Wave and Tidal Energy
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Edited by

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Since the 1990s the importance of developing renewable energies has been well recognised worldwide. At the time of writing, onshore wind, solar and hydropower are mature and making relevant contributions to the energy mix. However, the untapped potential of these land-based forms of renewable energy is not unlimited; therefore, new renewable energies, including wave, tidal and offshore wind, must be developed if carbon-based energy production is to be further reduced, in the spirit of the recent Treaty of Paris and previous agreements on climate change.

Offshore wind is technologically more mature than wave and tidal energy, arguably thanks to its similarities with its onshore counterpart. Indeed, as offshore wind moves into deeper waters, those facets that are not shared with onshore wind turbines, such as floating systems or hybrid (wave–wind or tidal–wind) systems warrant the greatest research effort at present.

Wave and tidal energy, the focus of this book, are technologically more challenging, not least because of the aggressive marine environment. Because of this, and the fact that their development began more recently, they are further away from full market commercialisation. Their trajectory has been similar to that of any nascent technology, with initial successes and failures.

Arguably the harsh marine environment has hindered the technological development of both wave and tidal energy, not least in relation to wind energy, the main elements of which were developed for a less aggressive environment. This also made possible the application of wind energy at different scales, from the domestic to the industrial, and its stepwise progression towards the large wind turbines that we see today. Nevertheless, the faster development of wind energy that we have witnessed does not detract in the least from the potential of wave and tidal energy. Given the intensive research efforts and the level of international interest in the field, there can be little doubt that the vast, so far untapped, wave and tidal resource in the ocean will be exploited within the next decades.

This new book aims to provide a reference text for students and practitioners in the wave and tidal energy industry. It presents a holistic view of the sector, the state of the art and the perspectives for future development. The main tools of physical and numerical modelling are explained, together with the technical aspects of device design and development, the environmental effects and the consent and legal processes. These are then illustrated with a series of case studies and a review of regional project developments.

Wave and tidal energy is a fascinating field with many exciting research challenges. Driven by the passion of the researchers and practitioners involved, the momentum in the sector is poised to transform wave and tidal energy from its present research and development status into a fully fledged renewable contributing substantially to the energy mix.

Foreword

Since the 1990s the importance of developing renewable energies has been well recognised worldwide. At the time of writing, onshore wind, solar and hydropower are mature and making relevant contributions to the energy mix. However, the untapped potential of these land-based forms of renewable energy is not unlimited; therefore, new renewable energies, including wave, tidal and offshore wind, must be developed if carbon-based energy production is to be further reduced, in the spirit of the recent Treaty of Paris and previous agreements on climate change.

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1

Introduction

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1.1 Background

More than 83\% of the energy conversion in the world is today based on fossil fuels; meanwhile scientists all over the world are debating the topic of peak oil \cite{1} and the secondary effects of the emissions from the fossil fuels \cite{2, 3}. Fossil fuels are a finite resource; burning them generates significant carbon dioxide emissions that are changing the world’s climate. The impact of climate change is thought to be changing habitats at a rate faster than many species can adapt, and the level of pollution in many of the world’s cities is today causing concern. As a future worldwide shortage of useful energy supply can have devastating consequences on the political stability and economy of the world, there is a growing consensus that the world needs to switch to a more sustainable energy system. The focus and requirement for clean and cheap renewable energy conversion techniques has therefore increased.

The Paris Summit of 2015 \cite{4} has driven further impetus for finding alternative sources of energy, and a deal was agreed to attempt to limit the rise in global temperatures to less than 2°C. The Paris agreement is the first to commit all countries to cut carbon emissions, and is partly legally binding and partly voluntary. The measures in the agreement include \cite{5}: to peak greenhouse gas emissions as soon as possible and achieve a balance between sources and sinks of greenhouse gases in the second half of this century; to keep global temperature increase ‘well below’ 2°C (3.6°F) and to pursue efforts to limit it to 1.5°C; to review progress every 5 years; and $100 billion a year in climate finance for developing countries by 2020, with a commitment to further finance in the future. There is clear acknowledgement of climate change and also a clearly stated will to address the anthropogenic causes of climate change and to reduce emissions and seek alternative sustainable and environmentally benign sources of energy. How this new agreement will be implemented within individual countries will be influenced by local factors.

Renewable sources of energy are essential alternatives to fossil fuels and to nuclear energy, which also has a finite resource as well as long-term safety concerns. Renewable energy sources include solar, wind, geothermal and marine renewable energy (MRE).
Their use reduces greenhouse gas emissions, diversifies energy supply and reduces dependence on unreliable and volatile fossil fuel markets. The world is moving on renewables, and they have become the cornerstone of any low-carbon economy today, not just in the future. The USA is targeting a 32% cut in power sector emissions by 2030, India plans 100 GW of solar by 2022, and China is investing heavily in wind and renewable energy: the transition to a low-carbon energy system is well under way.

Within this drive for renewable energy, MRE is poised to play a major role [6], in particular in certain countries where these resources are vast. Renewable energy from the sea is generated by the sun, wind and tides, and may be exploited through various technologies such as wave energy, tidal stream, tidal range, offshore wind energy and ocean thermal energy currents (OTEC). MRE, also often termed ‘ocean energy,’ has a major part to play in closing the world’s energy gap and lowering carbon emissions. Key global challenges that remain for MRE relate to technology, grid infrastructure, cost and investment, environmental impact, and marine governance. Of these technologies, offshore wind is mature and many commercial projects exist in shallow waters, although new offshore wind technology is needed to develop sites further offshore in deeper water. Technologically, the development of offshore wind in shallower water is a natural extension of onshore wind, and typical difficulties for onshore wind in gaining social acceptability and approval are often less problematic if turbines are located offshore. Also, the wind resource offshore is greater due to lack of obstructions to the wind flow. Offshore wind turbines are typically similar to those used onshore and consist of three blades rotating about a hub, and in shallower water the wind turbine structures are typically on piled foundations or fixed jackets. However, as development of wind farms moves further offshore and into deeper water, other solutions need to be sought involving floating structures and the costs increase significantly. Although offshore wind technology is rapidly being implemented, there remain many fascinating engineering problems to overcome. These include: offshore foundations and floating support structures; alternative turbine designs based on three-dimensional computational fluid dynamics; use of advanced materials for blades; ship manoeuvring for safe maintenance; and shared offshore platform applications (such as energy production, storage, and marine aquaculture).

Tidal power is approaching commercial maturity, and recent investments and commercial developments have been made. Tidal range projects exist, but there are concerns about the extent of the environmental impact they bring, and tidal lagoon technology is emerging as an attractive alternative. Tidal steam technologies have seen great advances in recent years. On the other hand, wave energy encompasses emerging technologies that are currently not economically competitive, but still attract engineering interest thanks to the significant resource in high power density sea waves and its potential exploitation [7].

Within Europe, ocean energy is considered to have the potential to be an important component of Europe’s renewable energy mix, as part of its longer-term energy strategy. According to the recent studies [8,9], the potential resource of wave and tidal energy is 337 GW of installed capacity by 2050 globally, with 36 GW quoted as the practically extractable wave and tidal resource by 2035 in the UK, representing a marine energy industry worth up to £6.1 billion per annum. Today 45% of wave energy companies and 50% of tidal energy companies from the EU [9,10] have been tested in EU test centres [11,12], and the global market is estimated to be worth up to €53 billion annually by 2050 [13].
The need to address climate change and concerns over security of supply has driven European policy-makers to develop and implement a European energy policy. In 2009, the European Commission set ambitious targets for all member states through a directive on the promotion of the use of energy from renewable sources (2009/28/EC). This requires the EU to reach a 20% share of energy from renewable sources by 2020. The directive required member states to submit national renewable energy action plans (NREAPs), that establish pathways for the development of renewable energy sources, to the Commission by June 2010. From their NREAPs, it is clear that many member states predict a significant proportion of their renewable energy mix to come from wave and tidal energy by 2020. This commitment should act as a strong driver at national level to progress the sector.

MRE can significantly contribute to a low-carbon future. Ambitious development targets have been established in the EU, including an installed capacity of 188 GW and 460 GW for ocean (wave and tidal) and offshore wind energy, respectively, by 2050 [10]. To comprehend how challenging these targets are it is sufficient to consider the corresponding targets for 2020: 3.6 GW and 40 GW for ocean and offshore wind energy, respectively. It is clear that for the 2050 targets to be met, a major breakthrough must happen – and there are huge benefits to be reaped if these targets are met, such as the reduction of our carbon footprint.

1.2 History of Wave and Tidal Energy

Although MRE and ocean energy can be interpreted to include all energy conversion technologies located in the ocean environment, including offshore wind, OTEC as well as wave and tidal, in this book we focus on wave and tidal energy. Tidal energy converts the energy obtained from tides into useful forms of power, mainly electricity. Tides are more predictable than wind energy and solar power. Among the sources of renewable energy, tidal power has traditionally suffered from relatively high cost and limited availability of sites with sufficiently high tidal ranges or flow velocities, thus constricting its total availability. However, significant learning has been gained through relatively long-term deployments of tidal turbines [14], and together with developments in tidal lagoon technology [15], and first array scale deployments [16], it is expected that the total availability of tidal power is significant, and that economic and environmental costs may be brought down to competitive levels.

Historically, tide mills [17] have been used both in Europe and on the Atlantic coast of North America for milling grain, and in the nineteenth century the use of hydropower to create electricity was introduced in the USA and Europe [18]. Tidal range projects include the world’s first large-scale tidal power plant, the La Rance Tidal Power Station in France, which became operational in 1966 [19]. It was the largest tidal power station in terms of power output, before Sihwa Lake Tidal Power Station in South Korea (described in Chapter 12) surpassed it. Many innovative tidal stream energy devices have been proposed. An example is Salter’s cross-flow turbine [20], which has blades arranged vertically, supported at each end on what are rather like enormous bicycle wheels. Although tidal power assessment seems easy, the very presence of tidal turbines alters the flow field, and in turn this affects power availability.

Tidal energy technology is dominated by in-sea/estuarine tidal stream devices; however, a significant number of developers have also been developing smaller in-river devices.
There is certainly potential for tidal energy to consolidate technologies and progress from small-scale to larger developments within the full-scale prototype field. The last few years to 2016 have seen the total number of globally active developers fall, perhaps as the technology naturally converges. Leading developers are actively testing at EMEC [21] and moving strongly towards commercial readiness and preparing for transition to large-scale commercial generation in the UK Crown Estate lease areas, north-west France and Canada’s Bay of Fundy. Alongside the progress to full-scale device deployment technology activity, there has been clear progress on site development, with the consent and finance secured for a 6 MW tidal array off the north of Scotland by MeyGen and the subsequent news of Atlantis Resources Ltd. having purchased the project. This is the first example of real value being attributed to a site and associated development consent [22].

The Severn Estuary holds the second highest tidal range in the world, and within this Swansea Bay benefits from an average tidal range during spring tides of 8.5 m. Plans to construct a tidal lagoon [15] to harness this natural resource would be the world’s first, man-made, energy-generating lagoon, with an expected 320 MW installed capacity and 14 hours of reliable generation every day. In a bid to overcome potential socio-economic and environmental concerns, the development also offers community and tourism opportunities in sports, recreation, education, arts and culture, conservation, restocking and biodiversity programmes as well as the added benefit of coastal flood protection.

Wave energy converter technology is a thriving area in which new inventions keep appearing. Here, engineers must find ways to maximise power output, improve efficiency, cut environmental impact, enhance material robustness and durability, reduce costs, and ensure survivability. Theoretical predictions of the power generated by wave energy converters require validation through laboratory-scale physical model studies and field tests. The latest simulation methods involve wave to wire modelling of arrays of wave energy converters, which integrates wave hydrodynamics, body responses, power take-off (PTO), real-time control, and electricity production.

There are more than one thousand patents for devices for capturing and transforming wave energy into useful energy. The first wave energy converter was patented in France in 1799, and oscillating water column navigation buoys have been commercialised in Japan since 1965 [6]. The oil crisis in 1973 raised interest in wave energy in Europe, but interest dwindled in 1980s and it was not until the 1990s that interest increased again.

Wave energy has the largest potential in Europe and worldwide, and can be captured in a number of ways through the use of different converters, such as point absorbers, attenuators, overtopping, oscillating wave surge convertors, and oscillating water columns. The technology has not yet reached the stage of commercial scale development [23], but progress continues to be made, as evidenced by the growing number of test sites and pilot zones being established across Europe [11]. Many different types of wave energy converters have been designed, but only a small proportion of these so far have reached the full-scale prototype stage. Wave energy has many advantages over other forms of renewable energy, being much more predictable than, for instance, wind, giving more scope for short-term planning of grid usage.

In the past, the wave energy industry faced some failures that delayed its development, for example the device in Toftestallen wrecked during a heavy storm [24] or the external wall of the Mutriku device that was damaged by a storm [25]. Attempting to set a framework for assessing the progress of potential developers on their way to
commercial applications, Weber [26] introduced the technology readiness level and technology performance level matrix, so that fewer failures occur in the future.

1.3 Unknowns and Challenges Remaining for Wave and Tidal Energy

Access to ocean energy systems is expensive and hazardous. Present and future challenges include remote monitoring, control systems, robotics for operational support, and real-time weather forecasting for predictive maintenance to ensure devices can survive in extreme sea states as they arise. Wave and tidal energy has huge potential, but demanding global challenges have to be met before the seascape will give up its precious energy resources. As in the Industrial Revolution, a new generation of engineers is required with the ingenuity, wisdom, and boldness to meet these interdisciplinary challenges. The unknowns and challenges still remaining in wave and tidal energy can be considered to fall within ten different technical research themes as identified by PRIMaRE [27]: materials and manufacture; fluid dynamics and hydrodynamics; survivability and reliability; environmental resources; devices and arrays; power conversion and control; infrastructure and grid connection; marine operations and maritime safety; socio-economic implications; and marine planning and governance.

1.3.1 Materials and Manufacture

The development of new materials and manufacturing processes is a key element in reducing costs and ensuring the survivability of MRE devices. Any technology submerged or in contact with the sea is likely to be affected by biofouling. The interaction of the devices or their components with marine growth is crucial as it affects the device performance and design conditions, and therefore the development of new materials to avoid or minimise biofouling is key. Use of steel or metallic alloys is common practice in the MRE industry. Correct understanding of the corrosion processes, of the use of new coatings and manufacture techniques, and of how to adapt the operation and maintenance inspections to maximise the lifetime and operability of MRE devices will help reduce their total cost. Application of novel materials and construction techniques that will reduce costs, improve reliability and extend the lifetime of devices is an active research area, necessary to move the sector forward – for example, novel materials such as reinforced concrete and composites, novel construction techniques, disposable materials are being investigated.

1.3.2 Fluid Dynamics and Hydrodynamics

As technology devices that harness energy from fluids in motion and are affected by the extreme forces produced by these motions, a proper understanding of the fluid dynamics and hydrodynamics of MRE devices is crucial to their development. In particular, turbulence and its effects on single and multiple devices is important in understanding how devices will interact and perform in arrays. In the real sea environment MRE devices commonly face the effects of combined waves, tidal currents and wind. The combined action of these forces on MRE devices makes characterisation of their
response at laboratory scale and with numerical models of special relevance to obtain a better understanding of how they perform under such circumstances. One of the particularities of MRE is that the devices need to face extreme loads and survive storms. Thus, the development of novel evaluation techniques to model these extreme loads appropriately at laboratory scale and by numerical models is required.

When deployed in real sea conditions, MRE devices are subjected to irregular waves and variable tidal currents. A feature of these variable resources is that the differences between maximum and mean values are particularly high, especially for wave energy. The standard engineering techniques to model the behaviour and response of MRE devices consider linear models in order to simplify the problems and obtain faster solutions. However, the reality is often far from the linear model and nonlinear effects must be considered to achieve a proper understanding of the performance of the devices in real conditions. Thus, the development of nonlinear models and tools to assess these effects is of special relevance. Advanced numerical models able to simulate accurately the response of full-scale devices require long computational times and resources. The development of validated tools and resources that optimise simulation times is necessary for the development of MRE.

1.3.3 Survivability and Reliability

The survivability and reliability of MRE devices in the marine environment need to be proven for the industry to become commercial. Ensuring the survivability of devices under the high loads occurring during extreme events is essential to reduce the risk of failure and increase their range of operability. The dynamic nature of many MRE devices means that traditional oil and gas or seakeeping mooring concepts are usually not valid, due to either their high cost or the different loading conditions. A competitive cost of energy which allows MRE to become viable in comparison with other renewable energies is fundamental for the development of the sector. This means that a compromise between reliability and cost of energy throughout the lifetime of the device should be found. The weakest of its components defines the entire reliability of a MRE device. This, together with the harshness of the marine environment, the frequent exposure to extreme loads, and near-constant exposure to varying cyclic loads, makes the design of all components crucial. Research is needed to assess each individual component and adapt it to the MRE industry needs, redesigning components where necessary and making use of available technology where possible, for example from the oil and gas sector. Furthermore, MRE devices are subject to potential impacts, for example, the impact of a marine mammal striking the rotor of a tidal turbine, or collision between wave energy converters due to a mooring failure, and these impacts could severely damage the integrity of the device.

1.3.4 Environmental Resources

Resource assessment for wave and tidal energy is described in Chapter 2, and a thorough understanding of the environmental resources is imperative to harnessing them in an economic and efficient manner. Even though wave, tidal currents and offshore winds are well understood at medium and large scales, there are still multiple physical processes related to them that require further study, especially when energy extraction