# Marine Renewable Energy

Zhaoqing Yang · Andrea Copping
Editors

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## Resource Characterization and Physical Effects

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*Editors*
Zhaoqing Yang
Marine Sciences Laboratory, Pacific Northwest National Laboratory
Seattle, WA
USA

Andrea Copping
Marine Sciences Laboratory, Pacific Northwest National Laboratory
Seattle, WA
USA

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# Preface

## Facing the Challenges of Resource Characterization and Physical System Effects of Marine Renewable Energy Development

Many nations have expanded their national energy portfolio to ameliorate the effects of climate change and to ensure the security and certainty of energy availability. These efforts have led to scrutiny of marine renewable energy (MRE) as one of several viable new renewable energy sources. In addition to the need to prove the reliability and efficiency of current and wave energy converters, effective siting and operation of MRE devices requires detailed and accurate characterization of the tidal stream, ocean current, and wave resource, as well as assessments of the potential risk to the physical marine environment from MRE development.

The desire to understand the many challenges to characterizing marine energy resources and the effects of energy extraction on physical systems motivated the compilation of the chapters in this book, which represent research and review efforts that address these two important topics. Chapters Wave Energy Assessments: Quantifying the Resource and Understanding the Uncertainty through Marine Hydrokinetic Energy in the Gulf Stream Off North Carolina: An Assessment Using Observations and Ocean Circulation Models address resource characterization of wave, tidal stream, and ocean current energy using laboratory experiments, field measurements, and numerical models. Chapters Effects of Tidal Stream Energy Extraction on Water Exchange and Transport Timescales through Planning and Management Frameworks for Renewable Ocean Energy cover topics related to the effects of energy extraction on physical systems, such as water exchange in coastal estuaries and bays, sediment transport, underwater noise, and marine spatial planning for MRE development.

In many parts of the world, harvesting wave energy seems very promising because of the very large potential resource located near many coastlines. Chapters Wave Energy Assessments: Quantifying the Resource and Understanding the Uncertainty through Analyses of Wave Scattering and Absorption Produced by WEC Arrays: Physical/Numerical Experiments and Model Assessment are devoted to techniques and methodologies for wave resource characterization. In Chap. Wave Energy Assessments: Quantifying the Resource and Understanding the Uncertainty, Robertson provides an overview of wave resource characterization and assessment using field measurements and numerical modeling approaches. The popular state-of-the-art, third-generation, phase-average spectral wave models that are suitable for wave resource characterization are reviewed by model framework, physical processes, computational requirements, and their applications to wave resource assessment at global, regional, and local scales. Techniques and methodologies for conducting baseline and high-fidelity resource assessments are presented, and the challenges of predicting extreme sea states and the uncertainty associated with wave resource characterization are discussed. The International Electrotechnical Commission (IEC) Technical Specification (TS) for wave resource characterization is also described in the chapter. The six parameters recommended by the IEC for characterizing wave energy resources are described—omnidirectional wave power, significant wave height, energy period, spectral width, direction of maximum directionally resolved wave power, and the directionality coefficient.

The Atlantic coast of Europe has some of the highest wave power resources in the world. In Chap. Wave Energy Resources Along the European Atlantic coast, Gleizon et al. present a joint effort by several European countries, including the UK, Portugal, France, Spain, and Ireland, to estimate the potential wave energy resource along the European Atlantic coast. Long-term hindcasts with high-resolution spectral wave models can greatly improve the accuracy of wave resource characterization and reduce the uncertainty associated with those estimates. A unique numerical modeling approach used in their study combines the regional-scale spectral wave model WaveWatch III (WWIII) for the continental shelf with high-resolution and the unstructured-grid Simulating WAves Nearshore (SWAN) model for the nearshore regions. Specifically, wave resource characterization was conducted based on 7-year high-resolution spectral wave hindcasts at five distinct coastal regions: Scotland (UK), Ireland, France, Galicia (Spain), and Portugal. Spatial and temporal variabilities in the wave climate are discussed. This study provides detailed information about the wave resource along the European Atlantic coast to help identify optimal areas for pilot-scale tests and commercial-scale development of wave energy converters (WECs).

While phase-averaged spectral wave models are commonly used in wave resource characterization, laboratory experiments and phase-resolving models enable the investigation of the dynamic interactions between WEC arrays and wave fields. In Chap. Analyses of Wave Scattering and Absorption Produced by WEC Arrays: Physical/Numerical Experiments and Model Assessment, Ozkan-Haller et al. evaluate the wave scattering and absorption induced by WEC arrays through laboratory and numerical experiments. The experimental study described was carried out with 1:33-scale commercial WECs under different array configurations subject to a range of regular waves and random sea states. Numerical experiments were carried out with the phase-resolving model WAMIT and the phase-averaged SWAN model. Model validations were conducted using data collected from the laboratory study. Their study results suggest that the environmental effects of WEC arrays can be minimized by designing WECs to operate optimally when the significant wave energy lies at periods near, or larger than, the period of peak energy extraction.

Chapters Hydrokinetic Tidal Energy Resource Assessments Using Numerical Models through Wave-Tide Interactions in Ocean Renewable Energy focus on tidal stream resource characterization and wave–tide interactions. Chapter Hydrokinetic Tidal Energy Resource Assessments Using Numerical Models by Haas et al. and Chap. Tidal Energy Resource Measurements by Thomson et al. present methodologies and techniques for tidal stream energy resource assessment and include case study examples from modeling and measurement perspectives, respectively. Both chapters discuss the importance of incorporating standards recommended by the IEC TS in the process of tidal energy resource characterization. These IEC standards include model grid resolution, bathymetric resolution, number of tidal constituents for the open boundary condition, measurement and simulation periods, and impacts of energy extraction.

In Chap. Hydrokinetic Tidal Energy Resource Assessments Using Numerical Models, Haas et al. provide clear definitions for theoretical, technical, and practical resources at different scales of resource assessment. Concepts and modeling approaches for tidal energy resource assessment at individual turbine, regional, and project scales are discussed in detail. Finally, model results from a case study in the Piscataqua River, located between the border of Maine and New Hampshire (USA), illustrate the processes of tidal resource assessment at turbine, project, and regional scales using the Regional Ocean Modeling System.

In Chap. Tidal Energy Resource Measurements, Thomson et al. address tidal energy assessments conducted using analytical and numerical models that should be complemented by information from field measurements, especially at large regional scales. High-quality field measurements can be used to characterize current spatial and temporal variations and site-specific tidal resource assessment, as well as to validate models that are used for tidal resource assessment at various scales. A full suite of parameters that can be obtained from field measurements, such as tidal harmonic constituents, turbulence spectra and intensity, current histograms, lateral shear and current asymmetry, power density, and annual energy production, are noted, and their application to resource assessment is described. In a case study in Admiralty Inlet of Puget Sound in Washington State (USA), the authors demonstrate that field measurements collected at high sampling frequencies and over long periods of time are required to resolve stochastic and deterministic components of tidal currents.

High wave and tidal energy resources may coexist in some coastal regions, such as the seas of the northwest European continental shelf, the Gulf of Alaska, New Zealand, northwest Australia, and the Atlantic seaboard of Argentina. In these coastal regions, wave–tide interaction may be an important factor in resource characterization. In Chap. Wave-Tide Interactions in Ocean Renewable Energy, Hashemi and Lewis evaluate the potential effects of wave–tide interactions on resource characterization using simple analytical methods and coupled wave–tidal modeling techniques. Their study shows that tidal stream energy resources may be reduced due to wave–tide interactions under extreme wave conditions, and wave properties may be altered as a result of wave–tide interactions. The authors recommend that wave–tide interactions be considered in either wave or tidal stream resource assessment in regions where high wave and tidal energy exist.

Chapters Use of Global Satellite Altimeter and Drifter Data for Ocean Current Resource Characterization through Marine Hydrokinetic Energy in the Gulf Stream Off North Carolina: An Assessment Using Observations and Ocean Circulation Models address the current state of the science and research on ocean current energy. Unlike waves and tides, which propagate in a form of gravity waves, strong ocean currents are mainly generated by wind and the Coriolis force, which result in "western intensification," a phenomenon occurring along the western boundaries of large-scale open-ocean basins. In Chap. Use of Global Satellite Altimeter and Drifter Data for Ocean Current Resource Characterization, Tseng et al. examine the large-scale ocean current resource using long-term global satellite altimeter data and SVP drifter data. They quantify averaged surface velocities in the global oceans based on long-term data sets and evaluate long-term-averaged velocity maximums in the four strongest western boundary currents (WBCs): the Agulhas Current in the Indian Ocean, the Gulf Stream in the Atlantic Ocean, and the Mindanao Current and the Kuroshio Current in the Pacific Ocean. Specific locations of the velocity maximums for these four WBCs are identified, and the temporal variability influenced by monsoon winds and the El Niño Southern Oscillation are investigated. Further detailed analysis is conducted to evaluate potential sites for ocean current power generation in the North Pacific, South China Sea, and Oceania, based on a set of criteria including current speed and frequency, water depth, and distance from the shore.

Meyer et al. examine the potential for energy extraction from the Agulhas Current along South Africa's East Coast in Chap. Mapping the Ocean Current Strength and Persistence in the Agulhas to Inform Marine Energy Development using an integrated approach that combines state-of-the-art satellite remote sensing, predictive modeling, and in situ observation techniques. They evaluate two specific locations, one at mid-shelf and one at offshore, for potential ocean current power generation. Current spatial and temporal variability and power density at these two potential sites are analyzed. Meyer et al. show that data generated from these combined methodologies can provide useful insight into the unique challenges encountered in resource assessment for the Agulhas Current. Finally, considerations of the technical challenges for energy extraction from the Agulhas Current and potential environment impacts are discussed.

Chapters Ocean Current Energy Resource Assessment for the Gulf Stream System: The Florida Current and Marine Hydrokinetic Energy in the Gulf Stream Off North Carolina: An Assessment Using Observations and Ocean Circulation Models are two companion chapters about resource assessment in the Gulf Stream, each focusing on different geographic locations and different methodologies. In Chap. Ocean Current Energy Resource Assessment for the Gulf Stream System: The Florida Current, Haas et al. evaluate the theoretical resource in the Florida Current portion of the Gulf Stream System, based on idealized and realistic numerical model simulations using the Hybrid Coordinate Ocean Model. Their study indicates that while the mean power in the Florida Current was found to be over 22 GW, extraction of only 5 GW of power from the Florida Current would require deployments of thousands of turbines under undisturbed flow assumption. In their study, Haas et al. demonstrate the importance of incorporating the additional dissipation due to the presence of turbines in model simulations for ocean current resource assessment, the result of which is a smaller level of technically extractable power.

In Chap. Marine Hydrokinetic Energy in the Gulf Stream Off North Carolina: An Assessment Using Observations and Ocean Circulation Models, Lowcher et al. assess the theoretical energy resource in the portion of Gulf Stream off the North Carolina Coast, based on a combination of observations and numerical model simulations. Current observation data were collected from moored and shipboard acoustic Doppler current profilers as well as from high-resolution ocean surface-current radars. Model simulations were generated from a high-resolution regional ocean circulation model for the Mid- and South Atlantic Bight. While it is challenging to accurately predict the high-frequency variability in spatial and temporal scales, the model estimates are in good agreement with the observed mean currents. Annual power density along three transects off the North Carolina Coast was calculated based on model outputs.

Chapters Effects of Tidal Stream Energy Extraction on Water Exchange and Transport Timescales and The Impact of Marine Renewable Energy Extraction on Sediment Dynamics address the effects of MRE extraction on physical ocean processes, such as water exchange and sediment transport. In Chap. Effects of Tidal Stream Energy Extraction on Water Exchange and Transport Timescales, Yang and Wang review the concept of transport timescales and numerical models for assessing tidal energy potential and its effect on volume flux and flushing time. Model results from idealized and realistic case studies show that the change in flushing time is linearly correlated with the volume flux reduction when the change in volume flux is small, but with a greater rate of change. Their study demonstrates the importance of using three-dimensional models in tidal stream energy resource assessment, as well as the importance of using flushing time as a transport timescale to quantify the effect of tidal energy extraction on transport processes.

In Chap. The Impact of Marine Renewable Energy Extraction on Sediment Dynamics, Neill et al. provide a detailed review of sediment dynamics and sediment transport processes in coastal and estuarine systems due to tidal current, wave action, or their combined effect. Impacts on morphodynamics of offshore sand banks as a result of tidal stream energy extraction, and on beach erosion and replenishment due to wave energy conversion are explored. The scale of impacts resulting from MRE extraction on sediment transport processes and coastal morphodynamics under extreme wave and storm, compared to scales of natural variability, is discussed.

Like other anthropogenic sources of sound, underwater noise can act as a stressor to marine animals in the marine environment and is an inevitable byproduct of energy generation. Chapters Assessing the Impacts of Marine-Hydrokinetic

Energy (MHK) Device Noise on Marine Systems by Using Underwater Acoustic Models as Enabling Tools and Challenges to Characterization of Sound Produced by Marine Energy Converters address the issue of underwater noise on the marine environment. In Chap. Assessing the Impacts of Marine-Hydrokinetic Energy (MHK) Device Noise on Marine Systems by Using Underwater Acoustic Models as Enabling Tools, Etter provides a comprehensive review of the theory of underwater acoustics and describes the background noise fields arising from natural and anthropogenic sounds as well as from MRE devices. A suite of underwater acoustic models is evaluated, and potential applications of different models toward understanding the impact of anthropogenic noise induced by MRE devices on the marine environment are discussed.

In Chap. Challenges to Characterization of Sound Produced by Marine Energy Converters, Polagye discusses the challenges of characterizing underwater noise generated by MRE devices and the role of field measurements in quantifying acoustic emissions from MRE devices and arrays. Specifically, this chapter addresses the factors influencing sound generation by an MRE device, methods for distinguishing device sound from ambient noise, and masking of the device sound by flow noise. Field measurements of spectrograms and annotated periodograms from a WEC are presented to illustrate these challenges. Potential solutions to overcome these challenges are also discussed.

Marine spatial planning (MSP) is a relatively new approach to analyzing and allocating parts of marine spaces for specific uses or objectives in order to achieve ecological, economic, and social objectives. In Chap. Planning and Management Frameworks for Renewable Ocean Energy, O'Hagan provides an overview of how the requirements of the ocean energy sector are taken into account when designing marine planning systems, how scientific information is reflected in the process, and the tools used to implement MSP. The chapter also identifies how possible or currently experienced conflicts between different sectors or users are managed. The chapter concludes with a section on the key limiting factors to implementation of MSP.

This book presents only part of the ongoing effort to enhance our understanding of the challenges of and barriers to MRE development. By no means does it cover every aspect of resource characterization and physical system effects in MRE development. We hope this book will serve as a useful tool to researchers, industry, and members of the general public who are interested in understanding the current state of the science in MRE development, especially the challenges and approaches to improving resource characterization and reducing system effects.

Finally, we thank the chapter authors for their hard work and contributions to the book, and the many reviewers for their valuable comments and input that improved the quality of the chapters. We also thank Ms. Susan Ennor of Pacific Northwest National Laboratory for technical editing of all of the chapters.

Pacific Northwest National Laboratory
Seattle, WA, USA

Zhaoqing Yang
Andrea Copping

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# About the Editors

**Dr. Zhaoqing Yang** is a chief scientist for coastal ocean modeling at the US Department of Energy's Pacific Northwest National Laboratory (PNNL) and a distinguished faculty fellow in the Department of Civil and Environmental Engineering at the University of Washington in Seattle, Washington. Dr. Yang's research covers broad areas related to coastal hydrodynamics and transport processes using advanced numerical models. His recent research has focused on marine renewable energy resource assessment and the impacts of extreme events and anthropogenic disturbances on coastal infrastructure and ecosystems. Dr. Yang leads PNNL's modeling effort on wave and tidal energy resource characterization as well as associated environmental impact assessment. He holds a Ph.D. in Physical Oceanography from the School of Marine Sciences at the College of William and Mary. Dr. Yang is a member of the Journal of Renewable Energy Editorial Board and served on the National Academy of Sciences—National Research Council's Committee on Marine and Hydrokinetic Energy Assessment.

**Dr. Andrea Copping** is a senior research scientist and program manager for Pacific Northwest National Laboratory (PNNL) and a distinguished faculty fellow in the School of Marine and Environmental Affairs at the University of Washington in Seattle, Washington. Dr. Copping's research focuses on the environmental effects of development of wave and tidal energy and offshore wind installations, and the role that these effects play in technology development and project initiation across the nation. Andrea leads international projects under International Energy Agency agreements on the environmental effects of marine energy development (Annex IV) and of wind (WREN) that share environmental effects information in order to benefit from progress made around the world. Prior to joining PNNL, Dr. Copping was the associate director of the Washington Sea Grant Program. Although trained as a blue water biological oceanographer, Andrea has spent most of her professional career examining the interactions of humans and the marine environment. Andrea holds a Ph.D. in Biological Oceanography from the University of Washington. Dr. Copping is an associate editor of the Coastal Management Journal, and on the Editorial Board of the International Journal of Marine Energy.