# Electricity from Wave and Tide

## An Introduction to Marine Energy

Paul A. Lynn

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***Paul A. Lynn,* BSc (Eng), PhD**

*formerly*

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WILEY

This edition first published 2014


*Registered office*
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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*Library of Congress Cataloging-in-Publication Data*

Lynn, Paul A.
Electricity from wave and tide : an introduction to marine energy / Paul A. Lynn.
pages cm
Includes bibliographical references and index.
ISBN 978-1-118-34091-2 (hardback)
1. Tidal power-plants. 2. Ocean wave power. 3. Tidal power. I. Title.
TK1081.L95 2014
621.31′2134–dc23
2013019102

A catalogue record for this book is available from the British Library.

ISBN: 9781118340912

Typeset in 10/12pt Times New Roman by Laserwords Private Limited, Chennai, India

1 2014

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# Preface

The world's waves and tides are eternal and non-polluting, and the technology for converting their energy into grid electricity has reached an exciting stage. Many ingenious large-scale devices are currently being tested by developers as a prelude to commercialisation, in the confident hope that marine renewable energy will add significantly to conventional power generation in the coming decades.

This book introduces the history, theoretical background and practical development of today's wave and tidal stream devices to a wide readership including professionals, policy makers and employees in the energy sector needing an introduction or quick update. Its style and level also make it suitable background reading for university students and the growing number of thoughtful people who are interested in the contribution marine energy can make to 'keeping the lights on' in the twenty-first century. This is probably the first book to introduce wave and tidal stream technologies in a single volume and, although it assumes some basic familiarity with physics and maths, words are used every bit as much as symbols to give a descriptive flavour, enhanced by about 200 colour photographs and illustrations.

In more detail, Chapter 1 covers the historical background and Chapter 2 some of the key concepts underpinning today's practical developments. I have decided to devote Chapter 3 to electricity generation, for readers with little or no background in electrical engineering. Large-scale wave and tidal energy converters feed electricity into AC grid networks for the benefit of us all; yet electrical generation, grid connection and distribution are hardly ever explained in the context of marine energy and their terminology is mysterious to many people. I hope the account given here, which is very similar to that in my recent book on wind energy (also published by Wiley), will prove helpful.

Chapters 4 and 5 present case studies of modern wave and tidal stream devices, selected for their advanced state of development, including the testing of full-scale, or near full-scale, prototypes in sea conditions. I have relied heavily on the various developers for information about their devices, many of which have been, or are being, assessed at the internationally famous European Marine Energy Centre (EMEC) in Orkney, Scotland.

My interest in renewable energy goes back over 30 years, but I no longer have links with academia or industry and the selection and presentation of topics is my own. I claim no originality for the technical material, which has been gathered, sifted, and sorted from many websites, books, technical papers and articles. I see my role as hunter-gatherer, not master chef, and hope the menu will help advertise the remarkable developments currently taking place in the international quest for 'Electricity from Wave and Tide'.

*Paul A. Lynn*
*Butcombe, Bristol, England*
*Summer 2013*

# Acknowledgements

I am very grateful to the following companies and organisations for information about their activities and devices, and for permission to use the excellent colour photographs and illustrations they have provided:

- Andritz Hydro Hammerfest, Hammerfest, Norway: Figures 5.1 and 5.2.
- Aquamarine Power Ltd, Edinburgh, Scotland: Figures 1.1, 2.15c, 4.6–4.12.
- Atlantis Resources Corporation, London, England: Figures 1.2, 2.33b, 2.38, 5.6–5.8.
- Datawell BV, Haarlem, The Netherlands: Figure 2.14.
- European Marine Energy Centre (EMEC), Orkney, Scotland: Figures 1.4, 2.43–2.45, 2.47–2.54.
- Marine Current Turbines Ltd, Bristol, England: Figures 2.33a, 5.9–5.13.
- Ocean Power Technologies Inc, New Jersey, USA: Figures 2.15b, 4.21, 4.23, 4.24.
- OpenHydro Ltd, Dublin, Ireland: Figures 5.14–5.19.
- Pelamis Wave Power Ltd, Edinburgh, Scotland: Figures 2.15a, 4.1–4.5.
- Pulse Tidal Ltd, Sheffield, England: Figures 5.20–5.25.
- Scotrenewables Tidal Power Ltd, Orkney, Scotland: Figures 2.41, 5.26–5.33.
- Tidal Generation Ltd, Bristol, England: Figures 2.33c, 5.34–5.37.

- Voith Hydro Ocean Current Technologies GmbH, Heidenheim, Germany: Figure 1.19.
- Voith Hydro Wavegen Ltd, Inverness, Scotland: Figures 2.15d, 4.13, 4.15, 4.16.
- Wave Dragon ApS, Copenhagen, Denmark: Figures 2.15e, 4.17–4.20.
- Wello Oy, Espoo, Finland: Figures 4.25–4.29.

The publishers acknowledge use of the above photographs and illustrations, which are reproduced by permission of the copyright holders.

I also acknowledge the following photos and illustrations obtained from Wikipedia: Figures 1.16–1.18, 2.21, 2.23, 2.24, 2.26–2.28, 2.35, 3.3.

The writer of an introductory book covering a wide field inevitably draws on many sources for information and inspiration. I make no claims for technical originality in the material presented and have tried to give an adequate list of references at the end of each chapter.

I would particularly like to thank staff at EMEC in Orkney for their enthusiastic cooperation and advice. I am also indebted to two books that have proved invaluable for clear explanations of difficult concepts which I have attempted to summarise. They are: *Ocean Wave Energy: Current Status and Future Perspectives* by Joao Cruz (editor), published by Springer in 2008; and *The Analysis of Tidal Stream Power* by Jack Hardisty, published by Wiley-Blackwell in 2009. Both are more comprehensive and advanced than my own offering, and I recommend them to anyone wishing to learn more about marine renewable energy.

Among the many figures in this book are 70 technical illustrations by David Thompson, who worked closely with me on two previous books, *Electricity from Sunlight* (Wiley, 2010), and *Onshore and Offshore Wind Energy* (Wiley, 2012). It has been a pleasure to repeat the collaboration.

*Paul A. Lynn*

1

# 1 Introduction

## 1.1 Marine energy and Planet Earth

For over a century most of the electricity used in our homes, offices and factories has been generated in large power plants based on fossil fuels and, in some countries, nuclear reactors and hydroelectric turbines. But as the new millennium gets into its stride important changes are taking place in the how, where and why of electricity generation due to increasing concerns about climate change, fossil fuel depletion and the risks of nuclear power. Terms such as *renewable*, *sustainable* and *carbon-free* have entered the popular imagination and most experts and politicians now accept that a major redirection of energy policy is essential if Planet Earth is to survive the twenty-first century in reasonable shape.

For the last few hundred years humans have been using up fossil fuels that nature took around 400 million years to form and store underground. A huge effort is now under way to develop energy systems that make use of natural energy flows in the environment – including those produced by waves and tidal streams. This is not simply a matter of fuel reserves, for it is becoming clearer by the day that, even if those reserves were unlimited, we could not continue to burn them with impunity. Today's scientific consensus assures us that the resulting carbon dioxide emissions would very likely lead to a major environmental crisis. So the danger is now seen as a double-edged sword: on the one side, fossil fuel depletion; on the other, the increasing inability of the natural world to absorb emissions caused by the burning of what fuel remains, leading to accelerated global warming.

*Electricity from Wave and Tide: An Introduction to Marine Energy*, First Edition. Paul A. Lynn.

Things were not always like this. Back in the 1970s there was little public discussion about energy sources and engineering courses in universities paid little attention to them. The environmental movement was in its infancy, far removed from the mainstream political agenda, and its proponents were often dismissed as eccentric busybodies. Few people had any idea how the electricity they took for granted was produced, or that the burning of coal, oil and gas might be building up global environmental problems. Those who were aware tended to assume that the advent of nuclear power would prove a panacea, a few even claiming that nuclear electricity would be so cheap that it would not be worth metering!

Yet even in those years a few brave voices suggested that all was not well. In his famous book *Small is Beautiful* [1], first published in 1973, E.F. Schumacher poured scorn on the idea that the problems of production in the industrialised world had been solved. Modern society, he claimed, does not experience itself as part of nature, but as an outside force seeking to dominate and conquer it. And it is the illusion of unlimited powers deriving from the undoubted successes of much of modern technology that is the root cause of our present difficulties, in particular because we are failing to distinguish between capital and income components of the earth's resources. We use up capital, including coal, oil and gas reserves, as if they were steady and sustainable income, but they are actually once-and-only capital. Schumacher's heartfelt plea encouraged us to start basing industrial and energy policy on what we now call sustainability, recognising the distinction between capital and income and the paramount need to respect the planet's finite ability to absorb the polluting products of industrial processes – including electricity production.

Schumacher's message, once ignored or derided by the majority, is now seen as mainstream. For the good of Planet Earth and future generations we have started to distinguish between capital and income and to invest heavily in renewable technologies that produce electricity free of carbon emissions. In recent years the message has been powerfully reinforced by former US Vice President Al Gore, whose inspirational lecture tours and video presentation *An Inconvenient Truth* [2] have been watched by many millions of people around the world.

Into this melting pot of hopes and concerns fall a number of promising renewable technologies based on the immense natural energy flows in Planet Earth's environment. These include winds and the ocean waves they produce (see Figure 1.1), tides and tidal streams (see Figure 1.2), and sunlight falling on the Earth's surface. All are eternal and inexhaustible; nothing is 'wasted' if we ignore them because they are there anyway. They are income, not capital, and we should surely regard them as precious gifts of nature to be harnessed in ways that are technically efficient, economic and environmentally

**Figure 1.1** Harnessing wave energy (Aquamarine Power Ltd).

sensitive. All this represents a hugely challenging and inspiring agenda for engineers and scientists – now and for the rest of the century.

Perhaps we should consider the meaning of renewable energy a little more carefully. It implies energy that is sustainable in the sense of being available in the long term without significantly depleting the Earth's capital resources, or causing environmental damage that cannot readily be repaired by nature itself. In his excellent book *A Solar Manifesto* [3], German politician Hermann Scheer considered Planet Earth in its totality as an energy conversion system. He noted how, in its early stages, human society was itself the most efficient energy converter, using food to produce muscle power and later enhancing this with simple mechanical tools. Subsequent stages – releasing relatively large amounts of energy by burning wood; focussing energy where it was needed by building sailing ships for transport and windmills to grind grain and pump water – were still essentially renewable activities in the above sense.

What really changed things was the nineteenth century development of the steam engine for factory production and steam navigation. Here, almost at a stroke, the heat energy locked in coal was converted into powerful and highly concentrated motion. The industrial society was born and ever since we have continued burning coal, oil and gas in ways which pay no attention to the natural rhythms of the earth and its ability to absorb wastes and by-products, or to keep providing energy capital. Our approach has become the opposite of renewable and it is high time to change priorities.

**Figure 1.2** Transporting a tidal stream turbine (Atlantis Resources; Mike Roper (photographer)).

Since the reduction of carbon emissions is a principal advantage of wave, tidal and other renewable technologies, we should recognise that this benefit is also proclaimed by supporters of nuclear power. But frankly they make strange bedfellows, in spite of sometimes being lumped together as ‘carbon-free’. It is true that all offer electricity generation without substantial carbon emissions, but in almost every other respect they are poles apart. The renewables, including wave and tidal stream energy, give us the option of widespread, relatively small-scale electricity generation, but nuclear must, by its very nature, continue the practice of building huge centralised power stations. Waves and tides give us ‘free fuel’ and produce no waste in operation; the nuclear industry is beset by problems of radioactive waste disposal. On the whole renewable technologies pose no serious problems of safety or susceptibility to terrorist attack – advantages which nuclear power can hardly claim. Finally, there is the issue of nuclear proliferation and the difficulty of isolating civil nuclear power from nuclear weapons production. Taken together these factors amount to a profound divergence of technological expertise and political attitudes, even of philosophy. It is not surprising that most environmentalists are unhappy with the continued development and spread of nuclear power, even though some accept that it is proving hard to avoid. In part, of course, they claim that this is the result of policy failures to invest sufficiently in the benign alternatives over the past 30 or 40 years.

However, we must be careful not to assume that renewable energy is an easy answer. For a start it is generally diffuse and intermittent. Quite often, it is unpredictable. The design and manufacture of efficient machines to harness natural energy flows pose big technical problems, and although the 'fuel' may be free and the waste products minimal, up-front investment costs tend to be large. There are certainly major challenges to be faced and overcome as we develop a new energy mix for the twenty-first century.

Our story now moves on to modern wave and tidal stream technology, currently enjoying rapid progress and poised to make a significant contribution to electricity generation in the coming decades. But before getting involved in the details, we should consider the natural resources that promise to help wean us away from our addiction to fossil fuels.

## 1.2 Marine resources

### 1.2.1 Waves of the world

Surface waves on the world's oceans are generated by the wind. They are not formed instantly but build up over time and with distance, known as the *fetch*. Waves produced by a storm, arriving from afar over deep water, produce a regular *swell* which may take hours or days to form and travel hundreds or even thousands of kilometres across an ocean with very little loss of energy (see Figure 1.3). But as waves approach the shore and move

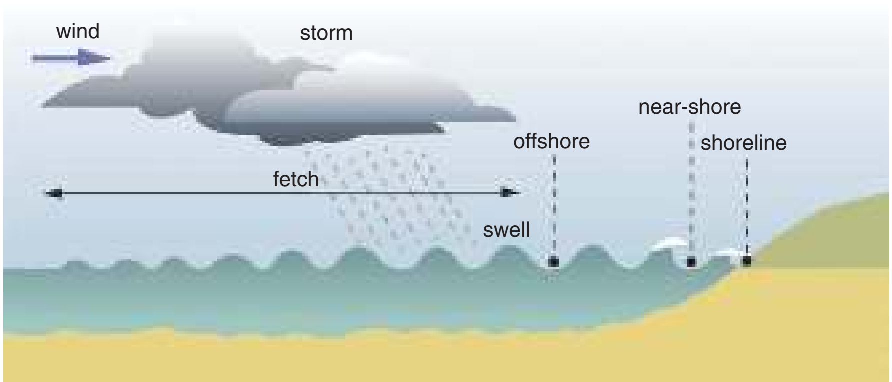


**Figure 1.3** Wind-generated ocean waves.


**Figure 1.4** Waves approaching a shoreline (EMEC).

into shallow water, they slow down, increase in height and start to break, dissipating lots of energy (see Figure 1.4). Wave characteristics close to shore can be very different from those of a regular, deep-water, swell.

From the engineer's point of view wind-generated waves represent a valuable source of renewable energy for generating electricity using *wave energy converters* [4, 5]. The design of effective machines depends on how far they are to be placed from the shore: *offshore*, in deep water; *near-shore*, anchored or fixed to the sea bed; or installed on land at the *shoreline* (see Figure 1.3). The great oceans cover about 70% of the world's surface and the total wave resource is huge; but it is diffuse, variable, somewhat unpredictable, and occasionally destructive. The engineering challenge is to develop robust machines that capture wave energy efficiently and reliably, not too far from land, while at the same time surviving the worst that angry seas can throw at them.

The global wave resource, expressed as an equivalent amount of electrical power, is around 2 terawatts (TW), or 2 million million watts. This is equivalent to the output of 2000 large conventional electricity plants, each generating 1 gigawatt (GW), and is comparable with global electricity production. However, wave resources are distributed very unevenly across the world's oceans and countries with strong prevailing winds and exposed coastlines are the most favoured. A good example is the UK's coastal waters which receive, on average, wave power roughly equivalent to the nation's electricity demand. Although the exploitable resource in terms of practicality and economics is only a small percentage of the total, there is no doubt that ocean waves could make a significant contribution to an energy mix based increasingly on renewables.

Why do some maritime nations receive much more wave energy than others? The answer to this question is closely related to the world's major wind patterns, set up as the earth spins on its axis. Variations in atmospheric pressure caused by differential solar heating propel air from high pressure to low pressure regions, generating winds that are greatly affected by the earth's rotation and tend to occupy certain latitudes.

The investigation of *latitudinal wind belts* has a long history. For centuries the captains of sailing ships depended on reliable north-east and south-east *trade winds* to speed them on their way, and tried to avoid the *horse latitudes* that could becalm them. They also had to contend with strong but variable *westerlies* that blow in the mid-latitudes between about 40° and 60°, north and south (see Figure 1.5). It is hardly surprising that wind meteorology exercised some famous minds throughout the great age of sail. Edmond Halley (1656–1742), an English astronomer best known for computing the orbit of *Halley's comet*, published his ideas on the formation of trade winds in 1686, following an astronomical expedition to the island of St Helena in the South Atlantic. The atmospheric mechanism proposed by George Hadley (1685–1768), a lawyer who dabbled productively in meteorology, attempted to include the effects of the Earth's rotation – a theory that was

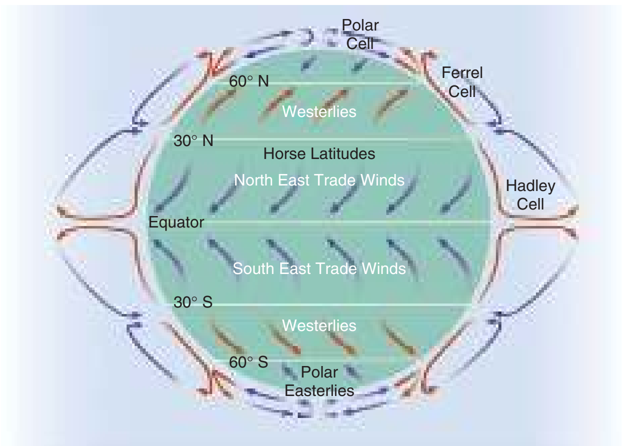


**Figure 1.5** Atmospheric cells and latitudinal wind belts.

subsequently corrected and refined by American meteorologist William Ferrel (1817–1891).

The contributions of Hadley and Ferrel to our understanding of latitudinal wind belts, and the waves they generate, are acknowledged in the names given to the atmospheric 'cells' shown in Figure 1.5. Essentially these are produced by the steady reduction in solar radiation from the equator to the poles. The associated winds, rather than flowing northwards or southwards as we might expect, deflect to the east or west in line with the *Coriolis effect*, named after French engineer Gaspard Coriolis (1792–1843), who showed that a mass (in this case, of air) moving in a rotating system (the Earth) experiences a force acting perpendicular to both the direction of motion and the axis of rotation.

The *Hadley cells*, closed loops of air circulation, begin near the equator as warm air is lifted and carried towards the poles. At around 30° latitude, north and south, they descend as cool air and return to complete the loop, producing the *north-east* and *south-east trade winds*. A similar mechanism produces *polar cells* in the arctic and antarctic regions, giving rise to *polar easterlies*.

The *Ferrel cells* of the mid-latitudes, sandwiched between the Hadley and polar cells, are less well defined and far less stable. Meandering high-level *jet streams* tend to form at their boundaries with the Hadley cells, generating localised passing weather systems. This makes the coastal wind patterns – and ocean climates – of countries such as Norway, Denmark, Britain and Ireland strong but famously variable. So although the prevailing winds are *westerlies*, they are quite often displaced by flows from other points of the compass, especially during the winter and spring months.

We can now summarise the significance of latitudinal wind belts for wave energy technology:

- The strong but variable *westerlies* that dominate global wind patterns between latitudes of about 40° and 60° (north and south) produce most of the world's exploitable wave energy. In the southern hemisphere they are famously referred to as the *Roaring Forties*. Countries with west-facing coastlines are especially favoured.
- *Trade winds* blowing between about 10° and 30° (north and south) may also be significant for wave energy conversion. Although less energetic on average than the westerlies, they are more consistent.
- *Polar easterlies* are much less important because the swells they produce tend to be relatively small (and may be hampered by sea ice).


**Figure 1.6** Coastlines with large wave energy resources.

The dominance of wave energy produced by prevailing westerly winds is emphasised in Figure 1.6, which shows coastlines that receive heavy swells generated over long fetches of ocean. Not surprisingly, they lie in countries presently showing great interest in wave energy, principally:

- **In Europe:** UK, Norway, Denmark, Ireland, France, Spain and Portugal.
- **In North America:** USA and Canada.
- **In the Southern Hemisphere:** Australia, New Zealand, Chile and South Africa.

We now come to a very important question: how much power do ocean waves possess as they travel across an ocean and approach a coastline? The first point to make is that it depends on the distance from the shoreline. Wave power is greatest well offshore in deep water but, as the waves move into shallower water, friction with the sea bed and their tendency to break cause energy losses. The usual way of expressing power levels is in terms of average kilowatts per metre length of wave front ($kW\,m^{-1}$). Figure 1.7 shows typical values well off the coastlines of Western Europe favoured with some of the world's best wave resources. We see that, for example, the average power of waves approaching the west coast of Portugal is around 50–60 $kW\,m^{-1}$; off the west coast of Scotland, one of the most productive areas in the world, around 70 $kW\,m^{-1}$; and along the coast of Norway, around 50 $kW\,m^{-1}$ and diminishing steadily towards the Arctic Circle.

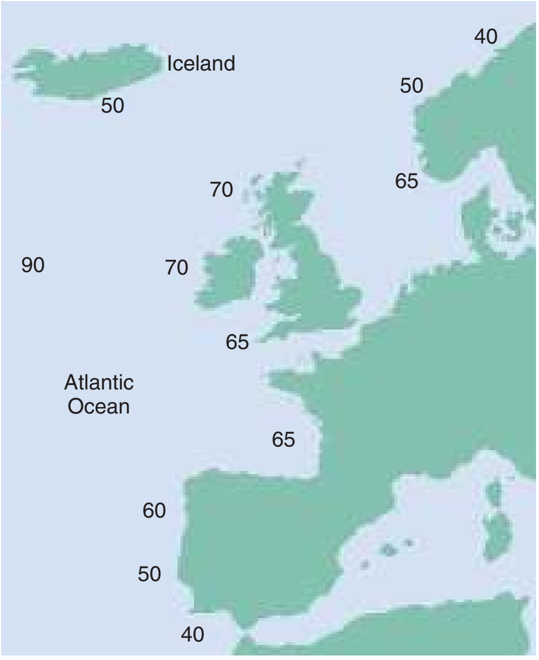


**Figure 1.7** Average values of wave power off the coasts of Western Europe, expressed in kilowatts per metre of wave front.

Out in the Atlantic ocean it can reach 90 kW $m^{-1}$. Elsewhere in the world such values are only matched along certain coastlines in Australia, New Zealand and Chile, especially those facing the *Roaring Forties* that blow unhindered from west to east across the Southern Ocean at latitudes around 40°S (see Figure 1.6). It is hardly surprising that the most powerful wave climate in the world, averaging some 140 kW $m^{-1}$, is found at latitude 48°S in the Southern Ocean – but so far from civilisation that it is extremely unlikely ever to be harnessed!

Such values are certainly impressive. It is sometimes said that 25 kW $m^{-1}$ is enough to interest wave energy enthusiasts, but the 50–70 kW $m^{-1}$ found off the coastlines of Western Europe is clearly a great deal better and represents a *power concentration* rarely found in natural energy flows. For example, it is far greater than that of the airstreams harnessed by wind turbines. Essentially this is because wave power is built up and concentrated gradually over long stretches of ocean; and because seawater is far denser than air – a point we will return to in the next chapter.

However, power concentration is not the only criterion of interest to designers of wave energy converters. It is certainly important because the