, use horizontal transport from breaking waves. Some 38 systems have been described that fit into four broad types: surface profile variations of travelling deep water waves, subsurface pressure variations, sub-surface particle motion, and naturally or artificially induced unidirectional motion of fluid particles in a breaking wave.[39]

Stahl had already in 1982 classified devices based on mechanical concepts: motors operated by the rise and fall of a float, by the waves' to-and-fro motion, by the varying slope of wave surface, and by the impetus of waves rolling up a beach.[40]

Converging wave channels, supplying a basin constituting the forebay for a conventional low head power station provide a high output. Their economic feasibility has been repeatedly put in doubt. Generators designed along the lines of conventional aero-generators have been proposed. Waves are commonly available and could be harnessed in far more sites than tides. Numerous large megapolis and conurbations located near the shore would be potential consumers of wave energy, but so would coast sited industries.

The systems involve thus either a movable body, an oscillating column or a diaphragm. Researchers usually cite as advantages of harnessing wave energy that they are pollution free, widely available, a low cost operation, that additional units provide easily additional power, their siting on unused shore-land, installations can double as protective devices for harbors and coasts, generators are more efficient than those of fossil fuel conventional plants, are a power source that is complementary to others, their output is unaffected by weather or climate, the size of waves can be fairly well predicted, potential coupling of stations to desalination plants, benign impact on environment and ecology.

Wave energy has been harnessed recently in sophisticated plants particularly in Sweden and Norway. A comprehensive British study yielded many proposals, but the matter has been, for all practical aspects, been laid to rest. Japan has a very active research program, on-going for decades, which led to some large scale efforts, e.g. the *"Mighty Whale"*, a floating power device with air turbine conversion to

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[38] You Yage and Yu Zhi, 1995, Wave loads and protective technology of an on-shore wave power device: *Chinese Oc. Eng.* **9,** 4, 455–464.

[39] Panicker, N.N., 1976, Review of the technology for wave power conversion: *Mar: Techn: Soc: J:* **10,** 3, 1–12.

[40] Stahl, A.W., 1982, The utilization of the power of ocean waves: *Trans. Am. Soc. Mech. Eng.* 13, 428–506.

electricity or compressed air[41], or the earlier *Kaimei,* a barge equipped with compressed-air chambers.[42,43]. Air turbine buoys are utilized in Japan—as in the US and the UK—as are air turbine generators (Osaka).

Like for tidal power, there are modest devices that can put wave energy to work and which, consequently are more affordable. In California, close to a hundred years ago, wave power was used to light a wharf underneath which panels had been suspended. At Royan, close to Bordeaux, France, waves provided electricity to a home using an air turbine driven by water oscillation in a vertical borehole. In Atlantic City, New Jersey, floats attached to a pier were activated by horizontal and vertical motion. A Savonius rotor operating pump was installed in Monaco's Musée Océanographique research laboratories. At Pointe Pescade, Sidi Ferruch a low-head hydro-electric plant supplied electricity from a fore bay with converging channels. In Sweden an auto-bailer bilge pump has been placed into service, the sea-lens concept has been developed in Norway, and hydraulic pumping over pliable strips in concrete troughs have been proposed by a Boston, USA firm. Though these approaches were either uneconomical or too small at the time, this may not be the case today. Efforts towards the design of economic devices are being made.[44]

T.J.T. Whittaker reminded his audience, at Queen's University Belfast, in his lecture on the occasion of the award of the Royal Society's Esso Energy Prize, that, for more than 20 years work on wave power harnessing had been pursued in China, Japan, India, Ireland, the United Kingdom, Denmark, Sweden and Norway.[45] Denmark tested some years ago a wave converter. Whittaker stated that wave power is a potentially viable technology that could make a significant contribution, to not only European, but also the world energy demand.

A somewhat similar *son de cloche* has been heard in the United States. Indeed, the US Electric Power Institute reports that wave power may be economically viable, but would need a production volume of 10–20 GW. Hawaii, Northern California, Oregon and Massachusetts are proposed as the best sites. It even expressed a preference for waves to wind because of lesser visibility and lower profile in addition to better dispatchability. American researchers concluded that to make such significant contribution sustained research is needed into the application of wave power to the offshore production of hydrogen. The State of Oregon set up a National Wave Energy Research, Development and Administration center; it is part of Oregon's effort

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[41] Hotta, H., Washio, Y., Yokozawa, H. and Miyazaki, T., 1996, Research and development on the wave power device "Mighty Whale": *Ren: En:* **9**, 1/4, 1223–1226.

[42] Kudo, K. and Hotta, H., 1984, Study of the optimal form of Kaimei-type wave power absorbing device: *ECH. Rep. Jap. Mar. Sci. Technol. Center* 13, 63–84.

[43] Cf. Charlier and Justus, 1993, *op. cit.* pp. 136–140

[44] French, M. and Bracewell, R., 1996, The systematic design of economic wave converters. In Chung, J.S., Molagnon, C.H. and Kim, A. (eds), *Proc. 6th Int. Offshore and Polar Engng Conf. (ISOPE CO)* I, 106–110.

[45] The lecture was delivered in 1995. Recent publications on wave power in India include e.g. Raju, V.S. and Ravindram, M., 1996, Wave energy: power and progress in India: *Ren. En.* **9**, 1–4, 339–345, and the assessment of wave power potential for the Indian coasts by Sivaramakrishnan, T.T., 1992, Wave power over the Indian seas during southwest monsoon: *Energy* **17**, 6, 625–627.

to kindle marine renewable and sustainable energy systems. Thus $5 million will buttress the a*d hoc* programs conducted by Oregon State University.

India's Institute of Technology considered combining a wave energy converter with a fishing harbor breakwater, thereby making double use of the concrete works, as suggested by Whittaker and this author (Charlier). The Indian researchers of IIT also developed a power system using the piezo-electric effect: plastic sheets are to be suspended from floating rafts and secured to the ocean bottom. As waves lift the rafts, the sheets bend and generate electricity in the process.

Among the more recent devices due for deployment *in situ* is the Pelamis P-750 Wave Energy Converter, tested since 1998, was placed on the market by Ocean Power Delivery Ltd®, a Scotland based company. A full-scale pre-production prototype was built in 2003, and field-tested in 2004. The 750, in the model's name, refers to 750 kW power.

Several Pelamis have been installed in a limited make up "wave farms"+ (Fig. 1.1) similar to "wind farms", "biomass farms", "fish farms", "oyster and mussel parks". This first try-out will take place in the Orkney Islands located European Marine Energy Centre.

The number of such machines required to offer a significant saving of traditional fuels, is however rather large, the space required not minimal. The company views a field of 1 to 2 km^2 wherein 40 Pelamis would be installed. The total output of the farm, 30 MW, is potentially sufficient power to fill the needs of 20,000 homes (Fig. 1.2).

The Pelamis device belongs to the group of semi-submerged articulated structures, of which other types have been tested and proposed in the past.[46] Pelamis heads on into the incoming wave and contains three 250 kW-rated power conversion modules, each a ≪generator≫ in its own right. Hydraulic arms resist the wave motion which pumps an intermediary fluid through motors by the way of smoothing accumulators. A single dynamic umbilical conduit is connected to the nose-located machine's tranformer leading the power to the seabed.

It is ≪sustainable≫, non-site specific, has good power capture efficiency, deployable in depths up to 100 m, is price competitive with an offshore wind power scheme, and an eventual lower kWh generation price is predicted by its manufacturer. Yet, some of the objections voiced against wave energy conversion schemes, and occasionally confirmed by experience, remained unanswered and proponents would gain support if addressed. First the WEC scheme's vulnerability to exceptional storms, next the obstacle the WEC constitutes to navigation. Except for Scandinavia, wave power had somewhat slid into a forgotten corner of Neptune's power potential. Nothing would prevent, except perhaps the need for space, this

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[46] Charlier, R.H. & Justus, J.R., 1993, *Ocean energies. Environmental economic and technological aspects of alternative power sources*: Amsterdam, New York, London & Tokyo, Elsevier [Oceanography Series Nr 57] pp. 122–153; Ross, D., 1981, *Energy from the waves: the first ever book on a review in technology*: New York, Pergamon; Salter, S.H., 1979, Recent progress on ducks: *Symposium on wave energy utilization-Chalmers University of Technology, Göteborg, Sweden.*

technology to be adapted to the limnology domain, even if schemes could conceivably have to be more modest in size.

A wave farm has been placed off the Portugal coast in 2006. The Archimedes Wave Swing generator—designed and developed by a Scottish company—completed successful trials in Portguese waters. The system is moored to the seabed and is invisible from the surface. Electricity is generated as waves move an air-filled upper casing against a lower fixed cylinder. The technology is Dutch in origin. The nearly €3 million input allows the completion of a full-scale plant that could be on-line by 2008.

The first M/V Sea Power was installed in late 2006 at a site some 7 km off the coast of northern Portugal, near Póvoa de Varzim. Ocean Power Delivery (OPD) signed a contract with a Portuguese consortium, led by Enersis, to build the initial phase of the world's first commercial wave-farm to generate renewable electricity from ocean waves.

The 2.5 MW project is expected to meet the electricity demand of more than 15,000 Portuguese households while more than 60,000 tonnes per year of carbon dioxide emissions from conventional generating plants will be displaced.[47]

On October 1, 2006 wave powered electricity for 1,500 families in Portugal was provided by a floating electric central sited some eight km offshore from Aguçadoura. Rui Barros, director of Enersis, is reported to have announced the central being placed on line as a world's first. Wave power has been used, however, for close to a century in Royan, Monaco, a pier had been lit by wave energy in Pacifica, California, a beach had hosted a simple machine, systems had provided mechanical power, etc and pilot plants provided current in Scotland and Norway to mention just two locations.[48]

It remains nevertheless gainsaid, that it is the first time wave energy has left the endless academic discourse and timid try-outs area, and be put resolutely to work. The Ocean Power/Enersis system encompasses three 3.5 m diameter 142 m long pipes, three generators and a set of hydraulic high-pressure pumps. Generated current is led to the continent via submarine cable. Refining of meteorological equipment and methods currently allows prediction of force and height of waves up to six to seven days in advance.

Costs are about the same as that of a wind-system—an approach to alternative energy already endorsed by Portugal earlier—but optimistic prognoses of the designers assert that the wave farm will yield three times that of the wind farm. The same optimists plan to establish 28 more floating centrals by mid-2008.

Besides wind and waves, the Portuguese are also eyeing the sun as an alternative source of energy. They started construction, in 2004, of what may well be the largest photovoltaic energy conversion plant, intending to connect no less than 100 hectares of sun-panels.

It is not always a matter of producing domestic or industrial electricity. The up and down movement imparted by waves to a ship produces power than considerably

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[47] *Cf.:* www.greenjobs.com/Public/IndustryNews/i_news_00411.htm; www.oceanpd.com; www.google.nl/search?hl=nl&q=wave+farm+portugal&btnG=Google+zoeken&meta

[48] Charlier, R.H. and Justus, J.R., 1993, *Ocean Energies*: Amsterdam, Elsevier.

exceeds that power to propel a ship; technology that would allow to convert one into the other would reduce considerably transportation costs. Some ships likewise have added to their upper-structure panels to absorb marine wind power. In Mexico experiments were conducted on a wave-powered pump system to flush stagnating water in foreshore lagoons. Ireland concentrated on oscillating water column systems. Other pumps have been designed by Isaacs of La Jolla (California) Scripps Institution of Oceanography—tested off Kanoehe Bay (Hawaii). The European Union contributed to the funding of an oscillating water column plant to substitute, on Pico (Azores) wave power to diesel. Of all the devices proposed and researched in the United Kingdom, only two were retained for further studies: an oscillating water column (OWC) and the circular "Sea Clam". The OWC was deployed on the Island of Islay utilizing a natural rock gully, thus saving on construction outlay and facilitating maintenance access. Another European Union funded project is a near-shore sea-bottom sited two-chamber OWC in Scotland. The University of Edinburgh was the site of S.H. Salter's "nodding duck" (rotating vane) research. Belgium examined a decade or so ago, the possibility to use wave power to reduce silting in the harbor of Zeebrugge.[49]

In Toftestallen, Norway, the world's largest oscillating water column system had a capacity of between 500 and 1,000 kW. It functioned properly but was unfortunately wrecked in 1998 during a particularly heavy storm. It has not been reconstructed thus far (2007).

1.1.4 Ocean Thermal Energy Conversion

Sometimes referred to as thalassothermal energy [conversion], commonly designated as OTEC. The OTEC uses the difference of temperature prevailing between different ocean waters layers to produce electrical power. Statisticians eager to impress the amount of energy available stress that in the waters between the tropics the quantity of heat stored daily by the surface water layers in a square kilometer equals the burning of 2,700 barrels of oil.

The pilot projects of Arsène d'Arsonval and Georges Claude have been abundantly and repeatedly described; they date back to the first half of the last century.[50] Following the oil crisis of 1973, there was a new flurry of interest for OTEC and "Mini-OTEC" and "OTEC-1" were launched respectively in 1979 and 1980. In 1981, Japanese researchers built a close-circuit central on Nauru that delivered 31.5 kW/h; they had placed the cold-water conduits on the ocean floor at a depth of 580 m. It was a result that went way beyond the most optimistic expectations.

Several technical improvements have been introduced into the plans of proposed schemes. Energy conversion reaches an efficiency of 97%, water exchanges are no longer made of titanium, but of the far less expensive aluminum, corrosion and

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[49] Charlier, R.H. and Justus, J.R., 1993, op. cit.

[50] id. fn. 30.

bio-fouling have been considerably reduced, and the closed circuit system is far more ecologically benign than the open circuit one. The 1993 closed-circuit prototype set up at Keahole Point (Hawaii) delivered 50 kWh net. Turbine improvements are under scrutiny.

These very small plants, alas, produced electricity at high cost. Newer systems have been developed by TRW and Lockheed, but have not been tried out. TRW's 103-m diameter concrete emerging platform tops four OTEC units connected to a single cold water adduction pipe plunging to a depth of 1,200 m. Ammonium gas is the intermediary fluid that is considered currently. On the other hand no platform is foreseen in the Lockheed scheme that also consists of four units connected to a concrete column reaching a depth of 450 m.

OTEC facilities could be coupled to desalination plants, aquaculture schemes, air conditioning systems. The Hawaii Ocean Science and Technology Park, on the island of Hawaii (the "big island") is the site of deepwater intake pipes for aquaculture operations; it is also the locale of significant alternate energy research where *i.a.* experiments are currently—and have been for some time—conducted for ocean thermal energy conversion. It is furthermore on Hawaii that research progresses on seawater use for air conditioning, for a variety of alternate energies, and where recently a new study group has perfected plankton growth for the manufacture of bio-fuels.[51] It is also on Oahu (Hawaii) that an "EnergyOcean 2007" was held from August 21 through 23, 2007.[52]

While research is proceeding on a modest scale, no full-size OTEC-central has ever been built nor placed into service.

1.1.5 Marine Biomass Conversion

Little new has been reported in the area of marine biomass conversion even though the increase in algal biomass has caused serious concern to coastal regions, and in particular to resort towns. This is in opposition to the considerable progress made with biomass utilization for other purposes than electricity production.

Experts hold that the marine biomass conversion holds promise, has a future but predict that its development will be rather on a regional level, and on a modest scale.

1.1.6 Marine Currents

There is no arguing that ocean currents represent an enormous energy potential. To harness it, there has been no shortage of proposals. Some projects envision turbines that are fixed on the seabottom, others would place them in the current itself, allowing several turbines to be attached at different depths to a single cable. As dis-

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[51] See further in Sect. 1.1.5.

[52] info@energyocean.com and www.Ocean-techexpo.com

tances to the consumer might be, in some instances, too great, industrial complexes were proposed in the middle of the ocean and the manufactured product would then be brought by ship to the continent.

A Canadian concern after testing six prototypes decided to construct a 2,200 MW ocean current energy conversion plant in the Philippines using a Davis Hydro Turbine. The scheme foresees a dam wherein a number of slow rotating vertical turbines are to be housed.

The projects clash however with concerns about navigation safety, climate modification, danger for ocean life, cleaning of floats if they were used. After rejecting the idea of harnessing the Mediterranean's waves—their height being far more modest—Italians are again considering a marine current central in the Straits of Messina.

1.1.7 Tidal Currents

Should tidal currents be discussed as part of tidal power or as a special type of marine current? The horizontal to and fro current due to the tidal phenomenon may be tapped in rivers as well as in estuaries or bays. It has thus seemed more logical to treat it separately here; tapping tidal current power has received recently more attention even if it has been a provider of mechanical energy in earlier times (tide mills).

Considering tidal currents, rather than tides themselves, poses new problems both from an environmental point of view and of that of power production. Considerations are in order because over the last two or three years there has developed (again) a real interest in tapping such currents for electricity production.

Robert Gordon University (UK) professors Bryden, Grinsted, and Melville have directed susbtantial efforts since the start of the new millennium in making possible a way to extract energy from the tidal current.[53] In a recent paper (intended for the *Journal of Applied Physics*), they developed a simple model to assess the influence that extraction of energy could have upon flow hydraulics. Ten percent extraction of raw energy would result in flow characteristics modifications, and could be used as an approximate guideline for the resource potential of a tidal energy extraction site.

Even though subject to meteorological vagaries, tidal currents, like tides, are an essentially predictable, sustainable and renewable source of energy. If in Scotland Spring tides may provide a kinetic energy flux of $175\,\mathrm{kW/m^2}$ there are many more regions throughout the world where the flux is about $14\,\mathrm{kW/m^2}$ which is sufficient for power production. Unlike atmospheric currents, tidal current fluxes are constrained between the seabed and the sea surface, may even be further constrained

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[53] Ian Bryden, now (2007) at the University of Edinburgh, see following fn., chaired a session dubbed "Wave and Tide Farming" at the conference "Oceans 2007, IEEE/OES, Marine Challenges: Coastline to Deep Sea", held in Aberdeen, Scotland 18–21 June 2007. [IEEE=Institute of Electrical and Electronics Engineers (UK); OES=Oceanic Engineering Society].

in a channel. Hence identification between wind, particularlymarine winds, currents and tidal currents is hardly appropriate.

There is a steady decrease in depth and increase in flow speed along a channel, but when energy extraction occurs, a substantial head drop develops where the extraction of energy takes place and flow speed decreases. In the Robert Gordon University model calculations are based upon 10% extraction at 2 km from the channel entrance. Obviously, energy extraction has a negative (reducing) effect on flow speed.

From a practical viewpoint it appears thus not possible to predict energy production only based upon natural river flow. The authors point out that in more complex systems, e.g. the Stingray, two, even three dimensional flow analyses are appropriate.[54]

1.1.8 Salinity Gradients

Membrane problems, particularly their cost, remain a major obstacle to progress in tapping that sort of ocean energy. A recent proposal led to the development of a prototype scheme wherein the surface of the ocean plays the role of membrane. In a nearby area fresh water can be stored. Based upon the osmosis principle, it will migrate in the direction of the salty seawater mass, passing through a turbine and mixes with the seawater on the other side. A handicap is the size of turbines required, but if salinity power has to be generated, this seems, today the least expensive approach.

The salinity gradient has been used for electricity production through batteries. The principle involved is reverse electro-dialysis; alternating cells of fresh and salt water are placed next to one another. Flowing seawater take on the role of electrolyte. Lockheed built a 180 MW experimental central. Such batteries are voluminous and the system uses up a good part of the produced current to activate the water pumps.

From an environmental viewpoint the use of salinity gradients does not appear to be free of problems: animals are apt of being sucked-up in the conduits, salt residues must be properly disposed of, and would sufficient fresh water be available in a time when it is at a premium.

Efforts to tap salinity differences may include use of dry holes drilled in the course of the search for oil wells that uncovered brines and brackish water "deposits".

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[54] Bryden, I.G., Bulle, C., Baine, M. and Paish, O., 1995, Generating electricity from tidal currents in Orkney and Shetland: *Underwater Technology* 21, 2, 17–23; Cave, P.R. and Evans, E.M., 1984, Tidal stream energy systems for isolated communities. In West, M.J. et al*., Alternative energy systems. Electrical integration and utilisation:* Oxford, GB, Pergamon Press; Macleod, A., Barnes, S., Rados, K.G. and Bryden, I.G., 2002, Wakes effects in tidal current turbines. In MAREC, Marine renewable resources *conferences*, Newcastle, September 2002. Bryden, I.W., (in press), Assessing the potential of a simpled tidal channel to deliver useful energy: *J. of Appl. Phys.*