Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2015, 41 (113), 17–23
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)

An overview of methods for wave energy conversion

Leszek Chybowski, Bolesław Kuźniewski

Maritime University of Szczecin
70-500 Szczecin, ul. Waly Chrobrego 1–2, e-mail: {l.chybowski; b.kuzniewski}@am.szczecin.pl

Key words: sea waves, energy conversion, renewable energy, waves energy, seas and oceans, power plants

Abstract

Legal and economic aspects connected with generating electricity from waves are discussed and a classification of wave energy converters is shown. The study discusses selected technical solutions generating electricity from sea and ocean waves. Research directions of the Maritime University of Szczecin, Poland, are presented in terms of energy conversion from wave energy into electricity and using sea wave energy for coast protection against waves. The potential of waves as a renewable energy source (in Europe and outside) is evaluated and problems connected with implementing wave energy conversion systems are outlined.

Introduction

Increasing demand for energy in highly developed countries, depletion of accessible fossil fuels, ecological requirements on generation of renewable energy and political situation demanding independence and energy safety policies result in real search for new, effective methods of energy generation from renewable sources [1]. Seas and oceans are one of these sources. Among technologies of wave (sea and ocean) energy conversion being currently developed, systems using the following phenomena must be distinguished:

a) waves;
b) currents;
c) tides;
d) salinity gradient;
e) temperature gradient.

Renewable sources for energy generation are very significant for Polish economy [2]. Directive 2009/28/EC of the European Parliament and of the Council describes a framework for the promotion of use of renewable energy and sets obligatory goals for every EU Member State in terms of its use. In other words, by 2020 a 20% target for the overall share of energy from renewable sources and a 10% target for energy from renewable sources in transport must be reached but Poland and 14 other EU Member States failed to achieve the goals set for year 2010 when it comes to the overall share of renewable energy in electricity generated by other methods. Currently wave power is estimated at 3 TW. To compare, tidal power is estimated at ca. 200 GW i.e. 15 times less [3]. The *World Energy Council* has estimated the market potential for wave energy to be in excess of 2,000 TWh/year [4].

Legal and economic aspects of energy conversion

In 2012 energy conversion in the European Union Member States (EU-28) equalled 22.3% of the overall share of energy generation from all sources [5]. Out of popular kinds of renewable energy, biomass and energy-from-waste were in the lead (65.5%) while water energy amounted to 16.2%, wind energy 10% and solar energy 5.1%. The remaining 3.2% refers to geothermal and only 0.02% to tidal, wave and ocean energy (the use of the latter group in 2012 was identified only in France and Great Britain). The United States of America is the world's leading country in wave energy generation.

Currently proposed world technologies of electricity generation from wave energy conversion are, at best, full scale prototypes. These results in high costs of energy generation but, considering wind energy development, the costs of wave energy conversion will also decrease when the conversion technologies are improved. Figure 1 shows the wave potential as an energy source. It also presents a relation between average wind speed and wave height.

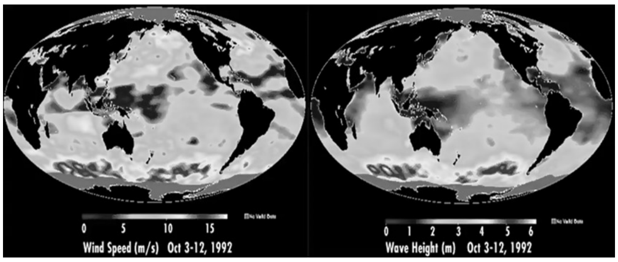

Fig. 1. Global wind speeds and wave heights correlation [6]

Using wave energy has a significant social, economic and environmental impacts because global renewable energy demand is high. This new source of energy contributes directly to a sustainable use of natural resources, reduction of CO_2 emissions and it raises social awareness on sustainable energy economy. According to report *Renewable energy statistics in 2012* of the EU statistical office Eurostat, in the period of 2003–2010 the primary production of renewable energy within the EU-27 increased every year to be the highest in 2010 when it equalled 12.2% for the EU-27 and 13.7% for Poland [7, 8].

The guidelines for renewable energy development for Poland have been set up by the Polish Government in the *Strategy for renewable energy development* [9] passed by the Polish Parliament on 23 August 2001, in the *Energy policy for Poland by 2030* [10] passed by the Council of Ministers on 10 November 2009 and in the *Programme for Power Engineering* [11] passed by the Council of Ministers on 28 March 2006. The strategic goal of the state is to increase the use of renewable energy sources for the renewable gross final energy consumption to amount to 15% in 2020 [8].

It is difficult now to demonstrate economic benefits of using waves as an energy source which despite their high potential are not taken into account in relevant statistics. Assuming that in 2020 wave energy will amount to 10% of overall share in renewable energy, wave power plants have a chance to equal 1.5% in renewable final energy generation. Great Britain (Scotland in particular) and western European countries facing the Atlantic i.e. Ireland, France, Spain, Portugal and Norway, have the biggest potential for the above [12]. North and South America, Southern Africa, Australia and New Zealand are also highly energetic.

The wave energetic potential is well shown by a wave energy global resource map in figure 2. Any area with yearly averages of specific power of over 15 kW/m has the potential to generate wave energy at competitive prices. It must be noticed though that the map excludes areas such as the Baltic Sea, the Mediterranean Sea and the Great Lakes of Northern America.

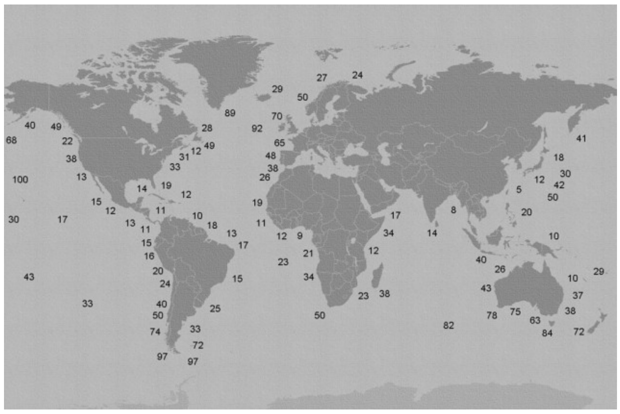

Fig. 2. Average annual wave energy resources [kW/m] [4]

For comparison, annual wave energy resources for the Baltic Sea are estimated at 14 TWh in its most energetic areas (Fig. 3). Additionally, the wave potential of the Baltic Sea in winter time is promising and enables to generate electricity from waves in sufficient amounts [7, 13].

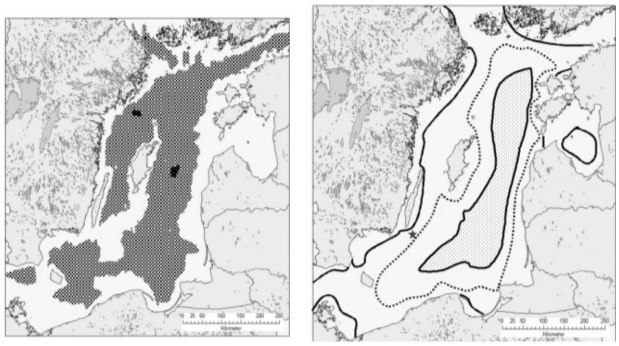

Fig. 3. Baltic Sea [14]; left – depth of Baltic Sea (white indicates 0–50 m depth, grey 50–200 m and black above 200 m; right – average significant wave height in December 1999 (solid line indicates 1 m, dotted line 1.6 m and solid line enclosing dotted surface 2 m)

The wave heights are of 1–2 m, in the areas boarding *Pomorskie* administrative district the height is of 1.6 m [14]. The wave power of the Baltic Sea ranges between 30 and 50 kW/m wave crest length.

State-of-the-art in wave energy conversion

There is no doubt that the potential of waves as a source of power is huge and wave energy conversion to electricity is simple. It is the wave power plant infrastructure and waves themselves that are a real challenge – siting, costs effectiveness, fatigue resistance and constant operation when it comes to the former and height variation as for the latter. Different methods and devices of wave energy conversion into electricity are known [1, 6, 15]. Taking depth and wave characteristics into account, they can be divided into: floating in deep water, tethered to seabed in intermediate depths, fixed to seabed in shallow water and coastal. Considering the way of operation of wave energy converters, they can be categorised into [6]:

- point absorbers, which are small sized relatively to incident wavelength,
- attenuators, where the principal axis of the device is perpendicular to the wave front and energy is intercepted by means of the movement of the device components caused by passing wave,
- terminators, where the principal axis of the device is parallel to the wave front and energy interception is simply wave interception.

Currently used constructions apply the energy conversion systems based on:

- power hydraulics,
- pneumatics,
- solenoids,
- complex gear boxes.

The so called *Searaser* invented by *Ecotricity* from Great Britain belongs to the most popular systems. It works like a pump with a vertical piston between two buoys. One buoy floats on the surface of the seawater, the other is suspended underwater (Fig. 4).

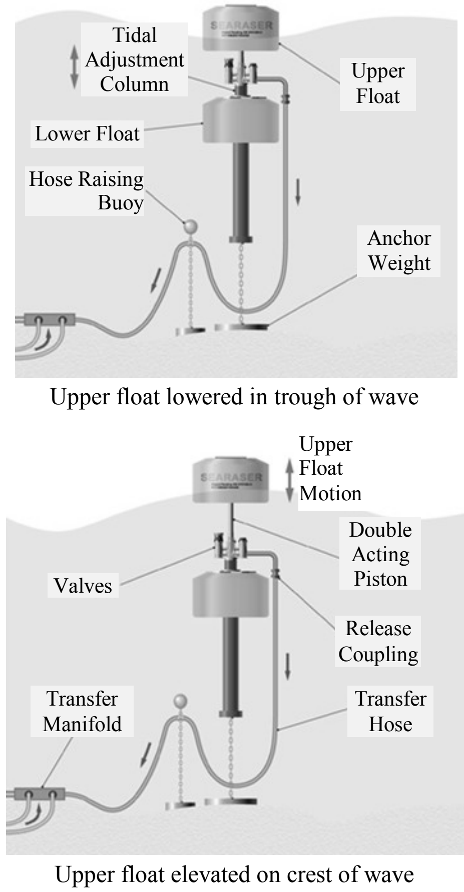

Fig. 4. The floating system *Searaser* of *Ecotricity* [5]

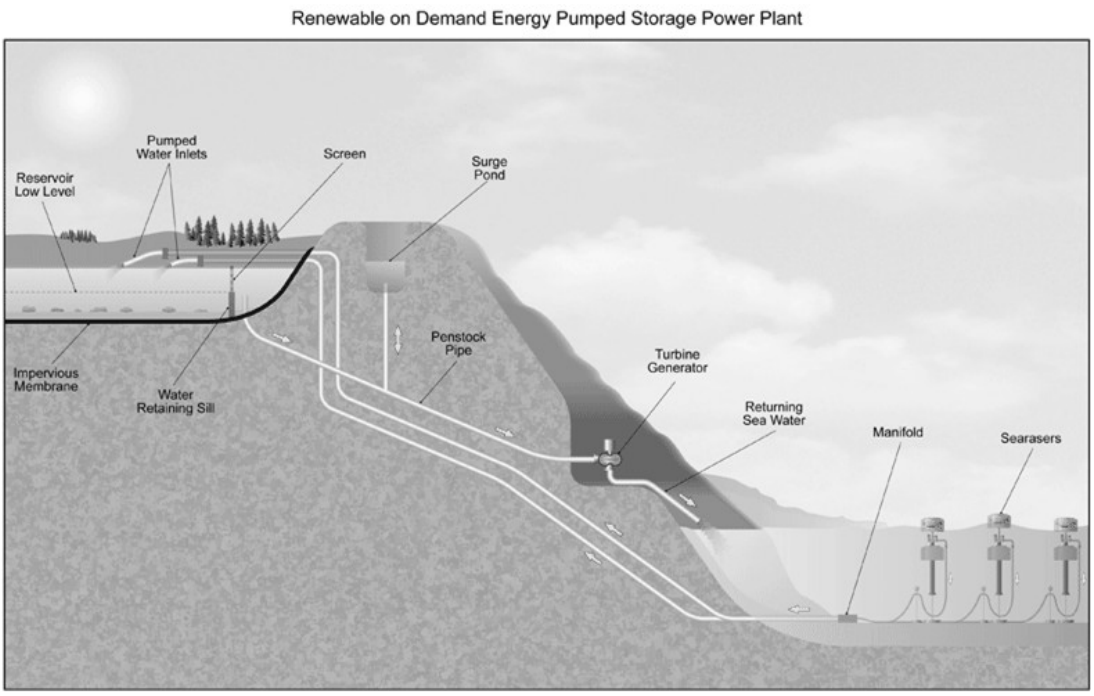

Fig. 5. Electricity generation method by *Ecotricity* [5]

The seawater is pumped through pipes to an upper onshore reservoir and then returns to the sea actuating the turbines which drive the alternators (Fig. 5).

Another wave driven device called *Pelamis* consists of four cylindrical sections linked by hinged joints (Fig. 6). The semi-submerged, moored construction is put into motion by waves which cause single construction components to move and drive the hydraulic motors which in turn drive electrical generators.

Fig. 6. Attentuators of *Pelamis* [16]

In Oregon, USA, *Ocean Power Technologies* has been constructing a wave park to transform wave energy to electricity. A single buoy is 45 m long, 12 m wide and weighs 200 t. Inside the buoy there is a generator. Electricity is transmitted to the shore by sub-marine power transmission cables (Fig. 7).

Fig. 7. *Ocean Power Technologies* power generating buoy [17]

Fig. 8. Wave Power Plant *Wave Star*, Hanstholm, Denmark [18]

Another solution is applied by Danish *Wave Star Energy*. Their device converts wave kinetic energy into oscillating motion of arms attached to the floats pumping hydraulic oil into actuators which then drive a hydraulic motor coupled with the generator (Fig. 8).

The prototype plant can supply from 500 kW to 1.1 MW of energy, amount equal to one wind power plant. It has been installed at a pier in Hanstholm, Denmark. Its operation is monitored and provides a lot of data on the power plant [19].

Research of the Maritime University of Szczecin on the use of wave energy

The use of wave energy has been studied at the Maritime University of Szczecin. One of the subjects is using wave energy to protect the seashore against hazardous effects of extreme waves.

Commonly used methods of shielding coastline against swells or extreme waves are breakwaters, dams and ferro-concrete, concrete or stone walls. Their main disadvantage is changing shores and affecting their recreational value. They are also environmentally unfriendly and expensive to keep.

The need to improve technologies of coast protection against waves is justified because lately we have observed longer duration, greater intensity and frequency of storms. High and steep cliffs, ca. 50 m in Poland, are particularly vulnerable to them.

As a result of studies at the Maritime University of Szczecin there appeared a concept of suppressing sea power with its own energy. An active technology of shore protection has been proposed which is different from passive methods used so far.

This active technology consists in wave damping before it reaches the shore [20]. In other words, it is a breakwater installed and submerged in the distance between several and several hundred meters off the coast.

The submarine breakwater consists of vertically installed polyethylene pipes closed from both sides mutually joint by rigid clamps. The breakwater weight is less than the displaced water quantity, it stays submerged and is stabilised by ropes moored to the sea floor. A modular breakwater construction is based on the principle of an equilateral triangle where the length of the triangle side determines the distance between the pipes which varies from one to several meters.

Wave induced forces compensate owing to their interaction with breakwater components whose distance to each other is equal to half of the wave length in the direction of wave propagation. Simultaneously, with forces compensation wave energy dissipates and wave height decreases. The breakwater effectiveness increases when additional components with improved damping properties are installed.

The construction of the active, submarine breakwater was built under the patent [21]. The breakwater prototype was developed under research project 03 0028 04 “A new method of seashore protection against the waves” funded by the National Research Centre which was implemented at the Maritime University of Szczecin between 2008 and 2010 [22].

Experimental research on wave damping was conducted in a pilot plant (half-scale plant) in a towing tank of the Ship Hydromechanics Division, Ship Design and Research Center SA, Gdańsk, Poland (Fig. 9). The results confirmed the worked out construction of the submarine breakwater and allow for further research in open sea conditions.

The proposed active technology of the coastline protection against erosion resulting from storm waves is environmentally friendly, does not affect the nature of the coast, reduces its running costs and its construction still enables to promote the attractiveness of the coastline for recreational and tourist purposes.

Fig. 9. Testing the submarine breakwater prototype in the towing tank of the Ship Hydromechanics Division, Ship Design and Research Center SA, Gdańsk, Poland [22]

There has also been a study at the Maritime University of Szczecin on wave energy conversion into electricity. This task is very complicated though and has its difficulties caused by:

– complex wave propagation process,
– continuous, cyclical change in wave direction in every vertical cross-section parallel to the direction of wave propagation.

The study result is a simple construction of a wave energy converter which has a patent pending [15]. The subject matter of the invention is the method of transforming wave energy to electricity. It consists in installing a generating set composed of a generator and an engine with a gear box at a distance from the shore, beneath the surface of sea rippled by waves, on a platform moored to the sea floor. Energy for the generator propulsion is acquired directly from the oscillating water by means of a driving unit installed on the engine shaft.

To increase the power and decrease the fluctuation of engine torque, a bigger number of identical prime movers is installed. They are located alongside and arranged angularly around the impeller. The impeller axis is located in a horizontal plane, perpendicularly to the direction of wave propagation. On the contrary to other commonly developed kinds of energy converters, the proposed submarine generator is much simpler and what follows less expensive and more efficient because intermediate hydraulic, pneumatic, mechatronic or electromagnetic systems are not applied (they are used in currently operating wave power plants). Building a prototype of the submarine generator is a subject matter of a few submitted projects and proposals under development.

Conclusions

Wave power plants generate electricity without air pollution and greenhouse gases. Despite wave energy conversion technologies being currently developed, few of them have been tested in open sea conditions. Therefore, their full environmental impacts remain uncertain (information officially announced by their producers) [23, 24]. The impacts are expected to be environmentally benign and will not affect existing currents or tides. The biggest concerns include impacts on marine ecosystems, local habitats and fisheries. These threats, however, depend on a siting and thus should be considered individually.

A wave power plant of the future requires construction optimisation by means of building and testing prototypes in open sea conditions. For any solution, however, detailed industrial research is necessary in order to:

– select construction parameters (dimensions and weight) and materials,
– determine the device energetic characteristics depending on wave propagation conditions,
– determine the device characteristics depending on the working mode (engine components configuration),
– estimate efficiency / cost effectiveness of the construction during operation,
– assess environmental impacts.

The infrastructure of such a power plant is a real challenge, in particular the necessity to solve problems referring to reliable, safe and cost effective operation of these systems [25] i.e.:

– power plant siting (energy transmission, aesthetics, navigational safety, administrative issues),
– its economic effectiveness,
– heavy duty,
– steady state of the generator,
– wave characteristic variation (wave height and length variation).

Today, the economic effectiveness of a wave power plant is rather a scientific theory than market practice. What is significant, previous implementations have been operating in few, selected geographical zones. A variety of existing technical solutions opens up opportunities for wave power plant development conditioned by progress in many scientific areas.

The wave power target consumers are sea resorts, shipyards, ports, marinas, islanders, drilling rigs, oil platforms, oil storage, production and offloading systems, as well as manufacturers of inland and sea navigation devices requiring electric power supply what is troublesome to do from established sources due to the distance to an existing infrastructure (which must be available 24 hours a day) and its high operational costs. Radio beacons, navigation lights, relay systems and buoys are meant here among others.

The potential market for electricity from wave energy is the same as for wind energy (offshore and onshore) and it is growing. Governments of developed countries which recognised significant opportunities coming from wave energy, have put their specific market support. The "green energy" conversion appears to be competitive and economic benefits will follow. The benefits must be calculated taking into account external costs. What is significant, for these kinds of projects requiring large investments there is returns to scale and a long payback period.

The authors are of the opinion that in the future the power of seas and oceans will become one of the strategic energy sources for the mankind but the way there is very long.

Disclaimer

Acknowledgments

The publication is financed through research grant 4/S/ITESO/14: "Diagnostics methods and efficient operation of complex technical systems in terms of failure prevention and environmental protection".

References

1. LEIJON M. et al.: An electrical approach to wave energy conversion. Renewable Energy 31 (2006) 1309–1319.
2. Poland 2030. Third wave of modernity. Long-term Strategy of Country Development, Ministry of Administration and Digitization Warszawa, 11.01.2013 (in Polish).
3. Energia z fal morskich, http://morzaioceany.pl/inne/archiwum/1311-energia-z-fal-morskich.html, access: 02.01.2015.
4. Wave energy global resource, http://www.pelamiswave.com/global-resource, access: 02.01.2015.
5. Ecotricity Britain's leading green energy supplier, https://www.ecotricity.co.uk/our-green-energy/our-green-electricity/and-the-sea/seamills, access: 02.11.2015.
6. WALLACE J.: Winds, waves & tides alternative energy systems. University of Toronto. Coursera Training Course Materials, Torronto 2014.
7. HENFRIDSSON U. et al.: Wave energy potential in the Baltic Sea and the Danish part of the North Sea, with reflections on the Skagerrak. Renewable Energy 32 (2007) 2069–2084.
8. Eurostat, Renewable energy statistics, http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Renewable_energy_statistics, access: 17.08.2014.
9. Development Strategy of Renewable Energy Production, Ministry of Environment, Warszawa 23.08.2001 (in Polish).
10. Energy policy for Poland by 2030, Ministry of Economy, Warszawa 10.11.2009 (in Polish).
11. Power Engineering Programme, Ministry of Economy, Warszawa 27.03.2006 (in Polish).
12. CLÉMENT A. et al.: Wave energy in Europe: current status and perspectives. Renewable and Sustainable Energy Reviews 6 (2002) 405–431.
13. BERNHOFF H., SJÖSTEDT E., LEIJON M.: Wave energy resources in sheltered sea areas: A case study of the Baltic Sea. Renewable Energy 31 (2006) 2164–2170.
14. BERNHOFF H., SJöSTEDT, LEIJON M.: Wave energy resources in sheltered sea areas: A case study of the Baltic Sea, Vth European Conference Energy From Waves, 17–20.09.03, Cork, Irlandia.
15. An underwater generating unit and a method of underwater installation of a generating unit under the sea surface. Inventor: Bolesław Kuźniewski, owner: Maritime University of Szczecin, patent application UP RP P406628 (filing date 20 Dec 2013).
16. Pelamis Wave Power powers up in North Portugal, http://ecogeneration.com.au/news/pelamis_wave_power_powers_up_in_north_portugal/042829/, access: 02.01.2015.
17. Ocean Power Technologies, http://phx.corporate-ir.net/phoenix.zhtml?c=155437&p=irol-IRHome, access: 02.01.2015.
18. Wavestar concept, http://wavestarenergy.com/concept/, access: 02.01.2015.
19. Renewable energy in 2012, Statistical analysis and data (in Polish), GUS Warszawa 2013.
20. KUŹNIEWSKI B., GRZĄDZIEL Z.: Computer simulation and experimental verification of loads acting on the components of wave damping device. MES Simulation 2010 Conference, Podklasztorze 2010, CD proceedings (in Polish).
21. A method of shore protection against sea waves and a unit damping the energy of sea waves. Inventor: Bolesław Kuźniewski, owner: Maritime University of Szczecin,

patent 210447 (filing date 23 March 2007, publication date 29 Sept 2008, in Polish).
22. A new method of seashore protection against waves. Project report 03002804 for the National Research Centre, Maritime University of Szczecin, Szczecin 2010 (in Polish).
23. Pelamis Wave Power – Environmental Impact, http://www.pelamiswave.com/environmental-impact, access: 02.01.2015.
24. Wave & Tidal Energy Technology http://www.rnp.org/node/wave-tidal-energy-technology, access: 02.01.2015.
25. CHYBOWSKI L.: Components Importance Analysis in Complex Technical Systems. ITE-PIB Radom 2014 (in Polish).

Others

26. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 27.03.2013.
27. Energia z fal morskich – jak można ją wykorzystać? http://fale.ekologicznie.com.pl/, access: 02.01.2015.