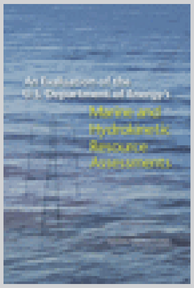

An Evaluation of the U.S. Department of Energy's Marine and Hydrokinetic Resource Assessments

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Belinda Batten, Oregon State University,
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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Lawrence Papay, Review Monitor. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

Increasing renewable energy development, both within the United States and abroad, has rekindled interest in the potential for marine and hydrokinetic (MHK) resources to contribute to electricity generation. These resources derive from ocean tides, waves, and currents; temperature gradients in the ocean; and free-flowing rivers and streams. One measure of the interest in the possible use of these resources for electricity generation is the increasing number of permits that have been filed with the Federal Energy Regulatory Commission (FERC). As of December 2012, FERC had issued 4 licenses and 84 preliminary permits, up from virtually zero a decade ago. However, most of these permits are for developments along the Mississippi River, and the actual benefit realized from all MHK resources is extremely small. The first U.S. commercial grid-connected project, a tidal project in Maine with a capacity of less than 1 megawatt (MW), is currently delivering a fraction of that power to the grid and is due to be fully installed in 2013.

In order to better understand MHK's potential, the Energy Policy Act of 2005 directed the U.S. Department of Energy (DOE) to estimate the size of the MHK resource base. DOE funded detailed assessments of five resources: waves, tides, ocean currents, ocean thermal energy conversion (OTEC), and rivers and streams. Its objective was to estimate the maximum practically extractable energy for each MHK category. These assessments have the potential to direct the developers of MHK devices and/or projects to locations of greatest promise and to inform the development of DOE's research portfolio. Additionally, the assessments could inform policies for commercial projects, technology development, environmental management, and funding. However, it is important to note that each of the independent assessment groups contracted by DOE employed different methodologies and terminology to describe conceptually similar results, probably because the DOE funding opportunity announcements (Appendix A) lacked clear direction.

As part of its assessment of MHK resources, DOE asked the National Research Council (NRC) to provide detailed evaluations. In response, the NRC formed the Committee on Marine and Hydrokinetic Energy Technology Assessment. As directed in its statement of task (SOT), the committee first developed an interim report, released in June 2011, which focused on the wave and tidal resource assessments (Appendix B). The current report contains the committee's evaluation of all five of the DOE resource categories as well as the committee's comments on the overall MHK resource assessment process. This summary focuses on the committee's overarching findings and conclusions regarding a conceptual framework for developing the resource assessments, the aggregation of results into a single number, and the consistency across and coordination between the individual resource assessments. Critiques of the individual resource assessments are contained in Chapters 2 through 6 of this report, further discussion of the practical MHK resource base is in Chapter 7, and overarching conclusions and recommendations are found in Chapter 8.

CONCEPTUAL FRAMEWORK

To shape its approach to the SOT and to review individual resource assessments within a single context, the committee created a conceptual framework for the overall MHK resource assessment (Figure S-1). The conceptual framework allowed the committee and those who read its report to conceptualize the processes used to assess the resources. It established a set of three terms—***theoretical resource***, ***technical resource***, and ***practical resource***—to clarify elements of the overall resource assessment process as described by each assessment group and to allow for a comparison of different methods, terminology, and processes used by the five assessment groups. An example of the relationship between the theoretical, technical, and practical resources is found in Box S-1.

- The ***theoretical resource***, shown in the left column of the conceptual framework in Figure S-1, is the average annual energy available for each source of MHK energy. The resource assessment groups produced two key outputs from their assessments of the theoretical resource: (1) overall regional or national numbers for the U.S. theoretical resource, expressed as an average annual

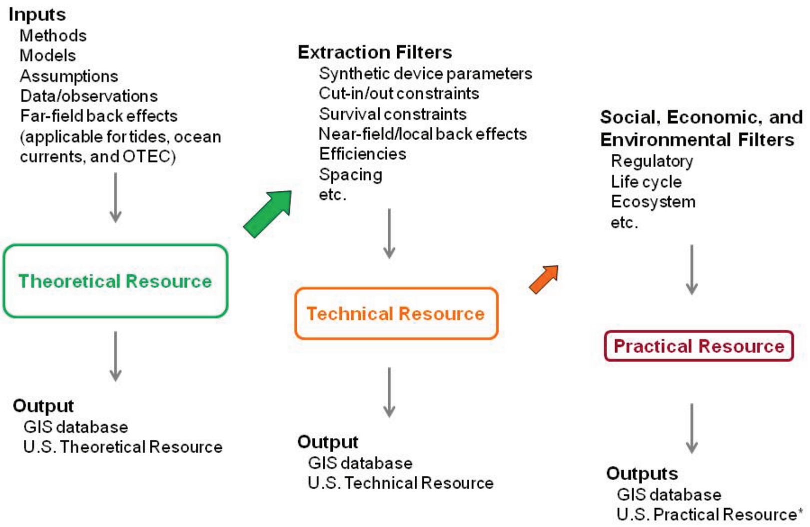

FIGURE S-1 Conceptual framework developed by the committee for MHK resource assessments. The asterisk in the third column denotes that the resource assessment groups did not attempt to evaluate the practical resource.

energy resource, typically in terawatt-hours per year (TWh/yr), and (2) a geographic information system (GIS) database that represents the spatial variation in average annual power density in units appropriate for each source—for example, W/m for waves or W/m^2 for tides.

- The ***technical resource*** (center column in Figure S-1) is defined as the portion of the theoretical resource that can be captured using a specified technology. Physical and technological constraints, conceptualized as extraction filters in Figure S-1, restrict how much of the theoretical resource can actually be extracted. Based on the presentations and discussions with the resource assessment groups, the committee found that each group offered a different interpretation of what types of constraints would need to be included among its extraction filters. However, it is clear to the committee that estimating the technical resource from the theoretical resource requires filters that represent the general physical and technological constraints associated with energy-extraction devices. In the committee's view, reporting of the technical resource represented completion of the assessment project for each group. The committee also recognizes that there are

BOX S-1
The Theoretical, Technical, and Practical Resource

MHK resource assessments are going to be of interest to a variety of parties, including electric utilities, project developers, and public officials. However, the orders-of-magnitude differences between theoretical, technical, and practical resources need to be stressed, especially because some resource assessments have been publicized in terms of a national or regional single-number estimate. To provide a better understanding of the difference among these resources, two scenarios are provided below.

- *Scenario 1.* A local official examines one of the MHK GIS databases and notes that there is a 100 MW theoretical resource nearby. After taking into account the efficiency of the extraction device, such as a turbine (30%), coverage of the resource by the device(s) (20%), and the efficiency of connecting the extracted energy to the electricity grid (90%), the technical resource amounts to only 5.4 MW. The local official notes that 50 percent of the remaining power would interfere with existing fisheries and navigation routes in the area, leaving a practical resource of 2.7 MW.

- *Scenario 2.* A developer is interested in building a 100 MW MHK plant. This would be considered the desired practical resource. In this case, 20 percent of the site is unavailable because it is in a Marine Protected Area. After taking into account device efficiency, site coverage, line efficiency, and the practical constraints posed by the use conflict, the site of interest would have to be endowed with a theoretical resource of 2,300 MW.

filters in addition to the extraction filters that influence when and where devices can be placed.

- The ***practical resource*** (right-hand column in Figure S-1) is that portion of the technical resource available after consideration of all other constraints. In the conceptual framework, these constraints are represented as social, economic, regulatory, and environmental filters.

Although a determination of the practical resource is beyond the scope of the tasks set for the resource assessment groups, the committee sees the constraints represented by the socioeconomic and environmental filters as being among the most important considerations influencing future MHK investments. These constraints are also critical when attempting to evaluate the maximum amount of U.S. MHK resources that could practically be used to generate electricity on a utility scale (greater than 10 MW). The regional approach used by the resource assessment groups was a top-down evaluation that is most useful in understanding the utility-scale potential for MHK rather than its small-scale potential (typically less than 10 MW). Compared with small-scale MHK deployments, utility-scale projects require significant infrastructure and could have more potential for substantial environmental impacts and conflicts with other ocean and freshwater uses. For example, extracting 1 GW of power from waves would likely require a row of devices at least 100 km long parallel to the coast; extracting a similar power from tides would effectively require a barrage. Similar examples can be envisioned for utility-scale in-stream, OTEC, and ocean current installations. Because of infrastructure costs and the potential for environmental impacts, MHK resources will probably be developed in only a limited number of discrete spots where the high energy density of the resource warrants such investment or in niche, small-scale applications where there are minimal local impacts. Such constraints will greatly reduce the aggregate practical resource as compared to the theoretical and technical resource.

Continued development of U.S. MHK resources requires clear conceptual and operational definitions and objectives. While many of the questions that are raised regarding MHK resource development will ultimately be decided at the local, state, and regional scale, there is an opportunity for DOE to play a leadership role by assessing resources and disseminating results. The committee noted that the U.S. MHK energy community has not settled on a common set of definitions for resource assessment and development. The committee has provided a conceptual framework for assessment of MHK resources that is consistent with terminology used by the European marine energy community. This framework was essential for understanding the factors considered when comparing the five MHK resource assessments.

> **Recommendation: DOE should develop or adopt a conceptual framework that clearly defines the theoretical, technical, and practical MHK energy resource** (Chapter 8)**.**

USE OF SINGLE NUMBERS FROM RESOURCE ASSESSMENTS

The committee has strong reservations about the appropriateness of aggregating theoretical and technical resource assessments to produce a single-number estimate for the nation or a large geographic region (for example, the West Coast) for any one of the five MHK resources. A single-number estimate is inadequate for a realistic discussion of the MHK resource base that might be available for electricity generation in the United States. **The methods and level of detail in the resource assessment studies do not constitute a defensible estimate of the practical resource that might be available from each of the resource types.** This is especially true given the assessment groups' varying degrees of success in calculating or estimating the technical resource base.

While the DOE may want an aggregated value for its internal research or for investment purposes—it might, for example, wish to compare the size of individual MHK resources with each other or with other renewable resources—**a single number is of limited value for understanding the potential contribution of MHK to U.S. electricity generation.** Challenging social barriers (such as fishery grounds, shipping lanes, environmentally sensitive areas) or economic barriers (such as proximity to utility infrastructure, survivability) will undoubtedly affect the power available from all MHK resources, but some resources may be more significantly reduced than others. The resource with the largest theoretical resource base may not necessarily have the largest practical resource base when all of the filters are considered. It is not clear to the committee that a comparison of theoretical or technical MHK resources—to each other or to other energy resources—is of any real value for helping to determine the potential extractable energy from MHK. **Rather, it is the practical resource that will ultimately determine the potential contribution of an MHK resource to U.S. electricity generation. Site-specific analyses will be needed to identify the constraints and trade-offs necessary to reach the practical resource.** Because the assessment groups were tasked by DOE to come up with a national assessment, they by necessity did not target their efforts on locations with high resource potential. However, many of these areas were identified even though their exploitation was not the sole focus of the assessment. It is these areas that most need characterization for their potential contribution to the U.S. electricity supply.

COORDINATION AND CONSISTENCY ACROSS RESOURCE ASSESSMENTS

Each of the resource assessment groups provides a useful contribution to understanding the distribution and possible magnitude of marine and hydrokinetic energy sources in the United States. The models, data sources, and visual display technologies, provided they are conveyed with appropriate caveats and documented assumptions, can aid in planning. However, the lack of a common framework allowed for a multitude of approaches to the individual assessments. **The resource assessments lacked coordination and consistency in terms of methodology, validation, and deliverable products.** Each of the assessment groups chose its own method of assessing the resource. While some variation between methodologies was due to differences among the MHK resource types, greater initial coordination among the assessors could have identified commonalities and led to easier comparison among the assessments.

Quantifying the interaction between MHK installations and the environment was a challenge for the assessment groups. **Deployment of MHK devices can lead to complex near-field and/or far-field feedback effects for many of the assessed technologies. Analysis of these feedbacks affects both the technical and practical resource assessments (and in some cases the theoretical resource) and requires careful evaluation.** The committee noted in several instances a lack of awareness by the assessment groups of some of the physics driving their resource assessments, such as the lack of incorporation of complex near-field and/or far-field feedback effects, which led to simplistic and sometimes flawed approaches. The committee was further concerned about a lack of rigorous validation.

A coordinated approach to validation would have provided a mechanism to address some of the methodological differences among the groups as well as provide a consistent point of reference. However, each validation group (chosen by individual assessment groups) determined its own method, which led to results that were not easily comparable to each other. In some instances, the committee noted that that there was a lack of sufficient analysis to be considered a true validation. Weakness of the validations includes using only a limited amount of observational data, the inability to capture extreme events, inappropriate calculations for the type of data used, and focus on validating technical specifications rather than underlying observational data. The lack of consistent, effective validation is especially problematic given the large uncertainties described in assessment results.

All five MHK resource assessments lack sufficient quantification of their uncertainties. There are many sources of uncertainty in each of the assessments, including the models, data, and methods used to generate the resource estimates and maps. Propagation of these uncertainties into confidence intervals for the final GIS products would provide users with an appropriate range of values, rather than the implied precision of specific values, and thus better represent the approximate nature of the actual results.

The GIS database products themselves are informative individual products for public use, but they are not able to be viewed as an aggregate product due to a lack of coordination during project development. Given that one of DOE's objectives is to compare the various MHK resources with one another and with other renewable energy resources, stronger initial coordination among the assessment groups could have led to products that were developed in a common format.

As part of the evaluation of the practical resource base, there seemed to be little analysis by the assessment groups of the MHK resources' temporal variability. This is in contrast to the spatial variability, which is comparatively well characterized through modeling and GIS displays. The committee recognized that **the time-dependent nature of power generation is important to utilities and would need to be taken into account in order to integrate MHK-generated electricity into any electricity system.**

> **Recommendation: Further evaluation of the MHK resource base should use the theoretical and/or technical results of the DOE resource assessments and appropriate decision support tools to identify the constraints that affect the practical resource and to help identify individual, highly promising sites for continued study of the practical resource. A site-specific approach to identify the practical MHK resource could help to estimate the potential contribution of MHK to overall U.S. electricity generation** (Chapter 8)**.**

For example, connecting and integrating the MHK resource to the electric utility grid may alter the number of developable sites or prioritize more easily connectable, economically viable sites. A next research step could be to create detailed assessments of two types of sites—"hot spots" with potential for large-scale MHK deployment and sites that might be promising for small-scale applications (for instance, remote communities without access to a regional transmission system).

Although DOE contracted for assessments that would provide the extractable U.S. MHK resource, the contractors focused on the theoretical and technical resource base at both national and regional levels. However, they did not make it to the level of estimating the practical resource.

> **Recommendation: Should DOE (or any other federal agency or regional/local decision-making body) decide to assess or support decisions on the potential practical MHK resource for specific regions of high potential MHK opportunity, it should include the best available socioeconomic and environmental filters for that region** (Chapter 8)**.** The tidal assessment group's identification of relevant socioeconomic factors is a good beginning.

Recommendation: DOE should ensure that spatial data resulting from the MHK resource assessments are readily and publicly available for use in siting and permitting decisions (Chapter 7)**.**

DOE has already made progress by making data on the spatial distribution of the theoretical energy resources readily available and should continue to play an active role in the characterization of the resource base and in developing decision support tools that can help guide considerations toward areas that could be the most productive and feasible for development. An accessible spatial database of theoretical and technological MHK resources would provide substantial information on the location of high-priority sites.

LIMITATIONS ON COMPARISON OF EXTRACTABLE MHK RESOUSCES

DOE requests for proposals did not offer a unified framework for the efforts, nor was there a requirement that the contractors coordinate their methodologies. The differing approaches taken by the resource assessment groups left the committee unable to provide the defensible comparison of potential extractable energy from each of the resource types as called for in the study task statement. To do so would require not only an assessment of the practical resource base discussed by the committee earlier but also an understanding of the relative performance of the technologies that would be used to extract electricity from each resource type. Simply comparing the individual theoretical or technical MHK resources to each other does not aid in making such a comparison since the resource with the largest theoretical resource base may not necessarily have the largest practical resource base. However, some qualitative comparisons can be made, especially with regard to the geographic extent and predictability of the various MHK resources. Both the ocean current and OTEC resource bases are confined to narrow geographic regions in the United States, whereas the resource assessments for waves, tides, and in-stream show a much greater number of locations with a large resource base. As for predictability, while there is multi-day predictability for wave and in-stream systems, especially in settings where the wave spectrum is dominated by swells or in large hydrologic basins, the predictability is notably poorer than for tidal, where the timing and magnitude of events are known precisely years into the future. The OTEC resource in the United States has little day-to-day variability but, like in-stream, is seasonally dependent. However, location and variability are but two of the many factors that will determine what MHK resources are capable of contributing significantly to power generation in the United States.

RESOURCE-SPECIFIC RECOMMENDATIONS

Each of the five resource assessments provides valuable information that can be used to identify geographic regions of interest for the further study of potential MHK development. However, utilizing this information to further assess the MHK resource that could be practically available for electricity generation will require improvements in methodology and characterization. The assessment and development of each MHK resource will face unique challenges. Overall, the committee would like to emphasize that **the practical resource for each of the individual potential power sources is likely to be much less than the theoretical or technical resource**. An additional criticism regarding most of the assessments was the lack of some degree of study prioritization based on existing knowledge, which could have led to a stronger focus on areas with higher potential. Recommendations for future study are considered below.

Tides

The tidal resource assessment is likely to highlight regions of strong currents, but large uncertainties are included in its characterization of the resource. Errors of up to 30 percent in the estimated tidal currents translate into potential errors of more than a factor of two in the estimate of potential power. Although maximum extractable power may be regarded as an upper bound to the theoretical resource, it overestimates the technical resource because the turbine characteristics and efficiencies are not taken into account.

> **Recommendation: In regions where utility-scale power may be available, further modeling should include the representation of an extensive array of turbines in order to account for changes in the tidal and current flow regime at local and regional scales. For particularly large projects, the model domain extent will require expansion, probably to the edge of the outer continental shelf** (Chapter 2).

Waves

The theoretical wave resource assessment estimates are reasonable, especially for mapping wave power density; however, the approach taken by the assessment group is not suitable for shallow water and is prone to overestimating the resource. The group used a "unit circle" approach to estimate the total theoretical resource, which summed the wave energy flux across a cylinder of unit diameter along a line of interest, such as a depth contour. This approach has the potential to double-count a portion of the wave energy if the direction of the wave energy flux is not perpendicular to the line of interest or if there is significant wave reflection from the shore. Further, the technical resource assessment is based on optimistic assumptions about the efficiency of conversion devices and wave-device capacity, thus likely overestimating the available technical resource.

> **Recommendation: Any future site-specific studies in shallow water should be accompanied by a modeling effort that resolves the inner shelf bathymetric variability and accounts for the physical processes that dominate in shallow water (e.g., refraction, diffraction, shoaling, and wave dissipation due to bottom friction and wave breaking)** (Chapter 3)**.**

Ocean Currents

The ocean current resource assessment is valuable because it provides a rough estimate of ocean current power in U.S. coastal waters. However, less time could have been spent looking at the West Coast in order to concentrate more fully on the Florida Strait region of the Gulf Stream, where the ocean current can exceed 2 m/s. This would have also allowed more focus on the effects of meandering and seasonal variability. Additionally, the current maps cannot be used directly to estimate the magnitude of the resource. The deployment of large turbine farms would have a back effect on the currents, reducing them and limiting the potential power.

> **Recommendation: Any follow-on work for the Florida Current should include a thorough evaluation of back effects related to placing turbine arrays in the strait by using detailed numerical simulations that include the representation of extensive turbine arrays. Such models should also be used to investigate array optimization of device location and spacing. The effects of meandering and seasonal variability within the Florida Current should also be discussed** (Chapter 4)**.**

OTEC

The OTEC assessment group's GIS database provides a visualization tool to identify sites for optimal OTEC plant placement. However, assumptions about the plant model design and a limited temperature data set impair the utility of the assessment. In addition, the committee considers the use of deep, cold water for air conditioning to be a potential use of this resource.

> **Recommendation: Any future studies of the U.S. OTEC resource should focus on Hawaii and Puerto Rico, where there is both a potential thermal resource and a demand for electricity** (Chapter 5)**.**

> **Recommendation: The OTEC GIS should be modified to display monthly resolution over a longer time period (at least a decade) to allow for evaluation of the thermal resource for the full seasonal cycle as well as for special periods such as El Niño and La Niña. Isotherm depths (at 1°C intervals) should be included in the database so other pipe lengths can be evaluated for OTEC and seawater air conditioning** (Chapter 5)**.**

Rivers and Streams

The theoretical resource estimate from the in-stream assessment group is based upon a reasonable approach and provides an upper bound to the available resource; however, the estimate of technical resources is flawed by the assessment group's recovery factor approach (the ratio of technical to theoretical resource) and the omission of other important factors, most importantly the omission of statistical variation of stream discharge. Further work is required with respect to the approach to estimate the technically recoverable resource before it will have value as an estimate to guide in-stream hydrokinetic development.

> **Recommendation: Future work on the in-stream resource should focus on a more defensible estimate of the recovery factor, including directly calculating the technically recoverable resource by (1) developing an estimate of channel shape for each stream segment and (2) using flow statistics for each segment and an assumed array deployment. The five hydrologic regions that comprise the bulk of the identified in-stream resource should be tested further to assure the validity of the assessment methodologies. In addition, a two- or three-dimensional computational model should be used to evaluate the flow resistance effects of the turbine on the flow** (Chapter 6)**.**

1

Introduction

Increasing renewable energy development, both in the United States and abroad, has rekindled interest in the potential for marine and hydrokinetic (MHK) resources to contribute to electricity generation. In particular, state-based renewable portfolio standards and federal production and investment tax credits have led to increased exploration of MHK technologies. This interest is reflected in the number of requests for permits for wave, current, tidal, and river-flow generators that have been filed recently with the Federal Energy Regulatory Commission (FERC); as of December 2012, FERC had issued 4 licenses and 84 preliminary permits while an additional 42 projects are in the pre-filing stage for a license.[1] Though permit activity is not a reliable predictor of the future development of MHK resources because developers apply for permits before completing project plans and financing, it does indicate increased interest in MHK resource development. However, most of these permits are for developments along the Mississippi River, and the actual deployment of all MHK resources is extremely small. The first U.S. commercial grid-connected project, a tidal project in Maine with a capacity less than 1 megawatt (MW), is currently delivering a fraction of that power to the grid and is due to be fully installed in 2013.

In response to the rising interest in MHK energy, the Energy Policy Act of 2005 (Public Law 109-58) directed the Department of Energy (DOE)

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[1] Available at http://www.ferc.gov/industries/hydropower/gen-info/licensing/hydrokinetics.asp. Accessed January 3, 2013.

to estimate the size of the MHK resource base. In order to assess the overall potential for U.S. MHK resources and technologies, DOE funded detailed resource assessments for estimating what it terms the "maximum practicably extractable energy" or "maximum practical, extractable energy" for each resource (see Appendix A for the funding announcements), as well as projects for generating the technological data necessary to estimate the expected performance of several MHK device designs currently under consideration (DOE, 2008 and 2009). The objective of DOE's MHK resource assessment work was to help prioritize its overall portfolio of future research, increase understanding of MHK's potential for generating electricity, and steer the developers of MHK devices and/or projects to locations of greatest promise.[2] Earlier estimates (EPRI, 2005 and 2007) of the potential MHK resource are based on limited, possibly inaccurate data and assumptions related to the total resource and the fraction that might prove extractable.

DOE contracted with five assessment groups to conduct separate estimates of the extractable energy from five categories of MHK resources: waves, tidal currents, ocean currents, marine temperature gradients (also known as ocean thermal energy conversion [OTEC]), and free-flowing water in rivers and streams (DOE, 2010). The resource assessment groups are listed in Table 1-1. Each group was tasked with estimating the average power density of the resource base, as well as basic technology characteristics for potential devices and spatial and/or temporal variability of the resource. DOE requests for proposals did not offer a unified framework for the efforts, nor was there a requirement that the contractors coordinate their methodologies. As a result, each assessment group used distinct methodologies and assumptions, although there is some commonality between assessments being overseen by the same groups. The DOE contracts did specify that each assessment would have a validation component; those groups are also listed in Table 1-1.

DOE asked the National Research Council (NRC) to convene a committee of experts to evaluate the detailed assessments produced by each group, review the estimates of extractable energy, typically represented as average terawatt-hours per year (TWh/yr),[3] and technology specifi-

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[2] H. Battey, U.S. Department of Energy, "DOE Water Power Program," Presentation to the committee on February 8, 2011.

[3] Note that TWh/yr is a unit of power and may be used to represent the average power generation over the time period indicated (1 gigawatt [GW] = 8.8 TWh/yr, 1 TWh/yr = 0.114 GW). However, a unit such as TWh/yr (or, as shown in an electricity bill, kilowatt-hours [kWh] per month) is a standard unit for the electricity sector. Energy units such as kWh or TWh measure the commodity that is generated by power plants and sold to consumers. For example, the Energy Information Agency's (EIA's) *Annual Energy Review 2011* includes a table of total electricity generation that is given in billions of kWh/yr (EIA, 2012, Table 8.2a).

TABLE 1-1 MHK Resource Assessment and Validation Groups Contracted by DOE

Resource Assessment	Assessment Group	Validation Group
Tides	Georgia Tech Research Corporation	Oak Ridge National Laboratory
Waves	Electric Power Research Institute, Virginia Tech	National Renewable Energy Laboratory
Ocean currents	Georgia Tech Research Corporation	Oak Ridge National Laboratory
Marine temperature gradients/OTEC	Lockheed Martin, Florida Atlantic University, University of Hawaii	National Renewable Energy Laboratory
Rivers and streams	Electric Power Research Institute, University of Alaska	National Renewable Energy Laboratory

cations, and compare the results across resource types. The committee members had expertise in oceanography, ocean engineering, hydraulics, civil engineering, electric power engineering and electric utilities, energy economics, and environmental and resource policy; their biographies can be found in Appendix C. The complete statement of task (SOT) can be found in Box 1-1. As requested in the SOT, the committee completed an interim report with initial commentary and review of the draft wave and tidal resource assessments. That report, *Assessment of Marine and Hydrokinetic Energy Technology: Interim Letter Report* (NRC, 2011), was released on July 12, 2011, and is reproduced in Appendix B. In it, the committee concluded that the wave and tidal assessments would be useful for determining the theoretical and technical resources, but it had concerns about the usefulness of producing a single-number estimate for the entire United States. It also noted a lack of consistency and coordination across the assessments. Each of these points will be discussed in full in this report.

A CONCEPTUAL FRAMEWORK FOR MHK RESOURCE ASSESSMENT

The nation's MHK community currently lacks a well-defined, consistent resource terminology. The committee observed that each of the assessment groups employed different terminology to describe similar results. This was likely due to imprecise language in the DOE funding opportunity announcements (DOE, 2008 and 2009), which called for an assessment of the "maximum practicably extractable energy" or the "maximum practical, extractable energy" without defining the terms. In addition, the NRC statement of task used language ("extractable energy,"

BOX 1-1
Statement of Task

This committee will evaluate detailed assessments produced by the U.S. Department of Energy (DOE) of the extractable energy from U.S. marine and hydrokinetic (MHK) resources (waves, tidal currents, ocean currents, marine temperature gradients, and free-flowing water in rivers and streams); review extractable energy estimates and technology specifications; and accurately compare the results across resource types. There are five assessments that will need to be evaluated by the committee addressing: (1) wave energy resources; (2) tidal energy resources; (3) hydrokinetic energy in streams and rivers; (4) marine thermal energy; and (5) ocean current energy. In addressing its statement of task, the committee will:

(1) Interact with the principal investigators of each individual assessment developed by DOE to understand and question their approach and perhaps suggest additional information or methodological approaches to facilitate consistent comparison across the assessments;

(2) Review and assess MHK technology-related data, critically analyzing methodologies, technical robustness, reliability, and assumptions related to the performance of the various technologies under consideration;

(3) Review and assess each of the resource assessments, critically analyzing methodologies, technical robustness, and assumptions related to the resources that might be practicably available for energy conversion and potential limitations on these resources;

(4) Based on its review and critique of the assessments, provide a defensible comparison of the potential extractable energy from each of the resource types;

(5) Make recommendations, as appropriate, for improving the assessments, improving the consistency among the assessments, or for improving the methodologies for making the assessments;

(6) Write an interim report reviewing the methodologies and assumptions, and provide any recommendations associated with the first two assessments being undertaken by DOE (wave and tidal energy); and

(7) Write a final report reviewing all five of the assessments.

"potential extractable energy") different from what DOE used for its funding opportunity statement.

In order to develop its approach to the SOT and to review individual resource assessments within a single context, the committee created a conceptual framework (Figure 1-1) of the overall MHK resource assessment.

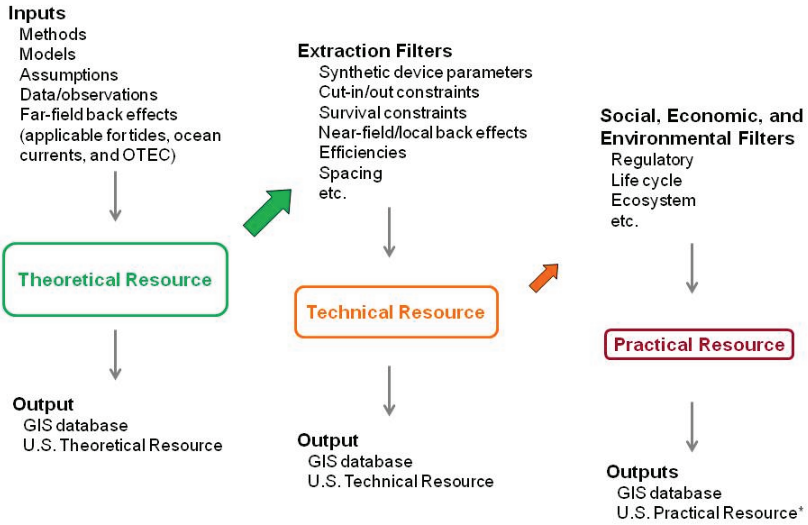

FIGURE 1-1 Conceptual framework developed by the committee for MHK resource assessments. The asterisk in the third column denotes that the resource assessment groups did not attempt to evaluate the practical resource.

This allowed the committee and those who read its reports to visualize the processes used to develop the assessment results requested by DOE. This framework establishes three terms—the ***theoretical resource***, ***technical resource***, and ***practical resource***—to clarify the overall resource assessment process as described by each assessment group and to allow for a comparison of different methods, terminology, and processes among the five assessment groups. Each of the three terms is defined in the following sections.

The committee recognizes that communities involved with other energy types, such as wind and fossil fuels, use different terms to describe their resource bases (such as "resources" or "proven reserves"). The committee's framework is consistent with terminology for MHK resources as used in the European marine energy community, including European Marine Energy Centre (EMEC)[4] terminology incorporated in International Electrotechnical Commission (IEC) technical specification 62600-1 (IEC, 2011). In addition, the committee created Table 1-2, which contains the definitions and units used in this report.

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[4] Available at http://www.emec.org.uk/standards.asp.

TABLE 1-2 Terminology and Definitions Used by the Assessment Groups

Term to Be Quantified	Definition	Unit	Note
General			
Energy	Capacity to do work	joules (J)	
Power	Energy per time	watts (W) = J/s	
Flux	Rate of flow of a property per unit area		
Resource	Average annual power	TWh/yr (1 TWh/yr = 114 MW)	Representing a potential energy resource base for the electricity sector in TWh.
Tides, ocean currents, and riverine/in-stream			
Current power density	Power of horizontal currents flowing through a vertical plane of unit area. $P = \frac{1}{2}\rho v^3$	W/m^2	Horizontal kinetic energy flux (power density). Applies to a single device. Excludes consideration of back effects.
Waves			
Wave power density (Mei, 1989)	Power of waves per unit crest length based on $\vec{P} = \rho g \int_0^\infty S(f,\theta) c_g df$	W/m	Horizontal energy flux. Applies to a single device. Vector quantity (has both direction and magnitude).
Wave power density (EPRI, 2011)	Power of waves per unit circle based on $P = \rho g \int_0^\infty \int_0^{2\pi} S(f,\theta) c_g d\theta df$	W/m	Horizontal energy flux. Applies to a single device. Scalar quantity (has no directional information).
Ocean thermal			
Ocean thermal power density (Nihous, 2007a)	Net extractable power per unit flow of upwelled cold water $\frac{P}{Q_{CW}} = \frac{\rho C_p \times TGE \times (\Delta T)^2 (1-PL)}{8(273+T_S)}$	$W/(m^3/s)$	Net power from pumping 1 m^3/s of cold water without consideration of back effects on the ocean.

NOTE: Variables are as follows:

ρ, water density;
v, tidal/ocean/river current speed (scalar);
g, gravitational acceleration;
S, wave spectrum (sea-surface height variance, per frequency and direction);
c_g, wave group velocity;
f, wave frequency;
θ, wave direction;
C_p, heat capacity of seawater (J/(K kg));
TGE, OTEC turbo-generator efficiency (~0.8-0.9);
ΔT, temperature difference between warm and cold water for OTEC plant (°C);
PL, pipe loss/fractional energy loss to cold water pumping (~0.2-0.3); and
T_S, warm water intake temperature for OTEC (°C)

Theoretical Resource

The ***theoretical resource***, shown in the left column of the conceptual framework in Figure 1-1, is defined as the average annual energy available from each MHK resource. Determining the theoretical resource requires a series of inputs (including methods, models, assumptions, and observational data) for each source of MHK energy (waves, tides, ocean currents, marine temperature gradients, and rivers and streams) in order to determine the physical upper limit on the total amount of available energy. For waves, the theoretical resource is effectively the power density of waves approaching the shore (see Table 1-2). For in-stream power from rivers, the theoretical resource is the power that is lost to friction as water flows from higher to lower ground.

For some of the theoretical resource assessments, it is also important to consider far-field back effects. These refer to the modification of an energy resource owing to the presence of an extraction device or devices. In particular, for tidal currents, ocean currents, and marine thermal gradients, the theoretical resource cannot be estimated without taking into account the far-field back effect. Here, the back effect refers to the reduced potential of the resource due to feedbacks from the presence of a device or device array. For tidal and other ocean currents, placement of a turbine will create drag, reducing the current velocity and therefore the potential power available for each turbine. As turbines are added to an array, at some point the extra power generated by an additional turbine will be less than the decrease in power due to the reduced current available for all the other turbines. This maximum available power is equivalent to the theoretical resource when far-field back effects are considered. Similarly, the operation of a series of OTEC plants can affect the ocean's thermal structure, decreasing the potential power of each plant. Depending on the community, back effects are also known as feedbacks or blockage effects.

In response to the original DOE request, the assessment groups produced two key outputs from their characterization of the theoretical resources: (1) overall regional or national numbers for the U.S. theoretical resource, expressed as an average annual energy resource (typically in TWh/yr), and (2) a geographic information system (GIS) database that represents the spatial variation in average annual power density with units appropriate for each source (e.g., W/m for waves or W/m^2 for tides). The committee equates the theoretical resource with the "potential extractable energy" mentioned in the SOT.

Technical Resource

The ***technical resource*** (center column in Figure 1-1) is defined as the portion of the theoretical resource that can be captured using a specified technology. For each resource, there are technological constraints that determine how much of the theoretical resource can actually be extracted. The committee conceptualizes these constraints as physical and technological extraction filters. These include physical near-field (local) back effects from turbine interactions in a river channel or wave system as well as technological characteristics associated with one or more energy-extraction devices: characteristics such as device efficiency, device spacing requirements, drag on supporting structures, and cut-in and cut-out parameters (the minimum or maximum speeds at which devices can operate). Some of these filters are resource-specific; others are applicable across all MHK resources. During presentations from DOE and the assessment groups and ensuing discussion with the committee, it became clear that each group offers a different interpretation of what types of constraints would need to be included among its extraction filters. However, it is clear to the committee that estimating the technical resource from the theoretical resource requires filters that represent the general physical and technological constraints associated with energy-extraction devices. In-water or field tests would assist in the quantification of realistic extraction filters and/or device-specific conversion efficiencies, because the data obtained could be used to calibrate numerical models. Outputs related to the technical resource include an estimate of the energy resource and a GIS that sets forth spatial and temporal variation in the resource associated with various technologies. In the committee's view, the assessment groups determined that reporting the technical resource (rather than the practical resource) represented the completion of their projects. The committee equates the technical resource with the review of "extractable energy" charged in the SOT.

Practical Resource

The committee also recognizes that, beyond the extraction filters, there are additional filters influencing when and where devices can be placed. The ***practical resource*** (right-hand column in Figure 1-1) is defined as that portion of the technical resource available after consideration of all other constraints. In the conceptual framework, these constraints are represented as social, economic, regulatory, and environmental filters. For example, some of the filters attempt to capture the logistical and economic considerations associated with building the MHK devices and connecting them to the electricity system, which could include costs of extraction and electricity delivery. Environmental constraints related to quantifying the practical resource include issues such as protecting threatened species or ecologically sensitive areas. Other use issues include sea–space conflicts raised by, for instance, shipping channels, navigation, and military considerations and multiple- or competing-use issues such as fisheries or recreation. Such filters are, by nature, specific to the local sites where decisions related to MHK projects will be made. The practical filters can greatly influence the timing of the permitting process and can lead to unpredictable consequences, which in turn can affect a project's economic viability. Box 1-2 presents two scenarios to help elucidate the differences between the theoretical, technical, and practical resource.

BOX 1-2

The Theoretical, Technical, and Practical Resource

MHK resource assessments are going to be of interest to a variety of parties, including electric utilities, project developers, and public officials. However, the orders-of-magnitude differences between theoretical, technical, and practical resources need to be stressed, especially because some resource assessments have been publicized in terms of a national or regional single-number estimate. To provide a better understanding of the difference among these resources, two scenarios are provided below.

- *Scenario 1.* A local official examines one of the MHK GIS databases and notes that there is a 100 MW theoretical resource nearby. After taking into account the efficiency of the extraction device, such as a turbine (30%), coverage of the resource by the device(s) (20%), and the efficiency of connecting the extracted energy to the electricity grid (90%), the technical resource amounts to only 5.4 MW. The local official notes that 50 percent of the remaining power would interfere with existing fisheries and navigation routes in the area, leaving a practical resource of 2.7 MW.

- *Scenario 2.* A developer is interested in building a 100 MW MHK plant. This would be considered the desired practical resource. In this case, 20 percent of the site is unavailable because it is in a Marine Protected Area. After taking into account device efficiency, site coverage, line efficiency, and the practical constraints posed by the use conflict, the site of interest would have to be endowed with a theoretical resource of 2,300 MW.

In its funding opportunity announcements (DOE, 2008 and 2009), DOE requested that the assessment groups determine the "maximum practicably extractable energy," which the committee originally interpreted as equivalent to the practical resource called for in the conceptual framework. After discussion with both DOE and the assessment groups, the committee concluded that the groups had interpreted "maximum practicably extractable energy" to mean the technical resource and that DOE did not expect the assessment effort to incorporate site-specific information needed to quantify the practical resource.

While a determination of the practical resource is beyond the scope of the tasks assigned by DOE, the committee sees the constraints represented by the socioeconomic and environmental filters as being among the most important considerations influencing future MHK investments. Box 1-3, which discusses these types of constraints on the development of solar energy, is presented as an example of what might be needed to assess the MHK practical resource. These filters are also central to evaluating the potential maximum contribution of MHK to U.S. electricity generation. The socioeconomic and environmental filters that need to be considered in an assessment of the MHK resource are described further in Chapter 7.

BOX 1-3
Determining the Difference Between the Theoretical and Practical Resource: Solar Energy as a Case Study

Assessing the potential for a particular renewable technology to address U.S. energy needs based on the theoretical resource alone would be inappropriate. As an example, solar power plants (which were first constructed nearly 30 years ago) currently provide less than 0.1 percent of the electricity consumed in the United States despite having a theoretical resource base that is orders of magnitude larger than current U.S. electricity consumption (EIA, 2012). While national-scale resource assessments may be useful for identifying geographic regions of interest for a particular MHK extraction technology, the practical resource will depend on a host of technical and environmental factors and may be significantly lower than what the assessments indicate is regionally or locally available. A survey of annual total energy outputs from several existing solar plants indicates that the ratio of plant outputs to the locally available theoretical resource ranges from as little as 2 percent for photovoltaics to as much as 12 percent for concentrated solar (National Renewable Energy Laboratory [NREL], available at http://www.nrel.gov/gis/solar.html; EIA, available at http://www.eia.gov/electricity/data/eia923/index.html). It is not possible to predict the practical MHK resource from national resource assessments until the constraints posed by both the technical extraction filters and the practical socioeconomic and environmental filters are better quantified for each of the specific resources.

It is also important to note the difference between utility-scale and small scale developments, as these terms are mentioned throughout the report. Utility-scale MHK developments would produce from tens to hundreds of megawatts and would require significant infrastructure and fully-proven MHK devices rather than prototypes. Utility-scale MHK deployment has the greatest potential for substantial environmental impacts as well as conflicts with other ocean and freshwater uses. In comparison, smaller-scale developments would typically produce less than 10 MW and potentially have fewer conflicts and adverse impacts. Small MHK developments could be deployed in locations with high local resource availability and low electricity demands (such as remote villages or small islands) or in locations that lack interconnection to a utility-scale electricity system. Additionally, a project developer would need to prove the feasibility of a smaller-scale pilot application before a utility would invest in building a utility-scale system. The regional- to global-scale approach used by the resource assessment groups was a top-down evaluation that is most useful in understanding the utility-scale potential for MHK.

THE "SINGLE NUMBER" ESTIMATE FOR RESOURCE ASSESSMENTS

Although each of the five MHK resource assessments is evaluated in detail in Chapters 2 through 6, here the committee draws attention to an important point that applies to the assessments both individually and for the project as a whole. **The committee is concerned about the appropriateness of aggregating the results of individual MHK resource assessments to produce a national or regional single-number estimate of the theoretical and/or technical resource for any one of these energy sources.** It finds that the theoretical resource assessments, especially when examined at a regional or national scale, have limited utility for developers and stakeholders and also have potential for misuse. As an example, the numbers associated with the wave and tide assessments do not accurately convey how the theoretical resources are concentrated along the coast, nor do they explain how much power would be practically available once devices are deployed. Although such estimates provide a broad order-of-magnitude idea of potential energy resources, many extraction filters are needed to determine the technical resource, and at this time the assessment groups can rigorously evaluate only a few of these filters. Most of the extraction filters require assumptions about which particular MHK technologies will be used and what their technical specifications will be; moreover, the technologies are likely to vary by resource and location—for instance, wave energy off the coast of Oregon and ocean current energy in the Florida Straits. In addition, socioeconomic and environmental filters will ultimately limit the practical resource to only a fraction of the technical resource, so it is unlikely that the resource assessments, which at best provide only a partial assessment of the technical resource, could serve as a defensible estimate of the available practical resource. **Although DOE may want overall numbers in order to compare individual MHK resources with one another or with other renewable resources, a single number is of limited value for understanding the potential contribution of MHK resources to U.S. utility-scale electricity generation.** Instead, site-by-site analysis will be needed to estimate the resource that might ultimately be available for electricity generation. This number is likely to be much smaller than the numbers generated by national resource assessments.

COORDINATION AND CONSISTENCY

Another issue that applies broadly to the entire DOE-funded assessment efforts was the coordination among and consistency between individual resource assessments. **These efforts suffered from a lack of coordination and consistency in terms of methodology, validation, and deliverable products.** Each of the assessment groups chose its own methodologies, and while the committee understands that there was likely to be variation simply because the resource types differ, greater coordination at the outset could have discerned some commonalities that would have allowed easier comparison of the assessments. In addition, each validation group chose its own method, which also led to inconsistent results. In some cases, the method appeared to be less of a validation than a spot-checking of results with varying degrees of thoroughness. The committee is also concerned about the scientific validity of some assessment conclusions; these concerns are addressed in later chapters. The lack of coordination and consistency also affected the GIS database products. While some are already integrated into GIS Web applications hosted by DOE's National Renewable Energy Laboratory (MHK Atlas and River Atlas[5]), others are currently hosted on platforms operated by individual assessment groups. Given that one of DOE's objectives is to compare the various MHK resources with one another and with other renewable energy resources, the lack of coordination and consistency between the assessment groups was counterproductive.

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[5] Available at, respectively, http://maps.nrel.gov/mhk_atlas and http://maps.nrel.gov/river_atlas.

REPORT ORGANIZATION

The committee evaluated the five assessments contracted by DOE (tides, waves, ocean currents, marine thermal gradients/OTEC, and rivers and in-stream). Each of the assessments is presented in a separate chapter, which introduces the basic resource, describes the project, comments on assessment methodology and validation, and offers conclusions and recommendations. The discussion of tides can be found in Chapter 2, waves in Chapter 3, ocean currents in Chapter 4, OTEC in Chapter 5, and riverine and in-stream flows in Chapter 6. A discussion of the practical MHK resource and constraints posed by socioeconomic and environmental filters is included in Chapter 7, and overarching conclusions and recommendations are presented in Chapter 8.

Evaluations of the resource assessments are based on presentations by the assessment groups and DOE to the committee at each of its six meetings (meetings and presentations to the committee are detailed in Appendix D). The committee also received written responses to its questions from each of the groups. Chapters 2 and 3 are based on information initially discussed in the committee's interim report (NRC, 2011). These chapters have been updated to include information that had not been available at the time of the interim report release. For this report, the committee reviewed final assessment reports for the waves, tides, and OTEC assessment groups and a July 2012 draft final report from the riverine assessment group.[6] No final report was available for review from the ocean currents resource assessment group; its report is expected to be complete by June 2013. Instead, the committee based its evaluation on presentations from and discussions with the assessment group.

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[6] The final report was published in December 2012 and is available at http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001026880.

2

Tidal Resource Assessment

Ocean tides are a response to gravitational forces exerted by the Moon and the Sun. They include the rise and fall of the sea surface and the associated horizontal currents. The potential of tidal power for human use has long led to proposals that envision a barrage across the entrance of a bay that has a large range of height between low and high tides. A simple operating scheme is to release water trapped behind the barrage at high tide through turbines, generating power in a manner similar to a traditional hydropower facility.

In recent years, considerable attention has been paid to the direct exploitation of tidal currents using in-stream turbines rather than a barrage, in a manner similar to the way that wind turbines work. By way of scale comparison, a current v is equivalent to a hydraulic head of $0.5v^2/g$ (where g is gravity), so that even a strong current of 3 m/s (~10 ft/s) is equivalent to a hydraulic head of only 0.5 m (~1.6 ft), which is considerably less head than a typical tidal range. Because the power produced by a turbine is related to the product of the head and the flow rate, it is clear that capturing tidal currents is considerably less effective than capturing the hydraulic head associated with even a modest tidal range. It is often claimed that in-stream turbines have less serious ecosystem impacts than barrages, though it is not at all clear that this is true for installations with the same average power output. In spite of these reservations, and because in-stream turbines could possibly be used in small-scale projects or in areas without a large tidal range, much work has gone into evaluating their potential.

The upper bound on the power from such an in-stream turbine is shown in Table 1.2 and is expressed by the Lanchester-Betz limit of $0.3\rho Av^3$, where ρ is water density, v is current speed, and A is the cross-sectional area across the blades (also referred to as the swept area).[1] The power density equation shows that the turbine power is related to the cube of the current and demonstrates the advantage of deploying turbines in regions of strong current. As an example, if the cross-sectional area A is 100 m^2 (~1,075 ft^2) and the current speed v is 3 m/s, the upper bound on the power from a turbine is 0.8 MW. The average power over a tidal cycle is, of course, less than that obtainable at the maximum current.

Several prototype turbines have been developed and tested in recent years, but tidal turbine technology has not yet reached convergence (as opposed to wind turbine technology, which has converged on a three-blade, horizontal-axis design). In the United States, there are multiple tidal turbine pilot projects under way, including the Verdant project in the East River in New York, which recently received approval from the Federal Energy Regulatory Commission (FERC); the Snohomish Public Utility project in Admiralty Inlet, Washington; and the Ocean Renewable Power Company (ORPC) project in Cobscook Bay, Maine, which has begun to deliver power to the grid. These projects demonstrate the variety of technology and the scales of power generation. In the East River, up to thirty 5-m diameter Verdant turbines will generate a nominal 35 kW each, using an open horizontal-axis design with variable yaw (Figure 2-1a). In Cobscook Bay, up to five 30-m-long ORPC turbines with a cross-flow helical design (Figure 2-1b) will have a total generation capacity of up to 300 kW (FERC, 2012). In Admiralty Inlet, two 6-m diameter OpenHydro turbines will have a nominal output of 150 kW of generation each, using a ducted horizontal-axis design with fixed pitch and yaw (Figure 2-1c). As with wind turbines or solar arrays, the actual average output will be much less than the nominal output (also known as "rated power" or "installed capacity") because the intensity of the resource varies greatly with time over a tidal cycle, even though it is predictable. Although site selection may be informed by the resource assessment reviewed below, it is expected that future projects and development will continue to require site-specific data collection.

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[1] The Lanchester-Betz limit is the maximum power which can be extracted by a turbine in an unbounded flow. If a turbine array occupies a significant fraction of the channel cross section, the flow is more constrained in going around the turbines than it would be in an unbounded flow. This partial blockage can cause an increase in the pressure on the turbines as well as force more flow through them, increasing the power, which ultimately approaches that from a barrage if the array blocks the entire channel cross section (Garrett and Cummins, 2007).

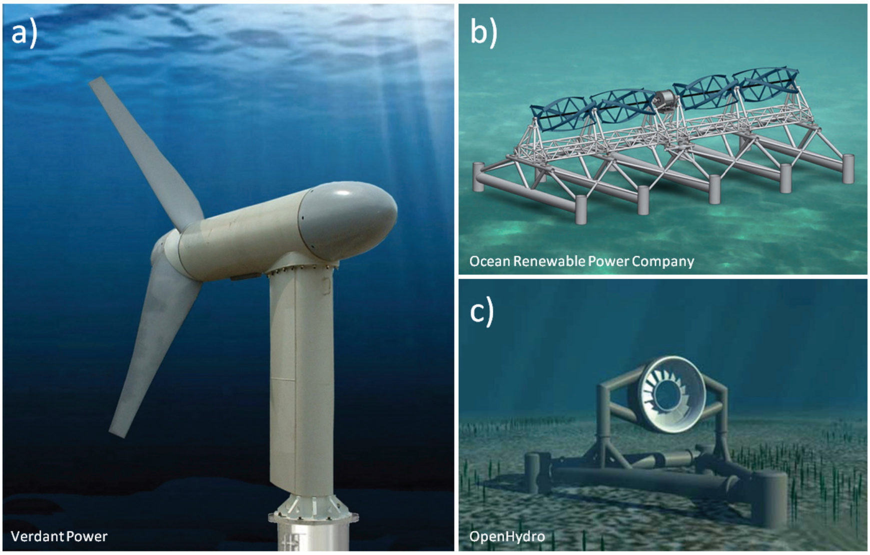

FIGURE 2-1 Turbine designs for U.S. tidal energy pilot projects. SOURCE: Verdant Power; Ocean Renewable Power Company; OpenHydro.

Another important consideration is the large-scale far-field back effect of an array of turbines. In addition to local flow disturbance around an individual turbine, drag associated with the presence of turbines will reduce large-scale flow. Open water currents will tend to avoid and flow around a region of extra drag associated with a turbine array, while the presence of turbines in confined channels will reduce the overall volume flux through the whole channel. The potential of a single turbine may be reasonably assessed using the natural flow, but the extra power from the addition of more turbines to an array will eventually be offset by the lower power due to reduction in flow from the turbines already present. The maximum power P_{max} (the theoretical resource) that can be achieved can be assessed only after taking large-scale back effects into account.

PROJECT DESCRIPTION

The tidal resource assessment group conducted its tidal energy assessment study by developing a set of models to simulate all U.S. coastal regions and to estimate the maximum tidal energy based on predicted tidal currents[2,3] (Georgia Tech Research Corporation, 2011). The model used in the study was the three-dimensional Regional Ocean Modeling System (ROMS),[4] which is often used in modeling studies of coastal oceanography and tidal circulation. The model was configured with eight vertical layers and set up for 52 model domains, with grid resolutions in the range of 350 m. Each domain included a section of coast or a particular bay, with offshore boundaries that included part of the adjacent continental shelf. The models were forced at their offshore boundaries by predicted tidal constituents, using the Advanced Circulation Model (ADCIRC) tidal database[5] for the East Coast and Gulf of Mexico regions and the TPXO database[6] for the West Coast region. River inflows and atmospheric forcing (such as wind) were not considered, and stratification and density-induced currents were not simulated. The landward model boundaries and bathymetry were defined using coastline data from the National Ocean Service of the National Oceanic and Atmospheric Administration (NOAA) and digital sounding data from NOAA's National Geophysical Data Center. The effect of tidal flats was initially evaluated but not considered in the final model setup and runs.

The tidal resource assessment group calibrated the tidal models by adjusting the single friction coefficient to improve the comparison among model results, NOAA predictions of tidal elevation and currents, and limited observations of depth-averaged tidal currents. Model calibration parameters include harmonic constituents for tidal currents and water levels, maximum/minimum tidal currents, and high/low tides. An independent model validation was performed by the Oak Ridge National Laboratory (ORNL), which compared model predictions with observed tidal elevations and currents at selected stations that were not included in the calibration exercises[7] (ORNL, 2011). Error statistics between model results and observed data were generated in this validation.

Model output was used (1) to provide an upper bound, $P_{\max}$, of the power available from tidal in-stream turbines for each bay and (2) to create a Web-based geographic information system (GIS) interface of quanti-

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[2] K. Haas, Z. Defne, H.M. Fritz, and L. Jiang, Georgia Tech Savannah; S.P. French, Georgia Tech Atlanta; and B. Smith, Oak Ridge National Laboratory, "Assessment of energy production potential from tidal streams in the United States," Presentation to the committee on November 15, 2010.

[3] K. Haas, H.M. Fritz, and L. Jiang, Georgia Tech Savannah, "Assessment of tidal stream energy potential for the United States," Presentation to the committee on February 8, 2011.

[4] See http://www.myroms.org/. Accessed June 21, 2011.

[5] See http://www.unc.edu/ims/ccats/tides/tides.htm. Accessed June 21, 2011.

[6] See http://www.esr.org/polar_tide_models/Model_TPXO71.html. Accessed June 21, 2011.

[7] V.S. Neary, K. Stewart, and B. Smith, Oak Ridge National Laboratory, "Validation of tidal current resource assessment," Presentation to the committee on February 8, 2011.

ties such as the local average power density (W/m^2) in a vertical plane perpendicular to the average current at each model grid cell. Visualizations of average power density could, in principle, be used to estimate the power available from a single turbine or a few turbines (an array small enough not to have a significant back effect on the currents). The ArcView GIS database developed by the tidal resource assessment group was well designed and executed, and it allows for downloading of the tidal modeling results for further analysis by knowledgeable users. Based on the final assessment report, the assessment group produced estimates of the total theoretical power resource. However, this was done for complete turbine fences, which essentially act as barrages. The group did not assess the potential of more realistic deployments with fewer turbines, nor did they incorporate technology characteristics to estimate the technical resource base. It is clear, however, that the practical resource will be very much less than the theoretical resource.

COMMITTEE COMMENTS

Methodology and Validation

ROMS is a structured-grid, open-source coastal ocean model. It has performed well in the prediction of coastal circulation and tides in a large number of applications (e.g., Warner et al., 2005; Patchen, 2007; NOAA, 2011a). Finer grid resolution may be needed to represent bathymetry accurately in high tidal current regions. Increasing the grid resolution in local areas of a ROMS model often results in a significant increase of the total model grid size, owing to the structured-grid framework. In contrast, unstructured-grid models, which have greater flexibility for high grid resolution in complex waterways, could provide an alternative, especially for areas of complex geometry with high tidal energy (see, e.g., Patchen, 2007). An evaluation of the effect of grid resolution in the most promising high tidal energy regions would be a critical next step for future studies.

The location of the offshore boundary, partway out onto the continental shelf, is adequate for this effort, assuming that only a single turbine or a limited number of turbines is represented. Extension of the model boundary farther away to minimize the boundary effect (e.g., to the shelf edge [see, for example, Garrett and Greenberg, 1977]) may be necessary in the future if models are rerun with representations of a large turbine array that would be extensive enough to have a back effect on offshore tides. Estimates of available power may not be accurate without considering the effect of the locations of open boundaries. This question could be evaluated in future studies. Comparisons of model bathymetry to acoustic Doppler current profiler (ADCP) measurements at selected stations indicated the bathymetric difference could be as large as 30 percent. Therefore, finer grid resolution and better accuracy of model bathymetry are critical for the improvement of model predictions.

According to the materials provided to the committee (Georgia Tech Research Corporation, 2011), the model tends to reproduce observed tidal elevations well. This is essential for the accurate prediction of the currents, but it may not be sufficient. It is possible for a model to reproduce tidal elevations well but still to have incorrect current patterns. Comparisons between predicted and observed currents indicated that errors associated with predicted currents may be 30 percent or more (ORNL, 2011). One of the main concerns surrounding the model calibration and validation efforts is the limited number of current observation stations used in the study—24 stations for model calibration and 15 for model validation (five stations are excluded because modeled and measured depths differ more than 30 percent), which means many of the 52 submodel domains do not contain any current data. Thus, the comparisons are more akin to spot-checking than actual validation, and comparisons are often poorest in the regions of most interest.

For example, at the site of the Snohomish Public Utility District pilot project in Admiralty Inlet, field data from the Northwest National Marine Renewable Energy Center shows a mean power density of 2 kW/m^2, which can be compared to the mean power density of 0.8 kW/m^2 given by the tidal resource assessment database. Field data also show a significant ebb dominance and directional asymmetry, in contrast to flood dominance and directional symmetry given by the resource maps.

The committee feels that efforts should have been focused on obtaining more observational data in the validation study rather than on producing a large metric of error statistics between model results and observations. It could be useful to consider more conventional model evaluation skill metrics used in the ocean modeling field (Warner et al., 2005; Patchen, 2007; NOAA, 2011a). Because power is related to the cube of current speed, errors of 100 percent or more occur in the prediction of tidal power density in many model regions. It is unclear whether model calibration through the adjustment of the single friction coefficient is more appropriate than adjustment or improvement of other factors, such as model bathymetry, grid resolution, or offshore boundary conditions. As noted by the tidal resource assessment group, errors in currents may be a consequence of inadequate model resolution rather than of an erroneous friction coefficient or uncertain forcing from the open boundary (ORNL, 2011).

Estimate of Available Tidal Power

One principal result of the tidal resource assessment is the maximum power, P_{max}, extractable from the tidal currents in a bay or other locations with constricted flow. P_{max} is the basis for the theoretical resource shown in the left column of Figure 1-1. P_{max} would result from the use of a complete turbine fence across the entrance to the bay, but, owing to large-scale back effects, it is *not* the time-average of the horizontal kinetic energy flux, $0.5\rho v^3$, times the area of the vertical cross section of the entrance to the bay (e.g., Garrett and Cummins, 2007 and 2008). Instead, P_{max} is given to a reasonable approximation by

$$P_{max} = 0.22 g \rho a Q_{max} \tag{1}$$

where g is gravity, a is tidal amplitude (the height of high tide above mean sea level), and Q_{max} is the maximum volume flux into a bay in the natural state without turbines (Garrett and Cummins, 2008). P_{max} increases with the tidal amplitude, a, and the surface area of the bay. For example, a tidal amplitude of 1 m (3.28 ft) would require more than 300 square kilometers (over 110 square miles) to produce 100 MW as an absolute maximum. This result is for a single tidal constituent. If the dominant tide is the twice-a-day lunar tide, P_{max} is equivalent to the provision from each square meter of the bay's surface of $0.3a^2$ watts if a is in meters. In an area with multiple tidal constituents, the potential power is greater than that available from the dominant tide alone (see, e.g., Garrett and Cummins, 2005). In the assessment, P_{max} was based on all constituents that were extracted for each site. The result makes it clear why serious consideration of tidal power is generally limited to regions with a large tidal differential. As reviewed by Garrett and Cummins (2008), this formula for P_{max} is also a reasonable approximation for the power available from a tidal fence across a channel that connects two large systems in which the tides are not significantly affected. In this case, a is the amplitude of the sinusoidal difference in tidal elevation between the two systems. In both situations, P_{max} is the average of the power over the entire tidal cycle.

In the P_{max} scenario, the fence of turbines is effectively acting as a barrage, so that P_{max} is essentially the power available when all water entering a bay is forced to flow through the turbines. P_{max} is thus likely to be a considerable overestimate of the practical extractable resource once other considerations, such as the extraction and socioeconomic filters shown in Figure 1.1, are taken into account. Reductions, even of the theoretical resource, can also occur in situations with more than one channel. In that case, installing turbines in one channel will tend to divert flow into other channels (Sutherland et al., 2007).

Lesser but still useful amounts of power could be obtained from turbines that are deployed in regions of strong current without greatly impeding a bay's overall circulation. As mentioned earlier, a single turbine can extract no more than the Lanchester-Betz limit. A total power P requires a volume flux through the cross-sectional area of the turbines of $P/(0.3\rho v^2)$, so that even with a current speed of 3 m/s, the volume flux required for a power of 100 MW is nearly 40,000 m^3/s (~1.4 million ft^3/s). Delivering such a flux would require a large number of turbines (for example, 120 turbines if each had a cross-sectional area of 100 m^2, or 24 turbines of 25 m diameter if full-scale turbines were employed). Many more turbines would be needed for more typical smaller average currents. Deploying an extensive array of turbines would impact other marine resource uses, such as other sea-space uses and ecological services, and would necessitate extensive site-specific planning.

More importantly, a single turbine or a small number of turbines would not significantly affect preexisting tidal currents, but an array large enough to generate tens of megawatts would have near-field back effects that reduce the current that each individual turbine experiences. In theory, this back effect is allowed for in a complete tidal fence considered in the calculation of P_{max}. However, other than for the case of a complete tidal fence, which results in estimates fairly close to the theoretical resource base, the tidal resource group's assessment cannot be used to estimate directly the potential power of strong currents in specific bays if more than a few turbines are considered.

Nonetheless, an early group presentation to the committee (Haas et al., 2010) attempted to evaluate the technical resource based on P_k, the power that could be obtained if turbines of a specific swept area and efficiency were deployed at a specified spacing in regions satisfying specified minimum average current and minimum water-depth criteria, while assuming that any back effects on the currents would be small. This assumption is likely to be false, particularly if P_k is a significant fraction of P_{max}. In that case, the turbines would have an effect on currents throughout the bay, and P_k would be an overestimate of the power available from the turbine array. If P_k is not a significant fraction of P_{max}, circulation in other areas of the bay might not be greatly impacted, but local reductions in the currents would still be likely and could again cause P_k to be an overestimate. The group could consider choosing the lesser of P_k and P_{max} as an estimate of the technical resource base. However, the committee notes that the tidal resource assessment group abandoned P_k and thereby any evaluation of the technical resource, because of the major uncertainties inherent in specifying parameters (personal communication to the committee from Kevin Haas, Georgia Institute of Technology, March 18, 2011).

Allowing for the back effects of an in-stream turbine array deployed in a limited region of a larger scale flow requires extensive further numerical modeling that was not undertaken in the present tidal resource assessment study and is in its early stages elsewhere (e.g., Shapiro, 2011). However, a theoretical study by Garrett and Cummins (2013) has examined the maximum power that could be obtained from an array of turbines in an otherwise uniform region of shallow water that is not confined by any lateral boundaries. The effect of the turbines is represented as a drag in addition to any natural friction. As the additional drag is increased, the power also increases at first, but the currents inside the turbine region decrease as the flow is diverted and, as in other situations, there is a point at which the extracted power starts to decrease. The maximum power obtainable from the turbine array depends strongly on the local fluid dynamics of the area of interest. Generally, for an array larger than a few kilometers in water shallower than a few tens of meters, the maximum obtainable power will be approximately half to three-quarters of the natural frictional dissipation of the undisturbed flow in the region containing the turbines. In deeper water, the natural friction coefficient in this result is replaced by twice the tidal frequency. For small arrays, the maximum power is approximately 0.7 times the energy flux incident on the vertical cross-sectional area of the array (Garrett and Cummins, 2013).

Estimates of the true available power must also take into account other uses of the coastal ocean and engineering challenges associated with corrosion, biofouling, and metal fatigue in the vigorous turbulence typically associated with strong tidal flows. This issue is discussed in greater detail in Chapter 7.

CONCLUSIONS AND RECOMMENDATIONS

The assessment of the tidal resource assessment group is valuable for identifying geographic regions of interest for the further study of potential tidal power. However, although $P_{\max}$ (suitably modified to allow for multiple tidal constituents) may be regarded as an upper bound to the theoretical resource, it is an overestimate of the technical resource, as it does not take turbine characteristics and efficiencies into account. More important, it is likely to be a very considerable overestimate of the practical resource as it assumes a complete fence of turbines across the entrance to a bay, an unlikely situation. Thus, $P_{\max}$ overestimates what is realistically recoverable, and the group does not present a methodology for including the technological and other constraints necessary to estimate the technical and practical resource base.

The power density maps presented by the group are primarily applicable to single turbines or to a limited number of turbines that would not result in major back effects on the currents. Additionally, errors of up to 30 percent for estimating tidal currents translate into potential errors of a factor of more than 2 for estimating potential power. Because the cost of energy for tidal arrays is very sensitive to resource power density, this magnitude of error would be quite significant from a project-planning standpoint. The limited number of validation locations and the short length of data periods used lead the committee to conclude that the model was not properly validated in all 52 model domains, at both spatial and temporal scales. Further, the committee is concerned about the potential for misuse of power density maps by end users, as calculating an aggregate number for the theoretical U.S. tidal energy resource is not possible from a grid summation of the horizontal kinetic power densities obtained using the model and GIS results. Summation across a single-channel cross section also does not give a correct estimate of the available power. Moreover, the values for the power across several channel cross sections cannot be added together.

The tidal resource assessment is likely to highlight regions of strong currents, but large uncertainties are included in its characterization of the resource. Given that errors of up to 30 percent in the estimated tidal currents translate into potential errors of more than a factor of 2 in the estimate of potential power, developers would have to perform further fieldwork and modeling, even for planning small projects with only a few turbines.

> **Recommendation: Follow-on work for key regions should take into account site-specific studies and existing data from other researchers. In regions where utility-scale power may be available, further modeling should include the representation of an extensive array of turbines in order to account for changes in the tidal and current flow regime at local and regional scales. For particularly large projects, the model domain extent should be expanded, probably to the edge of the continental shelf.**

As discussed in Chapter 7, further work on tidal assessments might include additional filters to progress from theoretical resource estimates to estimates of the technical and practical resource bases. Given that DOE's objective for the resource assessments is to produce estimates of the maximum practicable, extractable energy, it is clear that estimates of the practical resource base need to incorporate additional filters beyond those in the first column of the committee's conceptual framework (Figure 1-1). To investigate this, one might consider a region of strong tidal currents in which there is also a large tidal range, such as Cook Inlet. **Such an example could compare an in-stream tidal power scheme with a tidal**

power scheme involving a barrage across the head of a bay or involving a lagoon enclosing a coastal area. The reasons for this include the following: (1) as noted above, even a current of 3 m/s is equivalent to a head of only 0.5 m, much less than would be available with a barrage or lagoon; (2) the construction of a lagoon should be much simpler than the installation of a large number of in-stream turbines in a region of strong currents; and (3) the overall environmental impact of a lagoon might be less than that of an array of turbines producing the same average power.

3

Wave Resource Assessment

Power in ocean waves originates as wind energy that is transferred to the sea surface when wind blows over large areas of the ocean. The resulting wave field consists of a collection of waves at different frequencies traveling in various directions, typically characterized by a directional wave spectrum. These waves can travel efficiently away from the area of generation across the ocean to deliver their power to nearshore areas.

The theoretical resource estimate is a measure of how much energy flux is in the observed wave fields along the coasts. For the estimate of the theoretical resource, "wave power density" is usually characterized as power per length of wave crest; it represents all the energy crossing a vertical plane of unit width per unit time. This vertical plane is oriented along the wave crest and extends from the sea surface down to the seafloor. To capture this orientation, wave power is expressed as a vector quantity (see Table 1-2), and accurate representation of its magnitude and direction requires the consideration of the full directional wave spectrum.

Because wave energy travels in a particular direction, care must be taken when interpreting maps that show wave power density as a function of location but do not indicate predominant wave directions. It also must be recognized that if the energy is removed by a wave energy device from the wave field at one location, less energy will necessarily be available in the shadow of the extraction device. It would not be expected that a second row of wave energy devices would perform the same as the first row of devices that the wave field encounters because the spacing between rows of typical wave extraction devices does not allow adequate fetch to replenish the resource. This shadowing effect implies that one cannot estimate the theoretical resource as the sum of the wave power density over an area as one might do for solar energy. Note that the magnitude of this shadowing effect is likely to be highly dependent on the specific characteristics of the device (e.g., size, efficiency). Although there are some initial publications with rigorous analytical approaches for quantifying the effect of an arbitrary array of point absorber devices (e.g., Garnaud and Mei, 2010), shadowing effects due to actual devices are a topic of active research. The planning of any large-scale deployment of wave energy devices would require sophisticated, site-specific field and modeling analysis of the wave field and the devices' interactions with the wave field. This step is essential to refine any estimate of theoretical wave resource into an estimate of the technical wave resource.

DESCRIPTION OF WAVE RESOURCE ESTIMATE

The wave resource assessment group from the Electric Power Research Institute (EPRI) and Virginia Tech was tasked by DOE with producing estimates of the potential wave resource in U.S. coastal waters. To estimate the theoretical wave resource, the assessment group utilized a hindcast of wave conditions that was assembled by the National Oceanic and Atmospheric Administration's (NOAA's) National Center for Environmental Prediction using WAVEWATCH III, a state-of-the-art global wave generation and propagation model. Although the model was recently expanded to introduce physical processes specific to intermediate and shallow water (dispersion and refraction), the version available at the time of the assessment was the deepwater version, restricting its validity in intermediate and shallow water. The accuracy of WAVEWATCH III predictions is relatively well outlined in the scientific literature; in particular, WAVEWATCH III is known to reproduce wave height quite well (Chawla et al., 2009). However, it was unclear to the committee how well the reconstructed spectra represented the observed spectra, especially because the spectral reconstruction was optimized only at deepwater stations. Model accuracy is questionable in water depth shallower than about 50 m.

The assessment group first addressed several potential issues related to the available hindcast (e.g., a data record of only 51 months and the lack of full spectral information at all grid points) and then generated parametric fits of wave frequency spectra for all points of interest. To produce maps of wave power density, it computed a sum of the power density associated with all spectral components at a given location, regardless of wave direction. This is equivalent to considering the wave energy flux (i.e., power density) impinging on a cylinder of unit diameter that extends over the entire water column. The total theoretical resource was then computed by summation of these cylinders along an entire line of interest (such as a 50 m depth contour or a 50 nautical mile line).

The products of the wave resource assessment include a database of 51-month time series at 3-hour intervals of wave parameters that can be used to reconstruct the fitted frequency spectra, although directional spreading information is not available. In addition, the group provides maps of annual and monthly average wave conditions (such as wave power density, wave height, period, direction, shown in three-dimensional plots) in a geographic information system (GIS)[1] presented by the National Renewable Energy Laboratory's (NREL's) Renewable Resource Data Center. Bulk numbers for the total available theoretical wave resource and the total technical resource for different regions and for the entire United States are presented in the assessment group's written report (EPRI, 2011).

To produce an estimate of the technical wave resource, the assessment group adopted an approach based on analyzing the cumulative probability density function (PDF) of wave power converted by a wave-energy device of prescribed capacity as a function of wave height. For a given threshold operating condition (TOC) and maximum operating condition (MOC), the percentage of the wave power that can be recovered can be estimated as a function of the rated operating condition (ROC). Note that this approach considers several extraction filters (e.g., TOC, MOC, and ROC constraints) and simplifies or neglects others (e.g., efficiencies, device spacing). The group generated cumulative PDFs for sites along the U.S. coastline and estimated the technical wave resource using the TOC and MOC values specific to three devices (Archimedes Wave Swing, Pelamis, and Wave Dragon) for various ROC values.

Compared to the more rigorous approach taken to compute the theoretical resource, the technical resource estimate relies on considerably looser assumptions. In the report, many of the factors are bundled into a single "packing density" of power per kilometer of installed system and some simple assumptions about the range of conditions in which the installed system can operate. Inaccurate or overly optimistic assumptions in these evaluations could create misleading estimates of the technical resource. In fact, the numbers used by the wave assessment group indicate that the technical resource is between 30 percent and 90 percent of the theoretical resource, depending on location. These concerns are addressed in more detail below.

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[1] Available at http://maps.nrel.gov/mhk_atlas.

COMMITTEE COMMENTS

Methodology, Results, and Presentation

The committee benefited from three presentations by the wave resource assessment group[2,3,4] and their final report (EPRI, 2011). The committee commented on the work of the assessment group on the basis of these materials and has identified concerns related to the suitability of the hindcast data set in shallow waters, the technique used to generate the aggregate theoretical resource, the lack of directional information, and the technology assumptions utilized for assessment of the total technical resource.

Shallow Water Bathymetry

At a resolution of 4 minutes globally, the WAVEWATCH III simulations cannot capture wave transformation effects due to bathymetric features over shorter spatial scales because the simulations cannot resolve such variability. However, these bathymetric effects are known to be important at depths shallower than approximately 50 m (Dean and Dalrymple, 1984). Shallow-water regions might be of significant interest to developers who seek to optimize the ratio of construction and operating costs to the expected extractable power (largely a function of cable cost/distance to the coast). The methodology used precludes providing site-specific information to such developers. Reliable site-specific information in shallow waters can only be produced using results from models with higher spatial resolution that include the consideration of shallow-water physics (e.g., shoaling, refraction, diffraction). The wave resource assessment group acknowledges that its results are not accurate in the shallower waters of the inner continental shelf, and as such the shallowest water depths analyzed are 50 m (or 20 m on the Atlantic coast, where the continental shelf is smoother and less steep). Areas where inaccuracies due to these bathymetric concerns are most prevalent are blanked out in the GIS. While these regions could be assessed in the future using a shallow-water model such as SWAN, the results of

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[2] P. Jacobson, Electric Power Research Institute, G. Hagerman, Virginia Tech, and G. Scott, National Renewable Electricity Laboratory, "Assessment and mapping of the U.S. wave energy resource," Presentation to the committee on November 15, 2010.

[3] G. Hagerman, Virginia Tech, and P. Jacobson, Electric Power Research Institute, "Meaning and value of U.S. wave energy resource assessments," Presentation to the committee on February 8, 2011.

[4] G. Hagerman, Virginia Tech, P. Jacobson, Electric Power Research Institute, and G. Scott, National Renewable Energy Laboratory, "Assessment and visualization of United States wave energy resource," Presentation to the committee on September 27, 2011.

the present assessment are insufficient to initialize such a model because there is no available directional spectral information.

Validity of a Limited Dataset

An additional minor concern in the theoretical wave assessment is the limited statistical inference from the 51-month dataset. Although NREL conducted a "typicality" study to demonstrate the adequacy of the dataset, one could still argue whether the results of short time series are valid. A simpler approach could be to use confidence intervals to reflect the accuracy of the assessment. For example, when using a 20-year time series, the significant wave height representing a 50-year event on the East Coast is on the order of 8.5 m, with a 95 percent confidence interval between 7.5 and 9.5 m. This represents an expected theoretical power varying by a factor of 1.6 between the limits of the confidence interval; the mean value is accurate in a confidence interval of ±25 percent. Using a 51-month time series instead of 20 years significantly increases the range of the 95 percent confidence interval, although it could still be quantified.

Similarly, the occurrence of extreme events is not captured well in the 51-month time series, as acknowledged by the NREL validation group.[5] As a result, the cumulative probability distribution curves might be less accurate for large waves. It is unclear how this affects the results, but an accurate evaluation of the confidence interval for extreme events will be needed to assess device survivability.

Scalar Power Density

A further concern related to the theoretical resource assessment is the use of the unit-circle approach. This approach has the potential to double-count a portion of the wave energy if the direction of the wave energy flux is not perpendicular to the line of interest or if there is significant wave reflection from the shore. This technique was the subject of criticism in the committee's interim report (Appendix B). The assessment group responded to this point, and its final report correctly computes the wave-energy flux across lines parallel to the coast by integrating only the component of the wave energy flux vector that crosses the line (i.e., the normal component). It retains the results from the previous unit-circle approach in their report and shows that the line integral is 56-87 percent of the unit-circle estimate, depending on location (see Tables 2.16-2.19 in EPRI, 2011). Despite acknowledging the bias of the unit-circle approach for estimating

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[5] G. Scott, National Renewable Energy Laboratory. "Validation and display of wave energy resource estimates," Presentation to the committee on February 8, 2010.

the total theoretical resource, the assessment group continued to use the summation of scalar power density at all unit circles rather than the perpendicular component of power density. Although this is consistent with various European wave resource assessments, it clearly overestimates the total theoretical resource.

Recoverable Power

In order to take into account the technical details of the wave extraction devices, the assessment group utilized the concept of recoverable power. While this concept is an interesting initial approach to the technically recoverable resource, it assesses only the available power to specific devices and should not be confused with the technical resource as defined in the committee's conceptual framework. Recoverable power integrates the fundamental technical constraints based on wave frequency and wave height thresholds, as well as indirectly on the temporal variability, before loss in the mechanical and electrical power transformation. Hypothetical or selected devices are considered operational in given wave periods and significant wave height ranges, specific to the device's characteristics.

A similar methodology was applied to the Energetech Oscillating Water Column in Rhode Island coastal waters (Grilli et al., 2004). By applying constraints including MOC and TOC as well as the observed temporal variability, an estimated recoverable technical power of 30 percent of the theoretical power was obtained. This is of comparable order of magnitude to the assessment group's minimal packing density.

The committee agrees that the method provides a convenient correct bulk number of the recoverable power at an individual site but would like to strongly reiterate that (1) the method is a rough estimation and is therefore inaccurate and (2) the method does not represent the technically recoverable resource. The mechanical and electrical losses in the transformation processes and transmission significantly reduce the technical resource, typically to 15-25 percent of the recoverable power. Returning to the example above, the Energetech prototype would have had a technical power resource of just 4.5-7.5 percent of the incident wave's theoretical power.

Capacity Packing Density

The group's approach to recoverable power is highly dependent on the assumptions made in determining the devices' rated power and density. Packing more devices perpendicular to the wave direction of propagation would ideally allow for the extraction of most of the power from the waves (the fraction not extracted by the first row of devices would then be partially extracted by the second row, leaving a further reduced fraction to the third row, and so on). To estimate the fraction of recoverable power at a given point, the assessment group compared the power carried by the incident wave field to the estimated recoverable power assuming a priori a deployment of multiple devices, defined by their combination of rated power and density. This ad hoc approach prescribes such an array using a capacity packing density, specified as 10 kW, 15 kW, and 20 kW per meter. The capacity packing density is defined as "the maximum extractable power by the array of devices," similar in concept to the rated power (maximum extractable power by a single device). The range of values chosen is based on characteristics of the Pelamis (Pelamis Wave Power) and Powerbuoy (Ocean Power Technologies) extraction devices.

Their results indicate that 29-93 percent of the theoretical resource could be captured. The assessment group assumed that the devices could be packed in a series of parallel rows perpendicular to the main incident wave direction. Such a packing process alters the wave field because of the extractive characteristics of the device and the interaction of the wave field with the device, and the quantification of those interactions and resulting wave field constitute an active field of research. A focus of this research is optimizing the device layout to maximize the fraction of power extracted by an array or multiple arrays of *n* devices compared to the power extracted by *n* independent devices. This ratio is known as the *q* factor and represents the interaction of the wave field with the specified device(s) (Borgarino, 2011). This *q* factor is not explicitly included in the group's recoverable power estimate; however, its estimation could be implicit in the concept of capacity packing density.

One theoretical study on wave-device interaction modeled the Wave Dragon Energy Converter deployed in the highly energetic North Sea (Beels et al., 2009). It concluded that capturing 1 GW of power would require the deployment of either a 200-km-long single row of devices (5 kW/m) or a five-row staggered grid about 3 km wide and 150 km long (7 kW/m). Such capacity packing density values are significantly lower than those assumed by the assessment group. Furthermore, this result does not take into account that the recovered power must be transformed into electricity and then transmitted.

Figure 3-1 further clarifies the difference between the concepts of recoverable power and technical power. A wave energy facility will consist of many elements, such as the wave-motion absorber, the machinery to convert that motion to electrical energy, power conditioning, and power transmission. The wave-motion absorbing part of the device is unlikely to absorb more than a single-digit percentage of the incident wave energy for a typical point absorber (Falnes, 2007), but that limitation can be overcome by adding many devices, as described above. This is not

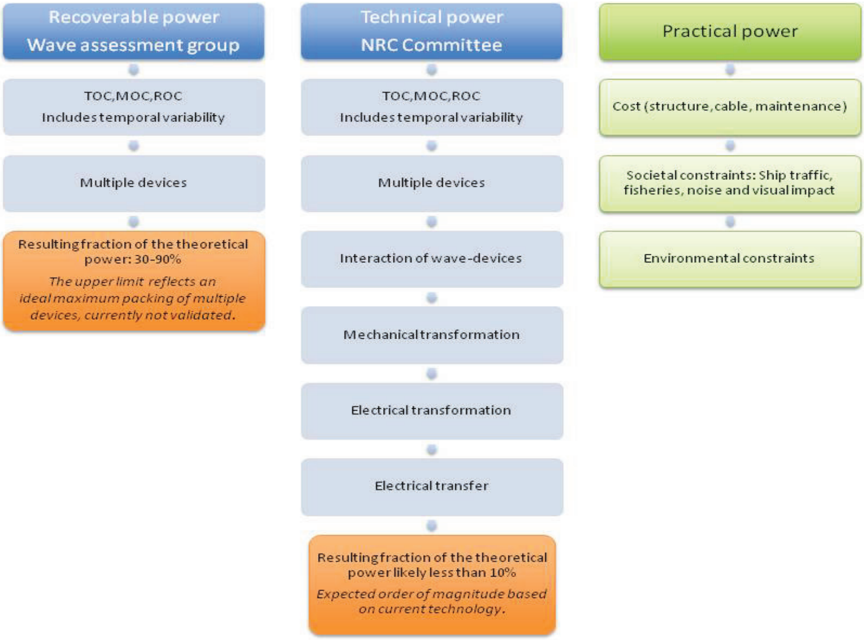

FIGURE 3-1 A comparison of the concepts of recoverable, technical, and practical power. The flowchart describes the filters adopted in each concept. TOC, MOC, and ROC stand for threshold operating condition, maximum operating condition, and rated operating condition.

necessarily cost effective but stays within the definition of the technical resource. However, all wave-energy conversion devices will have systems to convert energy from mechanical to electrical form and for electrical transmission needs. None of these systems are likely to operate at efficiencies much greater than 90 percent and will probably have more realistic efficiencies of 50-70 percent. This calls into question claims of wave energy facilities that capture 90 percent or more of the available energy. As emphasized in Figure 3-1, it is important to place these numbers in the appropriate framework.

Validation

The committee agreed that the assessed estimates of monthly or annual mean wave power were the primary metrics for validation. Inaccuracies in these estimates could result from two primary sources of error: (1) inaccuracies in the WAVEWATCH III simulations and (2) differences between the full and reconstructed wave spectra.

The NREL validation only examined average wave power estimates produced by the assessment group and did not address the validity of the spectral reconstruction.[6] The committee found that the validation was generally lacking in rigor, especially given the paucity of available data. The 44 observational locations were insufficient relative to the gradients in power density shown in the assessment, with order of magnitude changes in power density between some locations without validation. More important, no skill metrics were given.

While little can be done to address this shortcoming in the near term, data from the Northeast Regional Association for Coastal Ocean Observing System,[7] Scripps Institution of Oceanography's Coastal Data Information Program buoys,[8] and the network of the National Federation of Regional Associations for Coastal and Ocean Observing[9] could be used to provide additional validation information in the future.

Perhaps more important, the NREL validation group calculated wave power using a simplified formulation that is valid only in deep water, while the wave resource assessment group used the full reconstructed spectrum for this estimate. Finally, the validation effort did not report any statistical measures that would quantify the agreement between observations and estimates, such as root-mean-square error values, R^2 statistics, and the like.

CONCLUSIONS AND RECOMMENDATIONS

The wave resource assessment, especially the GIS visualization, could prove useful to developers who are interested in identifying general regions for their particular wave energy conversion devices. However, the spatial resolution of the assessment is of necessity very coarse, and there are numerous extraction and practical filters that will likely dominate the actual development of marine and hydrokinetic resources. **Site-specific analysis for wave-energy facilities will still be needed at candidate locations.** Additional information about the potential temporal variability of electricity generation would also be needed for electricity system operators to integrate wave power into utility-scale electricity systems.

The theoretical wave resource assessment estimates are reasonable, especially for mapping wave power density, although **the accepted unit-circle approach overestimates the aggregate total theoretical resource.**

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[6] G. Scott, National Renewable Energy Laboratory. "Validation and display of wave energy resource estimates," Presentation to the committee on February 8, 2010.

[7] Available at http://www.neracoos.org.

[8] Available at http://cdip.ucsd.edu/.

[9] Available at http://www.usnfra.org/.

The estimates are limited by sparse data and the assumptions inherent in the WAVEWATCH III model. Most notably, the assessment is limited to deep-water locations (depths greater than 50 m on the U.S. West Coast and 20 m on the East Coast). While there has been a recent trend to envision wave energy extraction in deep water to avoid ecological impacts, there are several potential projects seeking shallow-water siting because it affords closer proximity to transmission lines and other logistical requirements. Devices may be placed in shallow-water areas because such siting also reduces construction and maintenance costs.

> **Recommendation: Any future site-specific studies in shallow water should be accompanied by a modeling effort that resolves the inner shelf bathymetric variability and accounts for the physical processes that dominate in shallow water (e.g., refraction, diffraction, shoaling, wave dissipation due to bottom friction and wave breaking).**

The technical resource assessment is based on loose assumptions about how much average power is available from each kilometer of installed wave-energy conversion facility, indicating that nearly all of the available wave energy in some sites could be converted to electrical energy if enough wave-energy converters are installed. Since there will always be mechanical and electrical loss mechanisms, this seems unlikely. **Conversion percentages from theoretical wave power to electricity on the grid are expected to be dramatically less than the 90 percent values that are reported as the recoverable resource.** In addition, estimates of the current state of wave-energy technology are not based on proven devices.

Finally, although the optimal layout of wave farms designed to maximize wave power capture and minimize costs is still an open question, **the footprint of the infrastructure required to recover 1 GW cannot be reduced to less than a row of devices more than 100 km long and parallel to the coast, given current levels of technology.** Because of the high development and maintenance costs, low efficiency, and large footprint of wave converter technologies, such devices would be a sustainable option only for smaller-scale developments that are considerably less than 1 GW, ideally close to territories with limited demand, such as islands.

4

Ocean Current Resource Assessment

Ocean currents (excluding tidal currents) are mainly generated by wind and affected by Coriolis forces (Rossby number <1). While they can be affected by water density gradients, the dynamics of ocean circulation lead to ocean current patterns that can be largely unrelated to the local winds. In particular, there is the phenomenon of "western intensification," whereby wind stress causes strong, narrow currents that carry warm water from the tropics toward the poles along the western boundaries of ocean basins. One example is the Gulf Stream, with an ocean current in the Florida Strait that can exceed 2 m/s (Hanson et al., 2011).

The potential of exploiting ocean currents for power generation, in much the same way as is done with wind, has long been a matter of interest. However, the amount of power put into steady ocean currents by the local winds is estimated to be no more than about 1 TW (Wunsch, 1998). As expected, this is similar to the estimated losses through bottom friction (Arbic et al., 2009; Müller et al., 2010). It thus seems unlikely that power approaching 1 TW could be extracted from ocean currents worldwide without significant back effects. Nonetheless, turbines in strong currents might be able to provide significant amounts of power in some locations.

A single submerged turbine placed in an ocean current with a swept area A in water with density ρ and a current of speed v can produce power up to the Lanchester-Betz limit of $0.3\rho A v^3$.[1] For example, if A is 1,000 m^2 and v is 2 m/s, the power calculated is 2.4 MW. If currents are to

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[1] The Lanchester-Betz limit applies to a turbine in an unbounded flow.

be exploited, the cubic power of v demonstrates the advantage of deploying turbines in regions of strong ocean currents. As the density of water is approximately 850 times that of air, a marine turbine in an ocean current of 1 m/s can theoretically produce as much power as a wind turbine with the same swept area A in a wind with a wind speed of 9 m/s.[2]

Similarly, the drag on an ocean current device due to the higher water density is likely to result in forces on the marine turbine that are greater than that on a wind turbine. This can present significant engineering challenges. As mentioned in Chapters 2 and 7, problems with corrosion may also be significant for marine turbines, though this is also a consideration for offshore wind turbines. The reduction in turbine performance from biofouling of marine turbines may be more significant than the loss of performance caused by blade pitting due to dust particles and insects.

PROJECT DESCRIPTION

Based on presentations given by the ocean current resource assessment group,[3,4,5] the ocean current energy assessment is being conducted using two different approaches: (1) estimation of the total ocean current technical resource around U.S. coastal waters from the P_k method, which used the predicted undisturbed flow field output from an ocean model (see Chapter 2, "Estimate of Available Tidal Power," for more discussion on P_k), and (2) estimation of the total available power within the Gulf Stream by incorporating extra dissipation to represent energy extraction into theoretical models of the Gulf Stream western boundary current. Work using the first approach has been mostly completed,[6] but investigation of the second approach was not complete when this report was written.

In the first approach, the theoretical resource (kinetic power density) and the technical resource (P_k) are calculated using velocity fields gener-

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[2] It should be noted that a wind turbine deployed in an area with 9 m/s wind speed is likely to sweep out a much larger area than 100 m^2.

[3] K. Haas, H.M. Fritz, Z. Defne, and X. Yang, Georgia Tech Savannah; S.P. French and X. Shi, Georgia Tech Atlanta; V.S. Neary, P. Schweizer, and B. Gunawan, Oak Ridge National Laboratory, "Assessment of energy production potential from ocean currents along the United States coastline," Presentation to the committee on September 27, 2011.

[4] K. Haas, H.M. Fritz, Z. Defne, and X. Yang, Georgia Tech Savannah; S.P. French and X. Shi, Georgia Tech Atlanta; V.S. Neary, P. Schweizer, and B. Gunawan, Oak Ridge National Laboratory, "Assessment of energy production potential from ocean currents along the United States coastline," Presentation to the committee on December 12, 2011.

[5] K. Haas, H.M. Fritz, Z. Defne, and X. Yang, Georgia Tech Savannah; S.P. French and X. Shi, Georgia Tech Atlanta; V.S. Neary, P. Schweizer, and B. Gunawan, Oak Ridge National Laboratory, "Assessment of energy production potential from ocean currents along the United States coastline," Presentation to the committee on April 9, 2012.

[6] See preceding footnote.

ated from regional or global ocean models. To select the best suited models, the group initially assessed the configurations and performance of a set of models, including HYCOM-GLOBAL (Hybrid Coordinate Ocean Model), HYCOM-GOM (Gulf of Mexico), JPL-ROMS (NASA Jet Propulsion Laboratory Regional Ocean Model System), and NCOM (Navy Coastal Ocean Model).[7] HYCOM-GLOBAL is a real-time 1/12-degree global nowcast/forecast ocean circulation model maintained by the Naval Research Laboratory[8] and sponsored by the National Ocean Partnership Program, while HYCOM-GOM is a regional model with grid resolution of 1/25 degree nested within the HYCOM-GLOBAL model. HYCOM employs a hybrid coordinate system that combines (1) an isopycnal coordinate in the stratified ocean, (2) a terrain-following coordinate in shallow coastal regions, and (3) a *z*-level coordinate in the mixed layer and/or unstratified seas. This unique approach in vertical coordinates gives HYCOM the ability to simulate different physical processes in the ocean at different scales using a single model (Halliwell et al., 2000). Power density distributions and variability and confidence intervals of the probability distributions are calculated based on the daily HYCOM-GLOBAL and HYCOM-GOM results from 2004 to the present. Model selection for the ocean current energy assessment was based on a number of criteria, including model error statistics, model grid resolution, length of simulation period, and model output intervals. HYCOM-GLOBAL was selected for the U.S. West Coast, Alaska, and Hawaii coastal regions; a hybrid NCOM-HYCOM was selected for the East Coast; and HYCOM-GOM was selected for the Gulf of Mexico and the Florida Current. The assessment group created an ocean current database for coastal waters, up to 200 nautical miles offshore, using the selected models.

An independent validation of the database was conducted by the Oak Ridge National Laboratory (ORNL, 2012). The main challenge of validating the predicted ocean currents is the paucity of observational data. The most complete datasets are those from high-frequency (HF) radar and from a cable off Florida's east coast (both of which were quite limited in time), and an additional stationary acoustic Doppler current profiler (ADCP) dataset from Florida Atlantic University was also used. In general, the model results had a reasonably good match to the ADCP data but a poor one to the HF radar. Predicted daily flow from the model matched the distribution pattern of the submarine cable data, although the cable data showed a higher percentage of occurrence in the maximum flow range.

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[7] See footnote 3.

[8] Available at http://www7320.nrlssc.navy.mil/GLBhycom1-12/skill.html; http://hycom.org/.

A Web-based geographic information system (GIS) for the ocean current resource assessment will be created to disseminate the study results, as was done for the tidal energy assessment study (Georgia Tech Research Corporation, 2011). The GIS database was developed using ArcView GIS software that allows for downloading model results for further analysis, such as GIS layers of the monthly and yearly means, standard deviations[9] and power densities, probability distributions for current speed and direction, and the effective power using a specified number of turbines, efficiencies, and dimensions.

The project group finished compiling the database for flow field output from the models, and the validation group has a draft report of the group's results (Kevin Haas, personal communication; ORNL, 2012). The group began analysis of the database in June 2012. Web page design is scheduled to be completed by spring 2013 and the final estimate of total theoretical resource will be completed by June 2013.

COMMITTEE COMMENTS

Methodology

As part of the model selection process, model results were compared to about 1,250 Argo temperature and salinity profiling floats.[10] Scatter plots of current speed indicated that the Argo data were more scattered than model results, which is likely due to the difference in time interval between the model results (daily) and the Argo data (every 6 hours). Similarly, the higher occurrence rate in the maximum flow range for submarine cable data used during the validation process could also be caused by a shorter (6-hour) data interval. Comparison of model results and data might be improved by creating daily averages of both the Argo and the cable data.

Although HYCOM provides the most complete model outputs that are available for the ocean current energy assessment, there is a concern that using the undisturbed velocity field for the estimates of the theoretical and technical resource without considering the back effect due to the presence of turbines will overestimate the ocean current resource.

To calculate the technical resource, the assessment group used the P_k formulation (Haas et al., 2012), which accounts for the turbine array configuration (e.g., turbine size, spacing, efficiency):

$$P_k = \Sigma\, 0.5 \rho v^3 E_f A_s A_c N \tag{1}$$

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[9] In an early presentation, the project group indicated that it used a 2 percent exceedence value; the committee strongly suggested using a simple standard deviation instead.

[10] Available at http://www.argo.ucsd.edu/About_Argo.html.

where E_f is efficiency, A_s is the swept area of the turbine (m^2), A_c is the surface area of the computation cell (m^2), and N is the number of turbines per unit surface area. As discussed in Chapter 2, P_k is meaningful only when it is assumed that back effects on the surrounding flow fields are small. This assumption fails when P_k becomes large as the turbine size and density increase, causing P_k to overestimate the technical resource.

Validation

The validation for the ocean current resource assessment was conducted for the Florida Strait region with a very limited data set for HF radar (184 days) and ADCP measurements (1 year) (Haas et al., 2012; ORNL, 2012). A 7-year record of submarine telephone cable data was also used, although it did not provide direct current measurement. The validation results indicate some discrepancies between the model and the independent data but find that the HYCOM-GOM model provides an acceptable representation of Florida Strait ocean currents. Because there are extensive observational studies of the Florida Current (e.g., Schmitz and Richardson, 1968; Larsen and Sanford, 1986; Johns and Schott, 1987; Meinen et al., 2010), the validation could have been strengthened by obtaining more existing data for comparison with the model results. This is also noted in the validation report, with an emphasis on the value of additional stationary ADCP data.

Estimate of Ocean Power Potential

Although model results are available along the entire U.S. coast, calculated mean power density indicated that ocean energy in the Gulf Stream is significantly higher than that in other U.S. coastal waters. Therefore, the main effort of the resource assessment is focused on the Gulf Stream, primarily the Florida Current in the Gulf of Mexico. To demonstrate the P_k methodology, the assessment group presented some preliminary results of the total technical resource available for the Florida Current using a set of specific values for turbine configuration (Haas et al., 2012). Based on the group’s calculation, P_k in the Florida Current is 14.1 GW, ~62 percent of the calculated total natural kinetic energy flux (~20 GW). The committee is concerned about such a high P_k value, as the back effect on the currents could be significant. While the potential of a single turbine, or a small number of turbines, may be estimated using the existing currents, an array of turbines will impede and reduce the current in the region. Thus, it is incorrect to estimate power potential by adding up the potential of all the currents in an arbitrary array of turbines on the assumption that the current is unaffected.

Allowing for the back effects of an in-stream turbine array deployed in a limited region of a larger scale flow was discussed in Chapter 2. As noted, a theoretical study by Garrett and Cummins (2013) examined the maximum power that could be obtained from an array of turbines in an otherwise uniform region without lateral boundaries. The study assumes water of constant depth, with the turbines effectively assumed to occupy the whole vertical water column so that the flow is modeled as two-dimensional (horizontal variations only). The effect of the turbines is represented as a drag in addition to any natural friction. As the additional drag is increased, the power also increases at first, but the currents inside the circle decrease as the flow is diverted and, as in other situations, there is a point at which the extracted power starts to decrease. The maximum power obtainable from the turbine array depends strongly on the local flow. In most instances, the power from the array of turbines will be limited to a fraction of the kinetic energy flux impinging on the turbine array, most likely no more than approximately 0.7 times the incident flux. If, however, the array is very large (for example, hundreds of square kilometers), the theoretical power could be limited by friction and would be between 50 and 75 percent[11] of the natural frictional dissipation of the undisturbed flow in the region containing the turbines (Garrett and Cummins, 2013).

In other words, more than a fraction of the incident energy flux can be obtained only for very large arrays, and then it scales with the natural dissipation in the region. The technical resource will be less than the theoretical resource, possibly considerably less, because of factors that include wake losses and drag on supporting structures. Furthermore, this estimate does not allow for a reduction of the incident flow due to the impact of a large turbine farm on the larger-scale regional flow. High-resolution numerical modeling of disturbed flow due to MHK array deployment would provide a fundamental theoretical foundation for optimizing turbine locations. An optimal layout would locate turbines outside the wake of upstream turbines, while minimizing the distance between devices to lower cable costs. Because these types of optimizations are site-specific, it would be useful to model the most favorable layout for the Florida Current to provide a better estimate of the available technical resource.

The committee further considered the global potential of ocean currents. While there is 800 GW of global dissipation by steady currents, 80 percent of that occurs in the Southern Ocean. B. Polagye and M. Kawase of the University of Washington (personal communication, 2011) apportion the rest by area, assigning only 20 GW to the North Atlantic.

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[11] The fraction is 0.5 if the friction is taken to be linear in the local current speed and 0.75 if it is taken to be quadratic.

A greater estimate of 70 GW is obtained by Csanady (1988). However, if only a small fraction can be extracted without noticeably disrupting natural ocean circulation, it is unlikely that more than a few gigawatts can be obtained from the ocean current resource in U.S. waters.

The most promising site for the exploitation of strong currents in the North Atlantic is in the Florida Straits. Modeling the flow as if it were in a confined channel would be inappropriate, as the flow takes the form of a jet with weak currents on either side of the strait. Placing turbines in the jet would tend to broaden it, maintaining the volume flux to a first approximation but reducing the current speed. If the reduction in speed is to be no more than 10 percent, then the committee estimates that no more than 20 percent (4 GW) of the 20 GW incident energy flux could be extracted. Allowing for wake losses, drag on supporting structures, and internal turbine and transmission losses, it is unlikely that more than 1 or 2 GW could practically be transmitted to the electricity grid. Additionally, high turbine density in the water column may substantially divert the Florida Current and force the current flow around the Bahamas. This would reduce the local volume flux, creating a practical extractable power that would be even less than 1 or 2 GW. These preliminary estimates need refinement to account for the actual current profile and for stratification effects. The ocean current assessment group should properly account for back effects by simulating total extractable energy using three-dimensional numerical models that include representation of turbine arrays.

The committee also believes that the assessment group needs to further explore and discuss the effects of meandering and seasonal variability of the Florida Current on the extractable power estimate, as the current shows strong meandering and seasonal variability at various frequencies (Johns and Schott, 1987; Lee et al., 1995).[12] These aspects of spatial and temporal variability in the resource could potentially limit the placement of MHK devices to narrow regions with consistent flow and could impact the ability to bring ocean current power into the electrical grid. Furthermore, an accurate assessment of the large-scale technical ocean current resource requires consideration of the near-field wake effect near the device.

CONCLUSIONS AND RECOMMENDATIONS

The ocean current resource assessment is valuable because it provides a rough estimate of ocean current power in U.S. coastal waters. However, less time could have been spent looking at the West Coast

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[12] Available at http://oceancurrents.rsmas.miami.edu/caribbean/florida.html.

in order to concentrate more fully on the Florida Current. Overall, the committee does not expect the practical resource of the Florida Current to be more than 1 or 2 GW, though further work is required. Given that observation in the region of the Florida Current is very limited, a comprehensive field observation with focus on the Florida Current is necessary in the future. Additionally, the ocean current validation was conducted with a very limited data set and could be substantially strengthened by including more existing data for comparison with model results.

> **Recommendation: Any follow-on work for the Florida Current should include a thorough evaluation of back effects related to placing turbine arrays in the strait by using detailed numerical simulations that include the representation of extensive turbine arrays. Such models should also be used to investigate array optimization of device location and spacing. The effects of meandering and seasonal variability within the Florida Current should also be discussed.**

5

Ocean Thermal Energy Conversion Resource Assessment

Ocean thermal energy conversion (OTEC) is the process of deriving energy from the difference in temperature between surface and deep waters in the tropical oceans. The OTEC process absorbs thermal energy from warm surface seawater found throughout the tropical oceans and ejects a slightly smaller amount of thermal energy into cold seawater pumped from water depths of approximately 1,000 m. In the process, energy is recovered as an auxiliary fluid expands through a turbine. There are two basic OTEC plant design types—open cycle and closed cycle. Open-cycle plants use vacuum to flash evaporate warm surface seawater, and the resulting steam is used to drive a low-pressure turbine-generator. Cold seawater drawn up from depth is used to condense the steam. Desalinized fresh water is a by-product produced in an open cycle system. Closed-cycle designs use an intermediate working fluid, such as ammonia, to run a higher pressure turbine-generator system and require an additional heat exchanger.

Fundamentally, OTEC systems are similar to most other heat engines. There are, however, significant practical aspects of the technology that make it difficult to implement, largely resulting from the small available temperature difference ΔT (~20ºC) between the warm and cold seawater streams (Figure 5-1). The theoretical maximum thermodynamic efficiency of a heat engine is proportional to ΔT, with a ΔT of 20ºC being fairly low. Because of the low efficiencies, OTEC plants require very large equipment (e.g., heat exchangers, pipes) and seawater flow rates (~200-300 m^3/s for a typical 100-MW design) that would exceed those from any existing

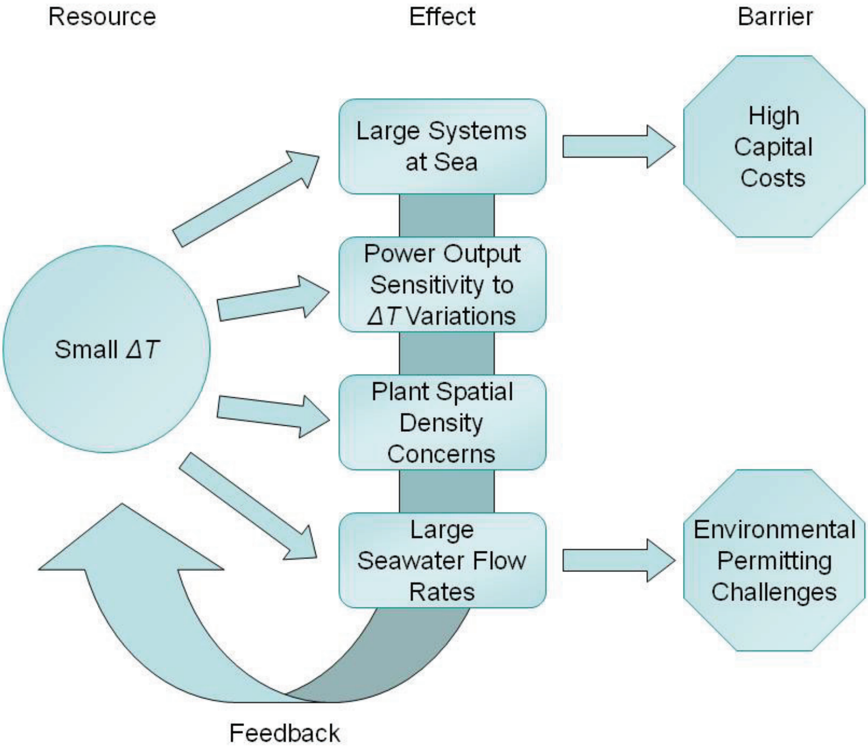

FIGURE 5-1 Barriers and concerns for OTEC deployment. OTEC plants work with a small temperature difference that necessitates large physical plants with high seawater flow rates. Such large flow rates may cause a decrease in the available temperature resource due to flow disturbance from the plant and may lead to significant environmental impacts.

industrial process in order to generate a significant amount of electricity. The cold-water pipe is one of the largest expenses in an OTEC plant. As a result, the most economical OTEC power plants are likely to be open-ocean designs with short vertical cold-water pipes. However, these designs face the issue of bringing power to shore. The earliest practical OTEC plants are likely to be based on or near tropical islands that have steep topography, which will make it easier to reach deep cold water and transmit power to shore. In the future, OTEC plants could also use the generated energy to produce hydrogen or extract carbon dioxide from seawater in order to produce synthetic fuel using a modified Fischer-Tropsch process in remote ocean locations. A side benefit could be in using pumped-up cold seawater for air conditioning systems, with costs of one-tenth or less that of running a regular air-to-air heat pump (Jagusztyn and Reny, 2010). Stand-alone seawater air conditioning systems modeled on this idea are already in use on some tropical islands.

The potential for harnessing power from the open ocean is attractive, especially for low-latitude island populations. In the United States, Hawaii has been a proving ground for OTEC, with several test plants built in the past four decades. These include a barge-based mini-OTEC (50 kW) in 1979, a ship-based OTEC-1 (1 MW) in 1980, and a shore-based Open Cycle 210-kW plant operated from 1993 to 1998 (Vega and Evans, 1994).

PROJECT DESCRIPTION

The most favorable sites for OTEC can be identified using local water temperature and depth data in a simple calculation of power density, adapted from Nihous (2007a). In the following equation, the power density per unit of upwelled cold water (W/(m^3/s))—where P_{net} is net power and Q_{cw} is the deep seawater flow rate—is expressed as a function of the environmental temperature difference (ΔT), the surface seawater temperature (T_s), the average density of seawater (ρ), the specific heat of seawater (C_P), the turbogenerator efficiency (TGE), and the fractional losses to pumping (PL) (both head losses and drag):

$$\frac{P_{net}}{Q_{CW}} = \frac{\rho C_P \times TGE \times (\Delta T)^2 (1 - PL)}{8(273 + T_S)} \qquad (1)$$

The quadratic dependence on ΔT arises from a linear heat transfer dependence and the expression for the Carnot efficiency (~ΔT/absolute T). Nonlinearity is weak within the limited temperature range of the ocean, so the assessment group used a linearized approximation of plant performance to simplify the calculations (Lockheed Martin Mission Systems & Sensors, 2012).

The OTEC resource assessment group conducted its study by using the output from a 2-year model run of the global HYbrid Coordinate Ocean Model (HYCOM) to determine the ocean's temperature structure.[1] HYCOM, maintained by the Naval Research Laboratory, is a real-time 1/12-degree global nowcast/forecast ocean model with 32 vertical levels. The group chose HYCOM because the model uses density as the vertical coordinate below the surface layers, which would provide realistic simulations of deepwater ocean physics. The model provides an approximately 7 km resolution, and the 2-year model run included strong El Niño and

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[1] H.P. Hanson, Florida Atlantic University, "Global OTEC resource assessment," Presentation to the committee on September 27, 2011.

La Niña events in order to assimilate extremes into the dataset. Within their database, sites can be evaluated for annual average and winter and summer temperatures.

The group chose the cold water source to be the temperature at either the bottom of the ocean, the depth at which the temperature gradient is less than 7°C/km, or 1,000 m, whichever was shallowest. The group chose to use a specific OTEC plant model that is proprietary to Lockheed Martin as the basis for its resource assessment.[2] This is a nominal 100-MW plant, a size generally considered to be large enough to be economically viable and of utility-scale interest yet small enough to construct with manageable environmental impacts (Whitehead and Gershenfeld, 1981). However, since no plants this large have yet been built, there are many technical and environmental challenges to overcome before even larger plants are attempted.

COMMITTEE COMMENTS

Methodology

In its approach, the assessment group noted that the theoretical resource and the technical resource are inextricably linked. The temperature differentials generated by the HYCOM model are essentially the theoretical assessment; evaluating the temperature differential via an assumed plant model leads to a technical resource assessment. Therefore, a key imperative for the OTEC resource assessment is to evaluate global ocean surface temperatures and their seasonal fluctuations, along with temperature gradients as a function of depth and location. The committee views the use of the HYCOM model for assessment of the theoretical resource to be inadequate and also regards the application of a specific proprietary Lockheed Martin plant model with a fixed pipe length to be unnecessarily restrictive. A more generic plant model—for example, Nihous (2007a)—would have been preferable to make it easier for developers to evaluate different plant models by varying pipe lengths or turbogenerator efficiencies.

The DOE funding opportunity for OTEC was the only one to specify that the assessment should include both U.S. and global resources, and the assessment group chose to focus on the global resource. The committee believed, however, that more emphasis should have been placed on potential OTEC candidates in U.S. coastal waters. To demonstrate this point, the committee evaluated equation 1 and used the National Oceanographic Data Center of the National Oceanic and Atmospheric Adminis-

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[2] See preceding footnote.

tration's World Ocean Atlas data to map this function for a 1,000-m pipe length, a TGE efficiency of 0.85, and PL of 30 percent (Figure 5-2). This simple exercise immediately shows that within United States territory, the coastal regions of the Hawaiian Islands, Puerto Rico and the U.S. Virgin Islands, Guam and the Northern Mariana Islands, and American Samoa would be the most efficient sites for OTEC.

The committee is also concerned that the 2-yr HYCOM run will not provide proper statistics on the temporal variability of the thermal resource. Although it does include both El Niño and La Niña events, 2 years is not sufficient to characterize the global ocean temperature field with any reliability. Longer datasets are widely available, so it is not clear why the assessment group limited itself in this way. Ocean databases that extend for more than 50 years are readily available; these data would allow assessment of the interannual variability in thermal structure due to El Niño/Southern Oscillation (ENSO) to be evaluated. The advantage of HYCOM's higher resolution over earlier estimates from coarser climatologies may vanish if HYCOM is used without appropriate boundary conditions near the coasts, resulting in inaccurate seasonal and interannual statistics on thermal structure. Without these abilities, this study is not much more valuable than prior maps of global ocean temperature differences (Avery and Wu, 1994), which already identified OTEC hot spots.

As an alternative to HYCOM, the committee notes that the U.S. Navy maintains the Generalized Digital Environmental Model (GDEM),

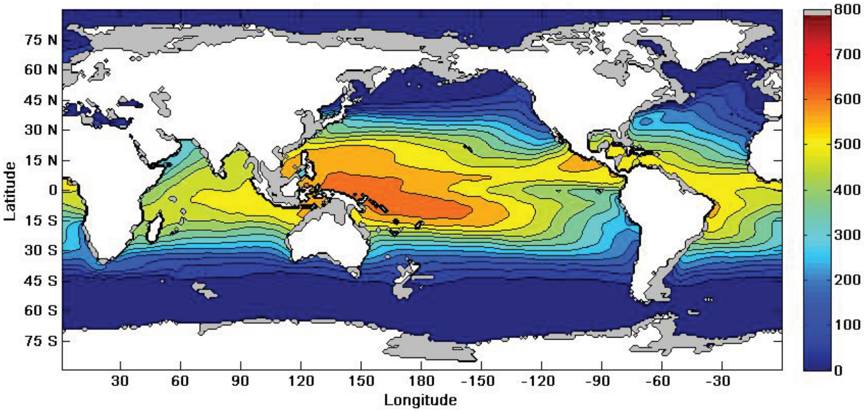

FIGURE 5-2 Global map of the annual OTEC power density available with a 1,000-m cold-water pipe, a turbogenerator efficiency of .85, and pumping losses of 30 percent. NOTE: The power density is expressed in kW/(m^3/s) of cold water pumped up. The entirety of the World Ocean Atlas data (1955-2006) was used.

a state-of-the-art gridded monthly full-depth climatology of temperature and salinity and their standard deviations (Teague et al., 1990; Carnes, 2009; Carnes et al., 2010). GDEM represents the monthly climatological averages of ocean temperature and salinity as a function of depth and location around the globe and is based on analyses of quality-controlled in situ profile observations throughout the historical record. These measurements rely primarily on expendable bathythermographs (XBTs, instruments that measure temperature at depth), conductivity-temperature-depth (CTD) data, and Argo float data sets. Moderate Resolution Imaging Spectroradiometer (MODAS) satellite records may also provide a better source for estimates of the sea surface temperature (SST) climatology than HYCOM, as the MODAS SST is a daily analysis of infrared satellite estimates of surface temperature (Barron and Kara, 2006; Kara and Barron, 2007; and Kara et al., 2009).

As an alternative to the methodology put forth by the assessment group, the committee used GDEM and MODAS to construct fields of the mean monthly temperatures averaged over all years from 1993 to 2010. The combined GDEM and MODAS data sets can be queried to find not only mean monthly SSTs over regions with subsurface temperatures below 4°C, but also average 4°C isotherm depth in regions where monthly mean SST exceeds certain thresholds (21°C, 24°C, and 27°C, for example). Performance predictions on monthly and seasonal timescales could be done with HYCOM (Hurlburt et al., 2008; Chassignet et al., 2009). However, the OTEC assessment group has not made such statistics accessible in its GIS.

The committee feels that the resource assessment should include an investigation of temperature variability that accounts for tidal variations, seasonal variations, and ENSO timescales. The assessment group's database currently contains only a summer and winter season contrast that was constructed from averaging two anomalous (El Niño/La Niña) years. Including more years in the model run, especially years without El Niño or La Niña, would allow for a better representation of the ocean environment. El Niño and La Niña occur on 3- to 6-year timescales, so approximately a decade of data would be needed to catch both instances. It is these longer-term signals that a planner would need for evaluation of a site beyond the seasonal cycle, and the 2-year average from the assessment group does not even allow exploration of the seasonal signal. The committee also notes that variations in isotherm depth due to internal tides can be significant near islands. For example, deep isotherm displacements of as much as 50 or even 100 m are common near the Hawaiian Islands (Klymak et al., 2008), which could induce a 5-10 percent variation in power output over the tidal cycle from an OTEC plant situated there. In addition, areas with strong internal tides will also impose strong shear currents on the cold-water pipe. With regard to seasonal variations, estimates based on equation 1 and the annual cycle of temperature suggest that a 20 percent variation in power output can be expected with a 1,000-m pipe at Hawaii over the course of the year (Rand Corporation, 1980; Cohen, 1982). Even more dramatic changes result from the SST fluctuations due to El Niño or La Niña in the central tropical Pacific, where the committee estimates variations in power production as high as 50 percent. The assessment group largely fails to address the temporal variability issue. The GIS database would be of much more use if it included at least monthly resolution, which for the present 2-year run would at least allow evaluation of specific El Niño or La Niña conditions that are important for OTEC in the tropical Pacific. It would also be useful to have some measure of internal tidal displacements, if only for high-priority sites like Hawaii.

Given the substantial seawater requirements of OTEC plants, the number and spatial density of plants would be a major consideration when considering available power. Plants need to be scaled and designed to minimize their own back effects so they do not adversely affect the locally available temperature contrast. There will also be a maximum plant spatial density beyond which plant discharges would begin to interfere with one another. At regional and global scales there could be a variety of impacts on the ocean arising from widespread deployment of OTEC. Since OTEC is essentially a mixing process, promoting the flux of heat down the vertical temperature gradient, massive deployment of OTEC could actually enhance thermohaline circulation. The potential impacts of these effects, such as decreased tropical surface temperatures or increased primary productivity due to an influx of nutrients from deep cold water, would require careful modeling and would remain speculative until actual plant operations commenced.

Instead of looking at plant spacing issues or the size of individual plants, the OTEC assessment group focused on the supply of cold water as the resource limit. They used the flow speeds at the depth of the cold-water pipe in the HYCOM model to estimate possible plant densities. The size of the ultimate resource available with massive deployment of OTEC plants is a highly speculative question worthy of significant study on its own. The assessment group chose to adopt a figure from the literature (Nihous, 2007b) that was developed by assuming that the net cold water upwelling from all OTEC plants would not be too large a fraction of the net thermohaline overturning circulation. The volume of cold water required by the plant was met by a specified change in the deep layer thickness, which was adjusted to meet the Nihous global estimate of OTEC potential. However, this assumes that the cold-water supply is limited in the ocean, an idea that is not universally accepted. Most modern theories and models (Bryan, 1987; Zhang et al., 1999) recognize that the thermohaline circulation is controlled by the mixing rate, not the cold water supply. Indeed, the ocean is certainly not lacking in cold water—its average temperature is ~3.5°C (Worthington, 1981). Nevertheless, it is not unreasonable to assume that OTEC's impact on global circulation should not be too large, and using the Nihous (2007b) limit is a plausible approach in the absence of a proper modeling study. However, the assessment group's use of it to address plant packing density is misguided.

The committee is disappointed that the OTEC assessment group did little to address device spacing requirements, individual plant size, or the limits of the ocean thermal resource. Clearly, a key question for determining the OTEC technical resource would be how closely plants could be spaced without interfering with each other or excessively disturbing the ocean thermal structure. A related issue would be how spacing might differ in coastal and open-ocean environments. Another issue would be the size limit of a single OTEC plant, due to back effects on the ocean thermal structure such as smaller temperature gradients owing to decreased thermal stratification. While a global resource assessment is difficult to constrain, the committee had hoped the assessment group would address constraints such as plant spacing, tidal amplitudes, and anchoring in deep water or strong currents.

Validation

The group focused its validation efforts on the Lockheed Martin OTEC plant operating model while neglecting validation of the thermal resource.[3] Focusing the validation process on the proprietary plant model seems inappropriate and not at all transparent to this committee. In fact, it appears rather to be a reverse engineering of their plant model, as the agreement on performance seems remarkably perfect (Lockheed Martin Mission Systems & Sensors, 2012). Assuring the accuracy of the temperature gradient in the assessment group's database would have been a more valuable effort, especially with a focus on how well the 2-yr HYCOM run represents the available temperature difference. The seasonal and interannual statistics and the model representation of nearshore deep temperatures are of particular interest, especially as the group noted a problem with deep temperatures off Florida.[4] The validation effort should have drawn on the many available hydrographic databases and compared surface and deep temperature contrasts between observational data and the

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[3] H.P. Hanson, Florida Atlantic University, "Global OTEC resource assessment," Presentation to the committee on December 12, 2011.

[4] See preceding footnote.

HYCOM model, which would have better paralleled the other resource assessment efforts.

Estimate of Available OTEC Power

There are many interesting physics, chemistry, and biology problems associated with the operation of an OTEC plant. Whitehead and Gershenfeld (1981) suggested that an optimal plant size would be around 100 MW in order to avoid adverse effects on the thermal structure the plant is designed to exploit. The ultimate size of the OTEC resource itself is an interesting question and an issue which has been discussed in both old (Isaacs and Schmitt, 1980) and new literature (Nihous, 2005; 2007a; 2007b). Previous work yielded a wide range of estimates for the global OTEC resource of between 3 TW and 1,000 TW (Nihous, 2005 and references therein), which compares favorably to the current global energy consumption of about 16 TW (IEA, 2011). If the committee uses its own estimate of the power density of ~500 kW/(m^3/s) of cold water upwelling, then a total added upwelling of 10 Sv[5] is equivalent to a total power of 5 TW, in agreement with Nihous (2007a). This would represent a 100-MW plant spaced approximately every 50 km in the tropical ocean. While this suggests that OTEC is a very substantial ocean energy source, the many technical and environmental obstacles to its deployment, especially the challenge of utilizing the power produced at sea, means that this concept is still quite far from such large-scale implementation.

The GIS created by the OTEC assessment group was a good way to visually identify sites that might be optimal for OTEC plant placement. However, despite the large global potential, the U.S. OTEC resource estimate provided by the assessment group seems unrealistically high. The assessment group arrives at a figure of 4,642 TWh/yr for the United States, but the majority of the resource is found near Micronesia (1,134 TWh/yr) and Samoa (1,331 TWh/yr) (Lockheed Martin Mission Systems & Sensors, 2012). Unfortunately, there is a serious mismatch between the supply and demand at those locations, as low population densities and levels of industrialization will not create a market for the electricity produced through OTEC. In addition, the 200-mile Exclusive Economic Zone was used as a limit for energy production. This does not fully address the DOE funding opportunity, which requested a discussion of both "resources available with near-shore, grid-connected ocean thermal energy systems and those requir[ing] floating offshore systems" (DOE, 2009). A more realistic limit would be needed to address nearshore options.

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[5] A sverdrup (Sv) is a unit of volume transport used in physical oceanography, equivalent to 10^6 m^3/s.

The total OTEC resource for the continental United States was 394 TWh/yr, less than 9 percent of the total U.S. resource estimated (Lockheed Martin Mission Systems & Sensors, 2012). The Florida Straits and the East Coast account for 87 percent of the continental U.S. resource. The Gulf of Mexico, which accounts for the other 13 percent, is not a viable source in winter. The continental U.S. resource is very seasonal and limited, and it is unlikely that plant owners would want to operate only part of the year. According to the assessment, Hawaii could generate 143 TWh/yr, the Mariana Islands (including Guam) could generate 137 TWh/yr, and Puerto Rico and the U.S. Virgin Islands could generate 39 TWh/yr (Lockheed Martin Mission Systems & Sensors, 2012). A further focus on these areas where the thermal resource and the societal need coincide would be worthwhile.

CONCLUSIONS AND RECOMMENDATIONS

The OTEC assessment group's GIS database provides a visualization tool to identify sites for optimal OTEC plant placement. However, the resource assessment falls short in other ways. The proprietary plant model used does not allow other plant designs to be optimized. Too little information is available on the temporal variability of the thermal resource, with only seasonal averages from two anomalous El Niño/La Niña years available. In addition, too few isotherm depths are available to allow users to optimize the cold-water pipe length.

> **Recommendation: The OTEC GIS should be modified to display monthly resolution over a longer time period (at least a decade) to allow for evaluation of the thermal resource for the full seasonal cycle as well as for special periods such as El Niño and La Niña. Isotherm depths (at 1°C intervals) should be included in the database so other pipe lengths can be evaluated for OTEC and seawater air conditioning.**

The validation effort, which was focused on the plant model instead of the thermal resource represented in their model output, is obviously an issue of great concern. There are plentiful, widely available oceanographic databases available for comparison of the thermal resource. **Because the ocean's thermal stratification is the key input for the OTEC resource assessment, it would have been more useful for the validation to have focused on its representation in the model rather than on a specific plant design.**

The group's estimate of the limit on plant spacing based on cold water supply was also physically unjustified. Instead, the focus should have been on using the numerical models to estimate the back effects of plant operation on the thermal resources. **As the back effects on the thermal resource will be the limiting factor on OTEC plant spacing in both the coastal and open ocean environments, models of the flow around OTEC plants must be developed to understand potential impacts on the ocean.** Site-specific studies would be needed to evaluate current (including tidal) and storm vulnerability, as well as distance from shore.

> **Recommendation: Any future studies of the U.S. OTEC resource should focus on Hawaii and Puerto Rico, where there is both a potential thermal resource and a demand for electricity.**

6

In-Stream Hydrokinetic Resource Assessment

In-stream hydrokinetic technology has been under development for the past several decades. Most of the research and engineering has been related to device development and optimization, impacts to aquatic systems, and the development of particular sites. Unfortunately, little research has been funded to advance the understanding of a systems approach for in-stream hydrokinetic potential. Several publications provide an overview of the state of knowledge for in-stream hydrokinetics (e.g., Khan et al., 2009; Kosnik, 2008).

Hydropower in one form or another has been in use for over 2,000 years, beginning with the use of water wheels to power machinery and leading to today's applications of hydropower from conventional dams to produce electricity (USBR, 2009). Hydropower can be classified by plant size (e.g., micro, mini, small, large); by the technology (e.g., impounded, pump storage, hydrokinetic), or by use in the energy sector to meet demand (e.g., peak-load, base-load). In general, hydropower generation broadly describes the process of converting potential or kinetic energy of stored or flowing water contained in rivers and streams into electricity. For any given stream segment (shown in Figure 6-1), the potential energy head E_p at any location is $z_1 + d_1$, where z is the distance from the datum to the streambed and d is the water depth. The kinetic energy head is defined by the velocity head at the section, $v_1^2/2g$, where g is gravity, and the total energy head is the sum of potential and kinetic energy heads, $E_1 = z_1 + d_1 + v_1^2/2g$. The energy gradeline along a stream (EGL) is the graphical representation of total energy at any point along the stream length. As seen in Figure 6-1,

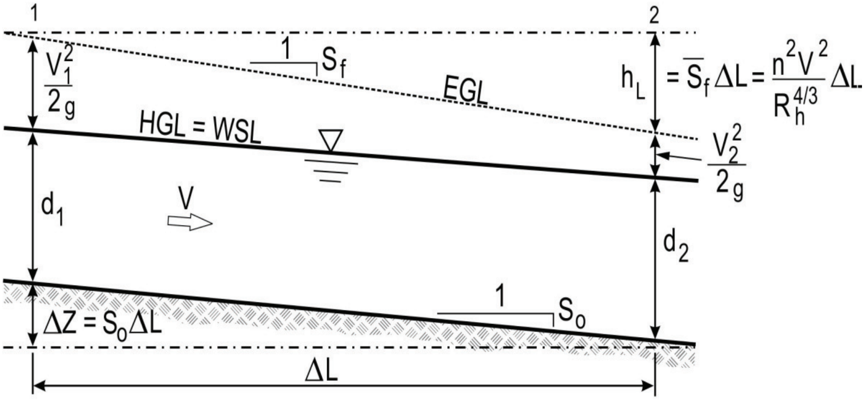

FIGURE 6-1 Stream flow energy definition. HGL is the hydraulic gradient line, which corresponds to the water surface line (WSL).

the loss of energy head (h_L) long the stream is energy slope (also known as the friction slope) multiplied by distance, or , where the friction slope $\bar{S}_f$ is approximated by use of Manning's equation, n is the Manning's roughness coefficient, R_h is the hydraulic radius, and ΔL is the channel length.

Conventional impounded hydropower works by recovering energy that would have been lost due to friction in a free-flowing stream or river (Figure 6-2). Specifically, as water flows from the stream into the impounded reservoir, the velocity is reduced as the depth of water increases, reducing the velocity head and the associated friction loss. In a deep reservoir the velocity, and therefore the friction loss per unit length, approaches zero near the dam. Therefore, the total available energy head at the dam location is approximately equal to the potential energy head, $E_p = z + d$.

More recently, the potential for recovery of hydrokinetic energy in streams has attracted increasing attention. In-stream hydrokinetic energy is recovered by deploying a single turbine unit or an array of units in a free-flowing stream (see Figure 6-3 for centerline view of a turbine array along a river reach). It is notable that the water surface will continue to rise in the upstream direction along the array until a new equilibrium normal depth is achieved due to the impedance of the devices. The distance required to reach the new equilibrium depth is approximately the water depth times the bottom slope, so the new depth will not be reached if the array is shorter than this. This back effect is expected to propagate further upstream from the array field; its distance is dependent on the overall water surface rise at the array, which itself is dependent on the density of deployed turbine units.

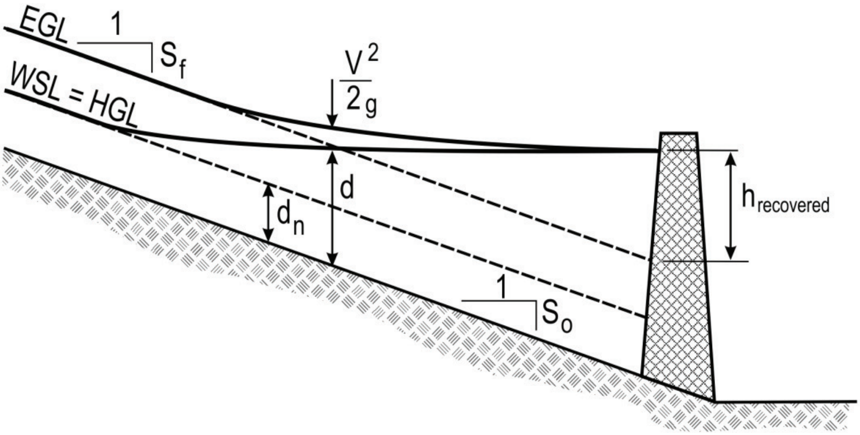

FIGURE 6-2 Conventional impounded hydropower. EGL is the energy gradient line.

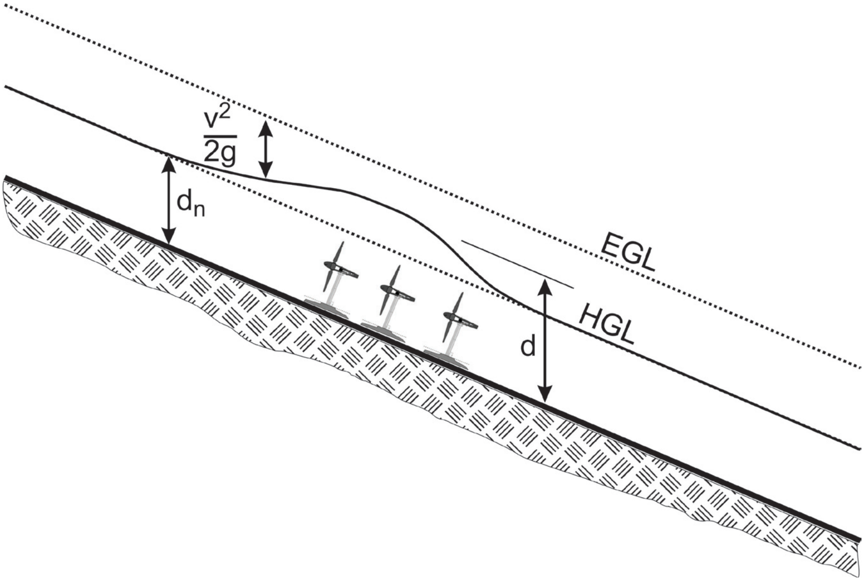

FIGURE 6-3 Centerline view of an array of bed-mounted hydrokinetic turbines deployed in a stream.

Whether in a conventional or in-stream deployment, the turbine captures a swept area of the rotor and converts flowing water velocity into power. Hydrokinetic power density of free-flowing rivers and streams is proportional to the cube of the fluid velocity and is usually expressed in the following (or similar) form:

$$\left(\frac{P}{A}\right)_{Water} = \frac{1}{2}\rho C_e v^3 \tag{1}$$

where P is the power, A is the cross-sectional area, ρ is the water density, C_e is an efficiency factor, and v is the water velocity. C_e is used to account for limiting factors that will impact the realizable total power extraction from a site, including cut-in/cut-out speeds (Figure 6-4), usable cross-sectional area (top, bottom, sides), and impacts to riverine environments. Estimates of the maximum extractable energy that minimizes environmental impact range from 10 to 20 percent of the naturally available physical energy flux (Black & Veatch Consulting, 2004; Bryden et al., 2004). Several in-stream hydrokinetic developers suggest using C_e = 0.3, which was also used by the in-stream assessment group (EPRI, 2012).

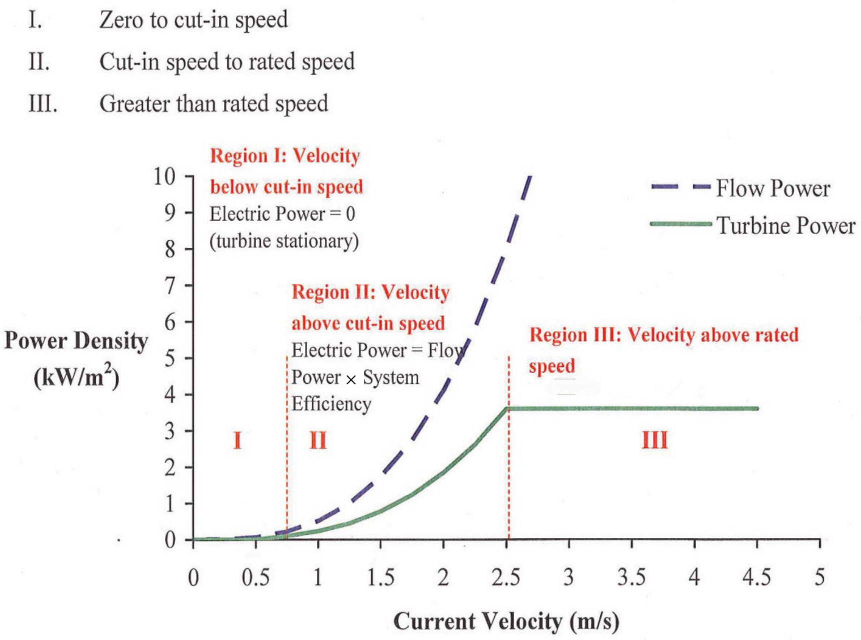

FIGURE 6-4 Turbine output versus flow velocity. SOURCE: Hagerman and Polagye, 2006.

One challenge with hydrokinetic power is that flow around a single device or an array becomes very three-dimensional and is not easily assessed with commonly used one-dimensional hydraulic analysis. Each turbine imparts resistance to the flow, resulting in a potential redistribution of high velocities to other portions of the channel as well as a small increase in water surface elevation, creating a backwater condition that extends upstream. To fully understand the flow redistribution and back effects, higher order (two- or three-dimensional) mathematical models or field testing is required.

Given that the power density varies with velocity cubed, power density can be readily calculated for a site once the velocity distribution is known. It has been noted (e.g., by Hagerman and Polagye, 2006) that the distribution rather than mean values of velocities must be used for the power density estimation, because the cube of the mean current velocity is not the same as the mean of the cubed current velocity.

The number and spacing of turbine units on the footprint of a project location have been estimated using turbine spacing across the channel with a 0.5D to 3D gap between turbines and a longitudinal spacing of 10D to 15D, where D is the turbine diameter.

PROJECT DESCRIPTION

The in-stream assessment group developed its analysis of the in-stream hydrokinetic energy resource by first examining the river reaches available in the United States. Using the NHD Plus[1] suite of data sets, the assessment group identified stream networks in the contiguous United States with mean annual discharge greater than 1,000 cubic feet per second (cfs). The resource assessment group then used this set of stream networks and slope data available from NHD Plus to estimate the theoretical in-stream resource for each stream segment:

$$P_{theoretical} = \gamma Q H \tag{2}$$

where γ is the specific weight of water (weight per unit volume), Q is the mean annual discharge, and H is the vertical elevation change calculated as stream segment slope multiplied by length.

To estimate the technical resource, the group evaluated the following expression at five locations (four on the lower Mississippi River and one on the Kuskokwim River in Alaska), using a simplified geometry, for seven river slopes and seven discharges:

$$P_{tech} = \xi \frac{\rho}{2} V^3 \left(N A_r \right) \tag{3}$$

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[1] Available at http://www.horizon-systems.com/nhdplus/.

where ξ is the machine efficiency (assumed to be 0.3), ρ is the density of water, V is the velocity (modified to account for flow resistance effects of the turbine array deployment on the water depth), N is the number of turbines in the river segment, and A_r is the swept area of the turbine. These calculations developed device array configurations for the 5th percentile flow, assumed the average recovery factor across all discharges for a given river reach was equal to the recovery factor for the mean flow, and assumed that device diameter D equaled 80 percent of the average depth with lateral and longitudinal device spacing of 0.5D and 5D, respectively. The in-stream assessment group then used these five river sites to calculate a recovery factor, RF, defined as the ratio of technical to theoretical resource. A simple expression was then developed from the Mississippi sites to relate the RF to discharge and slope (although this expression has little dependency on slope), and this parameterized expression was used to estimate the technical resource for all stream segments. A similar approach was applied to Alaska; however, given the lack of river slope information, it relied upon the relationship of RF to discharge. The theoretical and technical resources were then summed for different areas and presented online in the National Renewable Energy Laboratory (NREL) River Atlas[2] for each segment.

COMMITTEE COMMENTS

Methodology

The committee benefited from presentations by the in-stream resource assessment group[3,4,5,6,7] and also reviewed a July 2012 draft of the final report (EPRI, 2012). It is the committee's opinion that the theoretical resource estimate is based on reasonable data, methodologies, and analysis; however, the estimate of technical resources is flawed by the RF

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[2] Available at http://maps.nrel.gov/river_atlas.

[3] P. Jacobson, T. Ravens, and K. Cunningham, "Assessment of U.S. in-stream hydrokinetic energy resources," Presentation to the committee on February 8, 2011.

[4] P. Jacobson, T. Ravens, G. Scott, and K. Cunningham, Electric Power Research Institute, "Methodology and preliminary results for assessment of U.S. in-stream hydrokinetic energy resources," Presentation to the committee on September 27, 2011.

[5] P. Jacobson, T. Ravens, G. Scott, and K. Cunningham, Electric Power Research Institute, "Methodology and preliminary results for assessment of U.S. in-stream hydrokinetic energy resources," Presentation to the committee on December 12, 2011.

[6] P. Jacobson, Electric Power Research Institute, "Assessment and mapping of the riverine hydrokinetic energy resource in the continental United States," Presentation to the committee on April 9, 2012.

[7] Scott, G., Virginia Tech University, "Validation and GIS display of river in-stream resources," Presentation to the committee on April 9, 2012.

approach described in the previous section and the omission of other important factors, most important being the statistical variation of stream discharge. Insufficient data were provided in the in-stream resource assessment group's final report to reproduce the calculations of recovery factor for the stated example conditions. As noted earlier, Hagerman and Polagye (2006) assert that the distribution of velocities must be used for the power density estimation rather than the mean values, because the cube of the mean current velocity is not the same as the mean of the cubed current velocity. The committee encourages future efforts in in-stream resource assessment to estimate the distribution of technically recoverable resource across the range of flows at all locations. This is particularly important as rivers and streams exhibit large annual and interannual variation in flow. Future work could focus on developing an estimate of channel shape for each stream segment and then, using the flow statistics for each segment along with an assumed array deployment, directly calculating the technically recoverable resource based on equation 3 (above) over the range of expected flows.

Validation

Given the lack of existing deployments of in-stream hydrokinetic arrays as well as the proprietary nature of this industry, little or no field or laboratory data exist to validate the assessment group's methodology. However, a number of checks could be completed with respect to the reasonableness of the approaches. For example, although considerable effort was expended to develop a methodology to estimate back effects using a modified Manning's resistance coefficient to account for the resistance that a turbine array will impart on flowing water, limited information is reported with respect to evaluation of the practicality and reasonableness of applying this methodology at various stream conditions. A two- or three-dimensional computational model would be more appropriate to assess the flow resistance effects of the turbine on the flow. The validation effort would also have been stronger if it had focused on questions regarding RF, such as the group's assertion that slope contributes little to RF. A more thorough assessment of both modified Manning's coefficient and RF will be necessary to ascertain the validity of these approaches.

Estimate of In-Stream Power Potential

Overall, the in-stream resource assessment group estimates the theoretical resource to be 1,433 TWh/yr and the technically recoverable in-stream resource to be 101.2 TWh/yr. The technical resource is largest in the Mississippi, Alaska, Pacific Northwest, Ohio, and Missouri hydrologic regions. These rivers alone account for 95.3 TWh/yr, or ~95 percent of the estimated technically available resource. Given that the largest portion of the resource is estimated within these five hydrologic regions, further testing of the approach in these areas is needed. Also, it is noteworthy that the recovery factor for the hydrologic regions varies from a few percent to nearly 24 percent for the Lower Mississippi region, raising doubt about the effectiveness of the recovery factor approach.

As a simple estimate of RF's upper bound, one can assume a dimensionless flow depth h and a unit height D (equal to $0.8 \times h$), and a spacing between units of 2D. For a rectangular portion of a channel with a width of 3D, the swept area of the machine is ~0.5, the total flow area is 2.4, and the share of flow captured is ~20 percent. Factoring in turbine efficiency (~30%), lost area along sloping channel edges with depth less than D, lost flow area above the depth h when flows are above the minimum flow, and energy lost to friction along the longitudinal distance, the RF approaches 2-10 percent (arguably 5% or lower). The committee is concerned that RF is not necessarily defensible based on the above arguments.

Last, there are many limiting factors to be considered that will reduce the realizable in-stream hydrokinetic energy production. These factors include but are not limited to ice flows and freeze-up conditions, transmission issues, debris flows, potential impacts to aquatic species (electromagnetic stimuli, habitat, movement and entrainment issues), potential impact to sites with endangered species, suspended and bedload sediment transport, lateral stream migration, hydrodynamic loading during high flow events, navigation, recreation, wild and scenic designations, state and national parklands, and protected archeological sites. These considerations will need to be addressed to further estimate the practical resource that may be available.

CONCLUSIONS AND RECOMMENDATIONS

After reviewing the in-stream resource assessment report, the online information database, and additional information presented by the assessment group during committee meetings, it is the committee's opinion that **the estimate of the theoretical resource is based upon a reasonable approach and provides an upper bound to the available resource; however, the estimate of the technical resource is flawed by the assessment group's recovery factor approach and the omission of other important factors, most importantly the statistical variation of stream discharge. A more thorough assessment of both modified Manning's coefficient and the recovery factor used by the in-stream assessment group is needed to ascertain the usefulness of these approaches.** Further work is required with respect to the approach to estimate the technically recoverable resource before it will have value as an estimate to guide in-stream hydrokinetic development.

> **Recommendation: Future work on the in-stream resource should focus on a more defensible estimate of the recovery factor, including directly calculating the technically recoverable resource by (1) developing an estimate of channel shape for each stream segment and (2) using flow statistics for each segment and an assumed array deployment. The five hydrologic regions that comprise the bulk of the identified in-stream resource should be tested further to assure the validity of the assessment methodologies. In addition, a two- or three-dimensional computational model should be used to evaluate the flow resistance effects of the turbine on the flow.**

7

The Practical Marine and Hydrokinetic Resource Base

The Department of Energy (DOE) tasked the NRC to compare the "potential extractable energy" from each of the marine and hydrokinetic (MHK) resource assessments (see Chapter 1 for a discussion of terminology and the statement of task). The task statement further directed the study committee to review the methodologies and assumptions for assessing the resources that might be practically available for energy conversion and the potential limitations on these resources. Lacking a standard set of definitions, the committee created a conceptual framework of theoretical, technical, and practical resources for MHK in Chapter 1 (see also the interim report, Appendix B). During discussions with each of the resource assessment groups, the committee concluded that the groups were assessing the theoretical resource, and some were attempting to assess the technical resource. None of the assessment groups were tasked directly with evaluating what the committee considers to be the practical resource—the portion of the resource that is available for development after taking into account technical capabilities; social, economic, regulatory, and environmental considerations; and alterations to the physical environment. This is an issue of concern to the committee because these filters will be critical for determining the MHK resource that could practically be expected to provide energy for generating electricity, as well as for determining where future investments in MHK energy might be best located. **For many reasons, the site-specific and total practical MHK resource is likely to be significantly less than estimates of theoretically or technically available energy provided by the assessment groups.**

MOTIVATION FOR ASSESSMENT OF THE PRACTICAL RESOURCE BASE

The objective of this chapter is to discuss the filters involved in determining the practical resource; how those filters impact the size and spatial distribution of the practical resource; and how DOE might improve MHK resource assessment and development. The committee observes that, as with some other energy resources (see Box 1-3), the difference between the theoretical or technical resource estimates and the practical resource is large, making the practical resource small in a relative sense. While the theoretical (or technical) MHK resource can appear substantial (many tens of gigawatts or more), the practical resource tends to be small in most locations or diffuse in nature. When considering small-scale energy developments (typically less than 10 MW), MHK development may be feasible and valuable in some locations, but utility-scale MHK developments (more than tens or hundreds of megawatts) will involve significant infrastructure, can have substantial environmental impacts, and can potentially conflict with other uses for the same area.

As an example, extracting 1 GW from waves approaching the Washington and Oregon coastlines would probably require the deployment of a line of MHK devices extending at least 100 km parallel to and just off the coast, which could have major impacts all along the coast. Similarly, extracting more than a small fraction of the theoretical 9 GW resource from Cook Inlet's large tidal range and associated currents would probably require construction of a continuous fence of turbines that would effectively act as a barrage, which could potentially be unacceptable for societal and environmental reasons.

Determining the practical MHK resource will require a comprehensive evaluation of how the resource interacts with social, environmental, regulatory, and economic filters. Some of the assessment groups have already been moving to further evaluate the spatial variation, which has led to selection of far fewer areas that could have potential for in-depth siting studies and/or potential device installation. Part of the siting analysis will include much more detailed modeling of backflow, circulation, and other characteristics that are then calibrated and evaluated with field data. The detailed siting studies are important, because the scale of impacts for MHK development will probably be most significant at a site-specific or local level. As plans progress for any MHK project, developers will need to contend with two types of constraints: the impacts that it could have on the physical and biological environment and the constraints of working in an ocean or a river that has multiple uses and thus multiple management objectives (e.g., social issues, spatial conflicts). These permitting-related issues are in addition to the significant economic investments faced by development of commercial-scale marine renewable energy.

PRACTICAL CONSIDERATIONS FOR MHK DEVELOPMENT

The ocean, coast, and rivers support a number of established human uses, as well as an expanding array of new uses. These include well-established uses of the ocean, such as ports and harbors; commercial and recreational fishing; traditional hunting, fishing, and gathering; commerce and transportation; oil and gas exploration and development; sand and gravel mining; environmental and conservation activities; scientific research and exploration; security, emergency response, and military readiness; and tourism and recreational activities. The ocean also provides cooling water for thermoelectric power plants that use coal, natural gas, or nuclear fuel. In many cases, while the activity itself is well-established, the intensity of use has been escalating. In addition, there are several new or growing human use categories, such as aquaculture; maritime heritage and archeology; and, of course, offshore renewable energy.

Each of the uses listed above comes with its own set of environmental, regulatory, social, and economic filters that have potential to reduce MHK's potential applicability at any given location. For MHK, the committee identified a number of categories into which these filters might fall (shown in the right-hand column of Figure 1-1). Examples of each category are presented in Table 7-1, although it should be recognized that some of the filters fall under more than one category. Because of the large impact these filters have on the percentage of the resource that could be practically available, they are explored in more detail in the following sections.

Environmental Filters

MHK devices are likely to have a number of effects on the physical, biological, and ecological environment of rivers and the ocean. These environmental effects are in addition to the back effects addressed in earlier chapters that are created by the MHK device or array and reduce the available energy. Placing and operating the devices can have physical impacts on the subsurface, the water column, and the water surface (e.g., alteration of the bottom substrate, scour and/or sediment buildup, changes in wave or stream energy, turbulence, space taken up by devices operating at the sea surface). When looking beyond the impact of one or a few devices, large arrays of MHK devices could have significant effects on the physical environment. It would be important to compare the impact of an MHK array with the impact of other electricity generators having the same average power output.

The dynamic nature of the devices (for example, moving blades on turbines) has potential to lethally and/or behaviorally impact marine mammals, fish, and diving birds. The relatively slow speeds at which

TABLE 7-1 Examples of Filters That Could Impact the Development of the Practical MHK Resource

Category	Example
Environmental	Impacts on marine species and ecosystems (e.g., nursery, juvenile and spawning habitat, keystone species) Bottom disturbance Altered regional water movement
Regulatory	Endangered Species Act Coastal Zone Management Act Marine Mammal Protection Act Clean Water Act Federal agency jurisdictions—for example, National Oceanic and Atmospheric Administration (NOAA), U.S. Army Corps of Engineers (USACE), Federal Energy Regulatory Commission (FERC), State Department, U.S. Fish and Wildlife Service (FWS), Environmental Protection Agency (EPA), Bureau of Ocean Energy Management (BOEM), U.S. Coast Guard
Social and economic	Spatial conflicts (e.g., navigation, military operations, marine sanctuaries, wildlife refuges, viewsheds, fisheries, tourism) Interconnection to the power grid (e.g., transmission requirements, integrating variable electricity output, shore landings) Capital and life-cycle costs (e.g., engineering, installation, equipment, operation and maintenance, debris management, and device recovery and removal)

the devices operate could minimize the effects of direct animal strikes (Boehlert and Gill, 2010), but there are many other ways devices could affect animals, such as altering migration pathways (e.g., upstream of the device) or creating settlement surfaces for non-native species (as happens with oil rigs, for example). Some regions set aside for conservation purposes might be off-limits entirely for MHK siting, while others might have limited development in order to minimize impacts on sensitive ecosystems. There are many other potential impacts related to acoustic, chemical, temperature, and electromagnetic changes or emissions due to MHK devices. However, it is also important to note that environmental impacts related to MHK are likely to be mostly localized (within kilometers of the devices), rather than spread over large areas, which will make the impacts easier to assess spatially. This will also limit catastrophic impacts due to failure of a device or array (unlike, for example, an oil or gas well blowout).

Regulatory Filters

There are a number of state and federal agencies with overlapping jurisdiction for MHK power. Although FERC (an independent agency within DOE) was granted jurisdiction over hydroelectric development through the Federal Power Act, leases on the U.S. outer continental shelf require approval by BOEM (Department of the Interior) according to the Outer Continental Shelf Lands Act and the Energy Policy Act of 2005 (Righi, 2011). This is further complicated in the case of ocean thermal energy conversion (OTEC), because NOAA (Department of Commerce) was given responsibility for licensing commercial OTEC facilities under the Ocean Thermal Energy Conversion Act of 1980. Because no applications were received, in 1996 the regulations for licensing commercial OTEC plants were rescinded. OTEC demonstration projects are not required to receive a license but must instead be designated as a demonstration project by DOE.

FWS (Department of the Interior) and NOAA are charged with coordinating activities to protect marine mammals from potentially harmful development under both the Marine Mammal Protection Act of 1972 (16 U.S.C. § 31) and the Endangered Species Act (16 U.S.C. § 1531-1544). NOAA also has jurisdiction under the Magnuson-Stevens Fisheries Act to protect essential fish habitats (16 U.S.C. § 1855(b)(2)). Projects in navigable waters typically fall under the jurisdiction of USACE under the Rivers and Harbors Act but may also require involvement from the U.S. Coast Guard (Righi, 2011). USACE permitting may also be required for any projects involving dredging rivers or coastal areas under the Clean Water Act (PNNL, 2010). The Coastal Zone Management Act involves coordination among local, state, and federal agencies to ensure that plans are in accordance with a state's own coastal management program (PNNL, 2010). In addition to dealing with federal authorities, offshore renewable development in state waters will fall under state rules, with parts of the system (e.g., the transmission cable on land) also subject to county and municipal zoning.

A good example of the complexity of these jurisdictional issues is from California, where, owing to the state's own laws and regulations—for example, California Organic Act, California Harbors and Navigation Code, and California Coastal Act)—the California Natural Resources Agency, the California Environmental Protection Agency, and the California Public Utilities Commission were all involved in a memorandum of understanding with FERC regarding the development of MHK off the coast of California (CalEPA et al., 2010).[1]

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[1] The memorandum of understanding "seeks to develop a procedure for coordinated and efficient review of proposed [marine and] hydrokinetic projects that is responsive to

For electricity generation, most transmission-level interconnections are governed by federal rules through FERC. However, siting of transmission and distribution lines is controlled by state and local governments. This raises a number of jurisdictional problems for new generators. Even when a specific MHK site is determined, appropriate resource assessment will be governed by complex power regulations related specifically to how any needed transmission is developed and how the generator is connected to the grid.

Social and Economic Filters

Spatial Conflicts

Oceans and rivers are crucial resources for local communities, states and regions, and the country as a whole. Navigable waters are a resource for a number of sectors, and coordinating their use is an immense logistical challenge that will definitely impact MHK energy development. In the case of tidal power, some of the locations with the highest tidal energy density are also estuaries having ports with heavy commercial shipping traffic. It is likely that there will be limitations to the number and size of turbines and the depth at which they can be deployed so as not to interfere with established shipping lanes. In regions of the United States with an active U.S. Navy presence, there may be constraints on MHK siting owing to military operational, training, or security concerns. Tourism and recreational traffic pose another spatial conflict—impeding a popular bay with an array of turbines may affect not only recreational fishing but also tourism. This is also true of commercial fisheries, which could be unfavorably impacted if an MHK deployment restricts access to desirable fishing grounds. Finally, existing structures may have to be considered. A site may become more or less advantageous because of existing infrastructure—for example, while in-stream turbines may require limited deployment near a bridge due to their potential impact on river scour, it may be advantageous to deploy them in the discharge canals of power plants. Such site-specific logistical constraints due to multiple uses of rivers and the ocean are not adequately captured in a general technical resource assessment.

The potential for multiple uses may reduce conflicts and create opportunities for meeting shared objectives. For example, offshore aquaculture and MHK structures could be sited together, allowing them to jointly meet

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environmental, economic, and cultural concerns, while providing a timely and predictable means for developers of such projects to seek necessary state and federal approvals.” It further delineates the eight state and local agencies with which the California parties will coordinate in order to meet this objective.

fish and energy production management objectives while creating few spatial conflicts with other uses. It may also be economically beneficial to these companies as they might all benefit from access to similar resources for staging and maintenance of their structures.

Interconnection to the Electrical Grid

Even after a minimally conflicted site is found, there is still the issue of how to extract the electricity and distribute it to customers. Electricity is often generated at power plants or generators that may not be located near the demand for it, which necessitates long-distance transmission. To arrive at a true estimate of the costs of integrating an MHK installation into the electrical grid of a local utility or regional transmission operator, a number of factors would need to be considered, including the size of the generator (e.g., the size of a tidal turbine array), the strength or weakness of the overall electric system, reliability requirements for the generator and the electricity system, proximity of the generator to the potential interconnection, and configuration of the existing system. The local utility or regional transmission operator will conduct interconnection studies as required to determine the costs to interconnect with its existing electrical grid. These costs will include costs for interconnection and the costs for any required upgrades to the existing electrical grid to handle the additional generation from the MHK project. The process and costs for interconnection will vary depending on whether the device connects directly to either the transmission or distribution system (Figure 7-1).

The electric power system is planned, constructed, and operated to provide safe, highly reliable, and stable service to all customers, even during severe disturbances. The reliability rules for a system consist of requirements for resource adequacy, including generation reserve margins; transmission capability, including stability analysis; and emergency operations (NYSRC, 2011). Bringing MHK energy onto the grid, then, is complicated by many factors. Harsh environmental conditions, unstable load flows, variable energy output, lack of electrical demand near the generation, the length of cable from a device or array to a shore terminus, potential environmental impacts from the cable, permitting issues, and the need for specialized equipment for reactive power control are all challenging. However, the penetration of gigawatt-scale wind energy into the U.S. and European grid demonstrates that intermittent resources can be brought online and can provide a model for integrating MHK energy with traditional resources. It is unlikely that MHK resource variability would be a destabilizing element for a given electricity system or that it would require electricity storage technologies.

An offshore transmission system is needed to allow offshore genera-

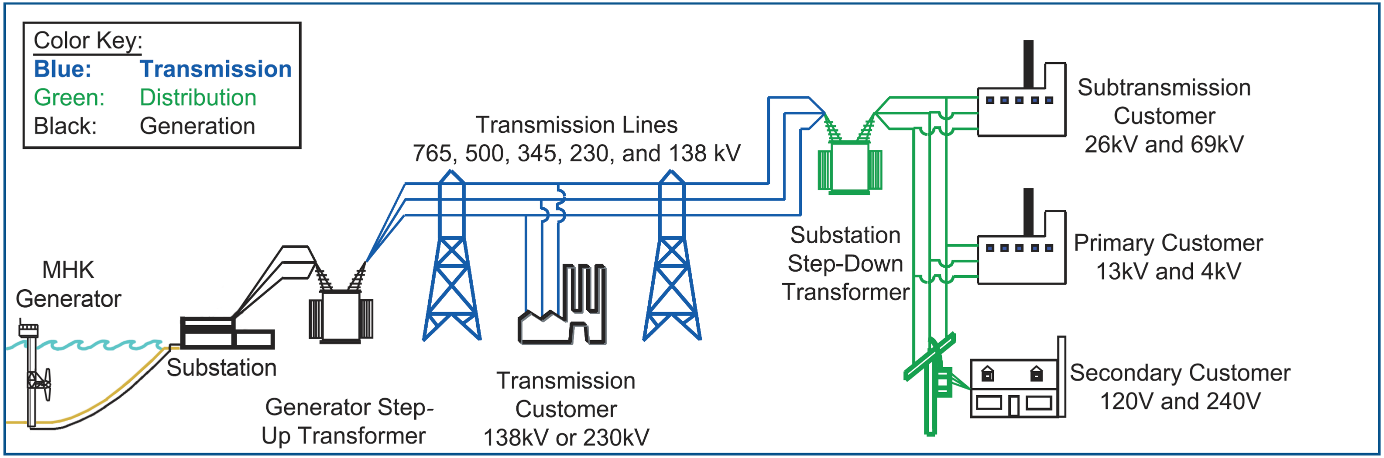

FIGURE 7-1 Basic structure of the electric system showing an MHK resource as the electricity generator connecting to the transmission system. For small-scale applications (<10 MW), the MHK generator will probably connect directly to the distribution system.
SOURCE: Adapted from U.S.-Canada Power System Outage Task Force, 2004.

tors, whether wind or MHK, to transport the electricity generated to shore and then to customers or utilities. The distance required to interconnect into the electricity system is critical, as it directly impacts the economic viability of a project. Additionally, the electricity from these generators then must be integrated into the power system, where the temporal variability of the resources might become important. The situation could be more complicated if there are large numbers of offshore generators, because connecting a large number of devices together with no load demand along the path of the network cable could produce an unstable system. Another issue is device and equipment reliability, discussed in the following section.

An important consideration for evaluating the practical MHK resource base is how the location of a potential MHK resource compares with the location of load centers that might utilize the resource. The overall attractiveness to coastal resources that has been identified in discussions and planning for offshore wind on the U.S. East Coast is that the resource is inherently close to major load centers. Close proximity to load centers can increase the value of a resource by reducing the costs and siting issues associated with the transmission requirements. In the case of offshore wind generation, the higher costs of offshore vs. onshore wind generation are to some extent offset by a higher local price environment that exists on the East Coast and the reduced cost and siting issues associated with locating transmission. Although a significant portion of wave, tidal, and in-stream resources are located in rural Alaska, each of those three assessment groups did mention other areas where the resources are located close to population centers. As noted in the OTEC resource estimate, most of the resources for U.S. territorial waters are in locations with low population densities (Micronesia and Samoa). In general, OTEC faces the challenge of utilizing power produced at sea far from demand centers.

Capital and Life-Cycle Costs

As with other energy devices or plants, there are costs associated with the device itself and its design, installation, operation and maintenance, and removal or replacement. The largest of these costs, and potentially the greatest barrier to MHK deployments, is the capital cost. An earlier NRC committee concluded that it will take at least 10 to 25 years before the economic viability of MHK technologies for significant electricity production will be known (NRC, 2010). A 2008 report evaluating the potential for renewable electricity sources to meet California's renewable electricity standard found that the cost of electricity from waves and currents was higher than that from most other renewable sources and had a substantially greater range of uncertainty (Black and Veatch, 2008).

Once installed, MHK devices will be subject to mechanical wear and corrosion that is more severe than that experienced by land-based equipment. Corrosion-related problems remain as key challenges for all MHK devices. In addition to the general galvanic corrosion in marine environments, issues related to stress corrosion in both static and dynamic loading environments, corrosion fatigue, biocorrosion, and marine fouling will have to be addressed. Advanced structural materials with appropriate coatings and paints will have to be identified in order to construct the robust, corrosion-resistant components for MHK energy generation (Bahaj and Myers, 2003; Hudson et al, 1980; Liu et al, 1999; Mueller and Baker, 2005). Some technology to address these challenges might be adapted from mature industries like the defense and oil and gas sectors.

Design for survivability becomes another important consideration for device siting, particularly in shallow water. Devices can be destroyed, damaged, or moved from their moorings under the actions of rough seas and breaking waves associated with 50- and 100-year storms that can occur well within the 20- to 30-year life expectancy of the devices. For example, stronger-than-expected currents in New York's East River caused Verdant Power's turbine blades to fail only one day after installation in 2006 and led to redesigned blades. Using more rugged design criteria for future MHK devices may drive up the product cost due to exotic materials or increased engineering costs and could also delay deployment until more robust designs are available in the market, all of which may play a role in the cost of electricity generated from an MHK device in the near term. In addition, power electronics on MHK devices will be a challenge to implement and operate reliably.

In addition to the hostile nature of the marine environment, there are other challenges that affect the survivability and maintenance of MHK systems. In shallow tidal and riverine areas, there is a great concern that debris will affect both the efficiency and durability of any installed devices. In Alaska, which is cited as a potentially large resource for development by the in-stream assessment group, river freezing in the winter months and scour incurred during spring ice break-up will make year-round deployment a challenge and may require seasonal device removal. These challenges affect not only installation and maintenance costs and electricity output, but also MHK scalability from small to utility applications.

MULTIPLE-USE PLANNING FOR MARINE AND RIVERINE ENVIRONMENTS

The basis of many of the critical social, economic, regulatory, and environmental filters identified in previous sections is meeting multiple management objectives from the shared coastal, ocean, and riverine environment. With a growing number of uses, users, and demands, there are increasing spatial and regulatory conflicts in meeting these management objectives. Planning for multiple uses can maximize the achievement of multisector goals while reducing conflict. While these conflicts can be perceived as having the potential to delay or deter future technology development, Verdant Power's Roosevelt Island Tidal Energy Project is an example of a small-scale commercial deployment navigating these regulatory hurdles successfully, and more projects are likely to be forthcoming. Furthermore, many of these filters are analogous to those faced by traditional power generation projects. With current rates of electricity usage, society will have to choose among various options for power generation, each with its own set of objectives, conflicts, and trade-offs.

MHK Siting

Offshore alternative energy, both wind and MHK, has been a primary driver for the development of local and regional ocean planning in the United States (e.g., Massachusetts, Rhode Island, Oregon, and the mid-Atlantic region [OORMTF, 1991; MAEEA, 2009a, 2009b; MAGA, 2009; RICRMC, 2010]). MHK theoretical and technical resource assessments can help initiate a planning process that explicitly addresses and reduces spatial conflicts with other users. Many other uses have much larger footprints, impacts, and conflicts with one another but are often entrenched uses with specific, single-objective management approaches (e.g., commercial fisheries). Because offshore alternative energy represents a new use of the environment and does not have an established management approach at the state, regional, or national level, it will probably need to fit with existing uses and users. Social and economic filters discussed in the above sections are critical for identifying and reducing conflicts between other uses and MHK siting.

As part of the DOE tidal resource assessment, Defne et al. (2011) illustrated how MHK resource data could be combined with socioeconomic and environmental GIS layers to identify where MHK projects might be sited (Table 7-2). They explicitly represented their analysis as an example of how the data can be combined, and the committee found this was the most advanced example by any group attempting to assess the practical resource. While still largely a single-objective rather than multiple-objective analysis, the authors try to identify how one might place a MHK project where the potential energy is great and conflicts are few.

As part of MHK site planning efforts, potential trade-offs increasingly need to be explicitly identified and quantified, including market and nonmarket values. For example, when deciding where to locate devices or arrays, these valuations could be used to quantify positive and negative impacts on multiple sectors such as fishing, shipping, whale watching,

TABLE 7-2 GIS Layers Showing Environmental and Socioeconomic Constraints Identified in the DOE Tidal Resource Assessment

Layer	Theme	Role
Environmental constraints	Fish Invertebrates Reptiles Birds Mammals Plants and habitats	Critical areas
Socioeconomic constraints	Urbanized areas Transmission Transportation Built-up areas	Favorable areas
	Restricted areas Fairways and shipping lanes Dumping sites Cable areas Pipeline areas Shoreline constructions Wreck points Mooring and warping points Recreation areas and access locations (boat ramps, diving sites, marinas) Management areas (marine sanctuaries, national parks, wildlife refuges, special management areas) Cultural heritage sites (archaeological sites, historical sites)	Restricted areas
	Resource extraction sites (Aquaculture sites, commercial fisheries, recreational fishing)	Not assigned

SOURCE: Adapted from Defne et al., 2011.

recreational sailing, scenic views, and rare species. Including these values explicitly in the cost-benefit analysis may result in a different decision about MHK sites than if only the energy sector is considered (NOAA, 2011b).

Tools for MHK Site Planning

While full trade-off analyses (including benefits and costs) have rarely been used in ocean planning efforts to date, there are many decision support tools that can help assess trade-offs. They can be analyzed with quantitative and qualitative methods (e.g., Barents Sea, Netherlands) or with expert judgment (Wadden Sea). Where there has been prioritization of spatial uses, trade-off analysis can avert incompatible uses (e.g., German Exclusive Economic Zone) or permitting decisions (e.g., Shetland Islands). They can also be used to compare alternative scenarios in order to identify potential least-cost solutions (e.g., St. Kitts and Nevis, Belgium, and California) (NOAA, 2011b).

One such spatially explicit decision support tool is MarinePlanner (formerly MarineMap), which is used in California, Oregon, Washington, and the mid-Atlantic region. This tool allows users to designate spatial use zones and to estimate the benefits, costs, risks, and impacts of their decisions. MarineMap and MarinePlanner were explicitly developed for extensive stakeholder engagement as part of spatial planning (Gleason et al., 2010). MarineMap is currently being used as part of Oregon efforts to identify areas where wave energy could be feasibly sited with fewer conflicts in an explicitly multiobjective context.[2] After extensive engagement with stakeholders and affected state agencies, policies, standards, and procedures were created to approve new energy development.[3] The next stage will result in maps to guide the location of renewable energy facilities while protecting areas that are important to ocean fisheries or are essential marine habitat.

Another set of decision support tools used in alternative energy development are the Prospector tools developed by the National Renewable Energy Laboratory (e.g., Solar Prospector, Geothermal Prospector). These tools are designed to bring together critical information about the resources and areas of concern in their development so that stakeholders can identify where they might maximize benefits and minimize conflicts. For example, stakeholders (including developers and environmental groups) can assess with Solar Prospector where theoretical energy resources (e.g., solar resources) are greatest and where conflicts may be fewest (e.g., away from areas of environmental concern). Such tools can be further improved to provide the most relevant information for MHK resource development by engaging with stakeholders, as has been done, for example, with MarinePlanner.

Approaches developed specifically for siting wind farms, based on macro-siting and micro-siting optimization, could provide a methodological template for optimizing MHK siting (Rhétore et al., 2011; Grilli et al., 2012). These approaches seek to optimize device locations by considering physical constraints (such as the complex aerodynamic wake effect behind turbines) as well as socioeconomic and environmental constraints associ-

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[2] Available at http://oregon.marinemap.org/.

[3] Available at http://www.oregon.gov/LCD/OCMP/Ocean_TSP.shtml.

ated with ecosystem services (e.g., foundation and cable costs, commercial and recreational fisheries costs, environmental cost). They are based on an explicit cost optimization approach and extend the traditional optimization of tangible costs to the intangible costs associated with the ecosystem services constraints (Oumeraci et al., 2009). Such approaches were recently applied in Denmark to the Middleground wind farm (Rhétore et al., 2011) and in Rhode Island via the Special Area Management Plan (Grilli et al., submitted 2012).

Incorporating MHK Resource Assessments into Ocean Planning

Each of the MHK resource assessments was required to create a GIS database, and most have included information related to the theoretical and technical resource identified in the assessment. Incorporating these databases into the variety of existing spatial decision support tools allows the MHK resource to be viewed in the context of other economic and ecological uses, such as shipping channels or areas associated with critical habitats. This information would be helpful to prioritize research that enables multiple uses and mitigates potential user conflicts, although it would not be sufficient for quantifying the practical resource base.

CONCLUSIONS AND RECOMMENDATIONS

Site-specific analyses will be needed to identify the constraints and trade-offs necessary to reach the practical resource. The site-specific, practical MHK resource is likely to be substantially less than assessment group estimates of the theoretical or technical resource. Although theoretical and technical MHK resource assessments are useful for prioritization and planning, site-specific filters will be needed for useful estimates of the practical resource. This chapter lists a selection of considerations that investors, developers, regulatory or permitting agencies, and the public are likely to weigh in making decisions about MHK site placement, permitting, and installation.

An estimate of the practical resource base and its geographical distribution is necessary for determining the potential MHK contribution to U.S. electricity generation. GIS resources generated by the DOE assessments, when completed, will assist stakeholders, investors, and regulators best fit MHK energy development into the regional ocean or riverine environment.

Recommendation: DOE should ensure that spatial data resulting from the MHK resource assessments is readily and publicly available for use in siting and permitting decisions.

DOE has already published data on the spatial distribution of the theoretical energy resources and should continue to play an active role in characterizing the resource base and in developing decision support tools that can steer consideration toward areas that could be the most productive and feasible for development. An accessible spatial database of theoretical and technological MHK resources would provide substantial information on high-priority sites.

8

Overarching Conclusions and Recommendations

This chapter presents the committee's overarching conclusions and recommendations that emerge from its consideration of all five of the marine and hydrokinetic (MHK) energy assessments. Based on the information reviewed, the committee concludes that the overall approach taken by the assessment groups contributed to understanding the distribution and upper bound of U.S. MHK energy sources. It notes that the models, data sets, geographic information systems (GISs), and visualizations should aid stakeholders and MHK energy developers, provided they are conveyed with appropriate caveats and include well-documented assumptions. In Chapters 2-6 of this report, the committee makes observations, outlines its concerns, and makes recommendations for each of the five MHK resource categories. Conclusions and recommendations that were originally presented in the interim report (Appendix B) have been reexamined for this report, and those that are relevant have been reiterated in this and other chapters.

A DEFENSIBLE ESTIMATE OF THE MHK RESOURCE

As first expressed in its interim report, the committee continues to have strong concerns about the usefulness of aggregating theoretical and technical resource assessments to produce a single-number estimate for any one of the five MHK resources. This single-number estimate is inadequate for a realistic discussion of the practical MHK resource base that might be available for electricity generation in the United States. **The**

methods and level of detail in the resource assessment studies do not constitute a defensible estimate of the practical resource that might be available from each of the resource types.

While the Department of Energy (DOE) may want an aggregated value for internal research and/or investment purposes, such as comparing the relative sizes of individual MHK resources or comparing the MHK resource base with other renewable resources, **a single-number estimate of each theoretical or technical MHK resource is of limited value for understanding the potential extractable energy that each resource might contribute to U.S. electricity generation.**

DOE contracted for assessments of extractable MHK resource levels. The five resource assessments focused mainly on the national level and did not reach the point of estimating the practically extractable resource in regions of high interest. Both the theoretical and technical resource bases are developed by summing all the energy available over large tracts of ocean or long river stretches. However, attempts to tap wide swaths of ocean or coastal straits and embayments for harvesting energy will run into challenging social or economic barriers (e.g., entrenched uses such as fisheries and shipping lanes or environmentally sensitive areas) as well as technology, materials, and engineering issues (e.g., proximity to utility infrastructure, survivability). The tidal assessment group's identification of relevant socioeconomic factors is a good beginning for this type of analysis.

> **Recommendation: Should DOE (or any other federal agency or regional/local decision-making body) decide to assess or support decisions on the potential practical MHK resource for specific regions of high potential MHK opportunity, it should include the best available socioeconomic and environmental filters for that region.**

Inevitably, some of these theoretical and technical resource estimates include large areas where the energy density is so low that energy development would be impractical. Such practical limits will undoubtedly affect the power available from all MHK resources, but some resources may be more significantly reduced than others, and the resource with the largest theoretical resource base may not necessarily have the largest practical resource base. Thus, it is not apparent that comparing the theoretical or technical resources of the various MHK types is of any real value for determining the potential extractable energy from MHK. Rather, it is the practical resource that will ultimately contribute to U.S. electricity generation. **To ascertain the practical MHK resource, site-specific analysis is necessary.** Because the assessment groups were tasked by DOE to create a national assessment, they by necessity did not target their efforts at locations with high resource potential. However, it is these areas that most need characterization for their potential contribution to U.S. electricity supply.

> **Recommendation: Further evaluation of the MHK resource base should use the theoretical and/or technical results of the DOE resource assessments and appropriate decision support tools to identify the constraints that affect the practical resource and to help identify individual, highly promising sites for continued study of the practical resource. A site-specific approach to identify the practical MHK resource could help to estimate the potential contribution of MHK to overall U.S. electricity generation.**

For example, the ability to connect or integrate the MHK resource into the electrical grid may influence the number of realizable sites or prioritize among more easily connectable, economically viable sites. A next research step could be to create detailed assessments of two types of sites—those hot spots with potential for large-scale MHK deployment and those that might be promising for small-scale applications (for instance, remote communities without access to the nationwide transmission/distribution system).

As part of the evaluation of the practical resource base, there seemed to be little analysis by the assessment groups of the MHK resources' temporal variability. This is in contrast to the spatial variability, which is comparatively well characterized through modeling and GIS displays. While this issue was not raised in the interim report, the committee recognized that **the time-dependent nature of power generation is important to utilities and would need to be understood in order to integrate MHK-generated electricity into any electricity system.**

For example, the predictability of the tidal resource would ease its integration into an electricity system. In contrast, large variations in the wave resource due to extreme weather can affect not just power availability but also a location's desirability. For ocean currents, seasonality and meandering could limit device placement to narrow regions where flow is consistent throughout the year. While OTEC is more predictable, large interannual variations in available temperature difference that would limit power generation in some locations may be masked by monthly or seasonal averaging. Even greater seasonal and interannual variability can be expected in riverine resources. The assessment groups did very little to quantify resource variability and in some instances averaged away the precise seasonal variation that may be of most interest to developers. It should be noted that utilities are increasing their experience with incorporating temporally varying renewable resources such as wind and solar power, and those resources are likely to show greater temporal variability than MHK resources.

COORDINATION FOR RESOURCE DEVELOPMENT

Continued development of U.S. MHK resources requires clear conceptual and operational definitions and objectives. While ultimately many of the questions raised about MHK resource development will be decided at the local, state, or regional level, there is an opportunity for DOE to play a leadership role in assessing resources and disseminating results. As first discussed in Chapter 1, the U.S. MHK energy community has not converged upon a common set of definitions for resource assessment and development. The committee has provided a conceptual framework for the MHK resource that is consistent with that of the European marine energy community. This common set of definitions was essential for understanding the factors considered when developing and comparing the five MHK resource assessments, and the committee feels it would be beneficial for DOE to either develop its own framework or adopt an existing framework.

> **Recommendation: DOE should develop or adopt a conceptual framework that clearly defines the theoretical, technical, and practical MHK energy resource.**

Each of the resource assessment groups provides a useful contribution to understanding the distribution and possible magnitude of marine and hydrokinetic energy sources in the United States. However, the absence of a common framework allowed for a multitude of approaches to the individual assessments. In its interim report, the committee noted that **the assessments suffered from a lack of coordination and consistency in terms of methodology, validation, and deliverable products.** Each of the assessment groups chose its own method of evaluating the resource. While some variation between methodologies was due to differences in the MHK types, greater initial coordination among the assessors could have identified commonalities and facilitated comparison among the assessments.

Quantifying the interaction between MHK installations and the environment was a challenge for the assessment groups, as described in previous chapters. **Deployment of MHK devices can lead to complex feedback effects for many of the assessed technologies. Analysis of these feedbacks affects both the technical and practical resource assessments (and in some cases the theoretical resource) and needs to be carefully evaluated.** The committee was disappointed by the resource groups' lack of awareness of some of the physics driving their resource assessments, which led to simplistic and often flawed approaches. The committee was further concerned about a lack of rigorous statistics, which are essential when a project involves intensive data analysis.

A coordinated approach to validation would have provided a mechanism to address some of the methodological differences between the groups as well as a consistent point of reference. However, each validation group (chosen by individual assessment groups) determined its own method, which led to results that were not easily comparable. In some instances, the committee noted a lack of sufficient data and/or analysis to be considered a true validation. The weakness of the validations included an insufficiency of observational data, the inability to capture extreme events, inappropriate calculations for the type of data used, and a focus on validating technical specifications rather than underlying observational data. The lack of consistent, effective validation is especially problematic given the large uncertainties described in assessment results.

All five MHK resource assessments lacked sufficient quantification of their uncertainties. There are many sources of uncertainty in each of the assessments, including the models, data, and methods used to generate the resource estimates and maps. Propagation of these uncertainties into confidence intervals for the final GIS products would provide users with an appropriate range of values instead of the implied precision of a specific value, thus better representing the approximate nature of the actual results.

The GIS database products themselves also reflect an apparent lack of coordination in their development, which led to duplication of effort and additional time needed to integrate the final products. At the time of this writing, the wave and OTEC databases are the only MHK resource assessments integrated into the National Renewable Energy Laboratory's (NREL's) MHK Atlas; the in-stream resource assessment is hosted separately in the NREL River Atlas. The tidal resource database is currently hosted by the tidal resource assessment group and will be integrated with other NREL products; however, the visualization and analysis tools developed by the assessment group will not be implemented in the MHK Atlas. Given that one of DOE's objectives is to compare the various MHK resources with one another and with other renewable energy resources, stronger initial coordination among the assessment groups could have led to products developed in a common format.

LIMITATIONS ON COMPARISON OF EXTRACTABLE MHK RESOURCES

The different approaches taken by the resource assessment groups left the committee unable to provide the defensible comparison of potential extractable energy from each of the resource types as called for in the study task statement. To do so would require not only an assessment of the practical resource base discussed by the committee earlier but also an understanding of the relative performance of the technologies that would be used to extract electricity from each resource type. Understanding the performance characteristics of the technologies that might be used to tap these different resources is either just emerging, as is the case for wave and tidal devices, or limited to modeling or sparse pilot plant demonstrations, as is the case for OTEC and ocean currents.

Some comparisons can be made based upon attributes of the different MHK resources, especially their geographical extent and predictability. Clearly, both the ocean current and OTEC resource bases have very limited geographical extent in the United States. The main potential for ocean currents is in the Florida Straits, and the coastal regions of the Hawaiian Islands and Puerto Rico are the most likely places for efficient OTEC siting. In contrast, the resource assessments for waves, tides, and in-stream show a much greater number of locations with substantial resources, though by far the largest location for tidal resources in the United States is in the Cook Inlet of Alaska. Predictability is another important characteristic to consider if a resource is to be incorporated into an electricity system. Tidal resources are highly predictable, with the timing and magnitude of tidal events being known precisely years into the future. In contrast, waves and in-stream resources are related to meteorological conditions that unfold over days and weeks. There is multiday predictability for wave and in-stream systems, especially in settings where the wave spectrum is dominated by swells or in large hydrologic basins, but the predictability is notably less than for tidal systems. The OTEC resource in the United States has little day-to-day variability but, like in-stream, is seasonally dependent. However, location and variability are but two of the many factors that will determine what MHK resources are capable of contributing significantly to power generation in the United States.

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Appendixes

A

Department of Energy Funding Opportunity Announcements for the Assessment of Marine and Hydrokinetic Resources (excerpted)

FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U.S. Department of Energy
Golden Field Office

Advanced Water Power Projects
Funding Opportunity Announcement Number: DE-PS36-08GO98030
Announcement Type: Modification A001
CFDA Number: 81.087

Issue Date:	**04/15/2008**
Application Due Date:	**06/16/2008, 11:59 PM Eastern Time**

Topic Area 2: Marine and Hydrokinetic Renewable Energy Market Acceleration Projects

AWARD INFORMATION

A. BACKGROUND

Federal funding for the Marine and Hydrokinetic Renewable Energy Market Acceleration Projects for fiscal year 2008 is expected to be approximately $1.0-$2.5 million. DOE expects to make up to six awards where individual awards are valued between $100,000 and $500,000. Successful applications under this section can include universities, industrial companies, non-profits and other private sector companies. Partnerships, including partnerships with National Laboratories, are encouraged but not required. Although no cost share will be required, consideration will be given to applications providing cost share. The awards will be made to facilitate the market penetration of advanced water power technologies with project durations expected to be no more than 24 months from beginning to conclusion.

The Department of Energy will select applications that facilitate the market penetration of marine and hydrokinetic technologies. The applications will address one or more of the following areas:

1. The development of international power measurement, identification, and systems engineering and integration standards for marine and hydrokinetic renewable energy. The final product will be a report that must include a summary of the current state of international standards and a proposal for new international standards. Justifications for the proposed standards must be provided in the report. The primary audience for the report is intended to be members of the international standard committees and the standards communities;

2. Investigation into the efficient and reliable integration of marine and hydrokinetic renewable energy devices with the utility grid and reliable intermittency issues. The final product will be a report that addresses grid-integration issues faced by water power technologies, including the identification of system interconnection requirements and technologies, the evaluation of potential integration technologies, and a proposed pathway toward the development and deployment of such technologies. The audience for

the report will be project developers, regulatory bodies, and other interested parties and agencies;

3. Identification, in cooperation with the U.S. Coast Guard, of the potential navigational impacts of marine and hydrokinetic renewable energy technologies and measures to prevent adverse impacts on navigation. The final products will be 1) a formal report on the potential navigational impacts for the U.S. Coast Guard and 2) a brochure intended for project developers to understand how their project could impact shipping and steps (including siting) that can be used to mitigate these issues; and

4. Development, in cooperation with the relevant Federal siting authority(ies), protocol to identify streamlined best siting practices for marine and/or hydrokinetic technologies, accounting for both environmental and navigational impacts. The final products will include 1) a formal report on best practices for siting and a peer-reviewed proposal to streamline the current siting process. This report is intended for regulatory agencies and other interested parties and agencies; 2) a brochure intended for project developers on the siting process and a step-by-step how-to guide on siting an offshore system.

Waves

5. **An assessment of wave energy resources along the U.S. coastline to determine maximum practical, extractable energy in Watts per squared meter of water surface area. The assessment should assume optimal achievable energy conversion rates based on likely future technology performance and should account for device spacing requirements within wave energy conversion arrays. The final product will include a geospatial database, validated and verified by a third party with experience in renewable energy resource validation, that is capable of displaying power densities in Watts per squared meter of water surface area for specific geographic information system (GIS) coordinates, in a manner that is useful to developers and policymakers, that characterizes the seasonal variability and magnitude of wave energy, and can be updated on a regular basis. The third-party partner that will conduct independent validation shall be identified in the application, along with their method for validation. The methodology and results should allow the U.S. wave resource to be accurately compared to other renewable energy resources and conform, to the maximum extent possible, with widely-accepted**

resource assessment metrics and standards and incorporated as metadata in the final product.

Tidal Currents

6. **An assessment of tidal current energy resources in the U.S. to determine maximum practical, extractable energy in Watts per squared meter of water surface area. The assessment should assume optimal achievable energy conversion rates based on likely future technology performance and should account for device spacing requirements within tidal energy conversion arrays. The final product will include a geospatial database, validated and verified by a third party with experience in renewable energy resource validation, that is capable of displaying power densities in Watts per squared meter of water surface area for specific geographic information system (GIS) coordinates, in a manner that is useful to developers and policymakers and that can be updated on a regular basis. The third-party partner that will conduct independent validation shall be identified in the application, along with their method for validation. The methodology and results should allow the U.S. tidal resource to be accurately compared to other renewable energy resources and conform, to the maximum extent possible, with widely-accepted resource assessment metrics and standards and incorporated as metadata in the final product.**

B. TYPE OF AWARD INSTRUMENT

DOE anticipates awarding grants under this program announcement.

C. ESTIMATED FUNDING

Approximately $1,000,000 to $2,500,000 is expected to be available for new awards under this announcement.

D. MAXIMUM AND MINIMUM AWARD SIZE

Ceiling (i.e., the maximum amount for an individual award made under this announcement): $ 500,000
Floor (i.e., the minimum amount for an individual award made under this announcement): $ 100,000

E. EXPECTED NUMBER OF AWARDS

DOE anticipates making up to 6 awards under this announcement depending on the size of the awards.

F. ANTICIPATED AWARD SIZE

DOE anticipates that awards will be in the $100,000–$500,000 range for the total project period.

G. PERIOD OF PERFORMANCE

DOE anticipates making awards that will run for up to 2 years.

H. TYPE OF APPLICATION

Only new applications will be accepted under this announcement.

FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U.S. Department of Energy
Golden Field Office

Advanced Water Power
Funding Opportunity Announcement Number: DE-FOA-0000069
Announcement Type: Initial
CFDA Number: 81.087

Issue Date:	**04/08/2009**
Letter of Intent Due Date:	**05/06/2009, 11:59 PM Eastern Time** Only those Applicants who submit a letter of intent are eligible to submit final applications under this announcement.
Application Due Date:	**06/04/2009, 11:59 PM Eastern Time**

PLEASE NOTE:

> Applicants who are not registered with CCR and FedConnect, should allow at *least 21 days* to complete these requirements. It is suggested that the process be started as soon as possible. For those Applicants already registered in CCR, the CCR registration must be updated annually at http://www.ccr.gov/Renew.aspx.
>
> Questions regarding the content of this announcement must be submitted through FedConnect. Applications must be submitted through FedConnect to be considered for award. You must be completely registered before you can submit questions regarding this announcement or submit an application.

Topic Area 3: Advanced Water Power Market Acceleration Projects/Analysis and Assessments

AWARD INFORMATION

A. BACKGROUND

The Department of Energy is soliciting applications that propose to facilitate the market penetration of water power technologies. Applicants can submit multiple applications, though each application should address one, and only one, of the following sub-topic areas:

Ocean Currents

3A. ***An assessment of off-shore ocean current energy resources along the U.S. coastline, excluding tidal currents, to determine maximum practicably extractable energy.*** **The assessment should assume optimal achievable energy conversion rates based on likely future technology performance and should account for device spacing requirements within energy conversion arrays. The final product will include a geospatial database, validated and verified by a third party with experience in renewable energy resource validation, that is capable of displaying power densities in Watts per square meter of water surface area for specific geographic information system (GIS) coordinates, in a manner that is useful to developers and policymakers, that characterizes the seasonal variability and magnitude of current energy, and can be updated on a regular basis. The third-party partner that will conduct independent validation shall be identified in the application, along with their method for validation. The methodology and results should allow the U.S. ocean current resource to be accurately compared to other renewable energy resources and conform, to the maximum extent possible, with widely-accepted resource assessment metrics and standards and incorporated as metadata in the final product.**

In-stream/Riverine

3B. ***An assessment of in-stream hydrokinetic energy resources, defined as energy that can be extracted from free flowing water in rivers, lakes, streams or man-made channels without the use of a dam or diversionary structure, in the U.S. to determine maximum practicably extractable energy.*** **A successful application will demon-**

strate a comprehensive understanding of existing U.S. in-stream hydrokinetic resource assessments, including previous DOE-funded efforts, and how the proposed project will build and improve upon the existing assessments. The assessment should assume optimal achievable energy conversion rates based on likely future technology performance and should account for device spacing requirements within in-stream hydrokinetic energy conversion arrays. The final product will include a geospatial database, validated and verified by a third party with experience in renewable energy resource validation in a manner that is useful to developers and policymakers and that can be updated on a regular basis. The third-party partner that will conduct independent validation shall be identified in the application, along with their method for validation. The methodology and results should allow the U.S. in-stream hydrokinetic resource to be accurately compared to other renewable energy resources and conform, to the maximum extent possible, with widely-accepted resource assessment metrics and standards and incorporated as metadata in the final product.

3C. *An assessment of projected life-cycle costs for ocean thermal energy conversion in the United States over time.* Cost estimates will be presented as ranges, with at least three separate cost scenarios (e.g. high, medium, low) and will include projections for both installed capital cost and the cost of operations and maintenance (O&M) in $/kW, as well as future cost of energy in $/kWh. Cost estimates should make use of best available data, including existing ocean thermal energy component development costs and analogous technologies in related industries, and should be extrapolated over time and over multiple technology designs and industry deployment scenarios. The ocean thermal energy cost assessment will differentiate between costs associated with near-shore, grid-connected ocean thermal energy systems and those floating offshore. Cost estimates will include project development costs, including site selection and permitting, installation and mooring, and connection to the grid. A successful application will demonstrate an ability to improve significantly upon current cost assessments, and will propose sources for critical data and assumptions such as: component design and development costs; infrastructure cost; learning rates; reference cost build-ups; cost data indexing; load models; performance models; O&M strategies/costs; and project development costs. Projects are encouraged that propose to generate energy supply curves that can predict energy generation at a given cost level.

OTEC

3D. ***An assessment of global and domestic U.S. ocean thermal energy resources to determine maximum practicably extractable energy*. The assessment should assume optimal achievable energy conversion rates based on likely future technology performance and should account for device spacing requirements and the physical limitations of the ocean thermal resource. The assessment should distinguish between resources available with near-shore, grid-connected ocean thermal energy systems and those that require floating offshore systems. The final product will include a geospatial database, validated and verified by a third party with experience in renewable energy resource validation, that is capable of displaying available power for specific geographic information system (GIS) coordinates, in a manner that is useful to developers and policymakers, that characterizes the magnitude and any seasonal variability of ocean thermal energy, and can be updated on a regular basis. The third-party partner that will conduct independent validation shall be identified in the application, along with their method for validation. The methodology and results should allow the U.S. ocean current resource to be accurately compared to other renewable energy resources and conform, to the maximum extent possible, with widely-accepted resource assessment metrics and standards and incorporated as metadata in the final product.**

3E. *An assessment of projected life-cycle costs for wave, tidal, ocean current, and in-stream hydrokinetic power in the United States over time.* Cost estimates will be presented as ranges for each resource type, with at least three separate cost scenarios (e.g., high, medium, low) and will include projections for both installed capital cost and the cost of operations and maintenance (O&M) in $/kW, as well as future cost of energy in $/kWh. Cost estimates should make use of best available data, including existing marine and hydrokinetic technologies and analogous technologies in related industries, and should be extrapolated over time under at least three possible industry deployment scenarios, specified in total MW deployed. The assessment will address the full geographical range of marine and hydrokinetic energy deployment likely in the U.S. and incorporate multiple energy conversion technology types for each resource type. Cost estimates will include project development costs, including site selection and permitting, installation and mooring, and connection to the grid. A successful application will demonstrate an ability to improve significantly upon current cost assessments, and will propose sources for critical data and assumptions such as: component design and development costs; infrastructure cost; learning rates; reference cost build-ups; cost data indexing; load models; performance models; O&M strategies/costs; and project development costs. Projects are encouraged that propose to generate energy supply curves that can predict energy generation at a given cost level.

3F. *An assessment of the energy resources available from installing power stations on non-powered dams and in constructed waterways and the construction of new pumped storage facilities in the U.S. to determine maximum practicably extractable energy*. A successful application will demonstrate a comprehensive understanding of existing U.S. hydropower resource assessments and how the proposed project will build and improve upon the existing assessments. The final product will include a geospatial database, validated and verified by a third party with experience in renewable energy resource validation in a manner that is useful to developers and policy-makers and that can be updated on a regular basis. This database should be coordinated and compatible with the geospatial data standards used in other ongoing incremental hydropower resource analyses supported by WHTP, including the National Hydropower Asset Assessment Program. The third-party partner that will conduct independent validation shall be identified in the application, along with their method for validation. The methodology and results should allow the U.S. advanced hydropower resource to be accurately compared to other renewable energy resources and conform, to the maximum extent possible, with widely-accepted resource assessment metrics and standards and incorporated as metadata in the final product.

Federal funding for the Advanced Water Power Market Acceleration Projects for fiscal year 2009 is expected to be approximately $4 million. DOE expects to make up to 6 awards where individual awards are valued at up to $0.5 million DOE share for subtopics 3A – 3E and up to $1 million DOE share for subtopic 3F.

B

Interim Letter Report

NRC ASSESSMENT OF MARINE AND HYDROKINETIC ENERGY TECHNOLOGY: INTERIM LETTER REPORT

Released on July 12, 2011

Division on Engineering and Physical Sciences
Board on Energy and Environmental Systems

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July 12, 2011

Dr. Henry Kelly
Acting Assistant Secretary
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585

RE: NRC Assessment of Marine and Hydrokinetic Energy Technology: Interim Letter Report

Dear Dr. Kelly:

The Department of Energy's (DOE's) Wind and Water Power Program requested that the National Research Council (NRC) provide an evaluation of the detailed assessments being conducted by five individual resource assessment groups for the DOE, estimating the amount of extractable energy from U.S. marine and hydrokinetic (MHK) resources.

In response, the NRC formed the Committee on Marine and Hydrokinetic Energy Technology Assessment, which has begun its review of the resource assessments.

In this letter report, the committee responds to its charge of writing an interim report assessing the methodologies, technologies, and assumptions associated with the wave and tidal energy resource assessments. The DOE specifically requested that these two MHK resource assessments be evaluated in the interim report and that the committee's final report also cover the three other assessments—those on free-flowing water in rivers and streams, on marine temperature gradients, and on ocean currents. Attachment A contains the committee's statement of task. Attachment B presents biographical information on the committee members.

The committee presents this letter report, in accord with the statement of task, as its preliminary assessment of methodologies and assumptions used in the estimation of wave and tidal resources. The committee's review is based on the presentations that it received from the wave resource assessment group (which consists of the Electric Power Research Institute [EPRI] working with Virginia Polytechnic Institute and State University [Virginia Tech] and National Renewable Energy Laboratory [NREL]) and the tidal resource assessment group (consisting of Georgia Institute of Technology [Georgia Tech] working with Oak Ridge National Laboratory [ORNL]). These presentations were made at the committee's first two meetings, in November 2010 and February 2011. The committee also received presentations from the DOE as well as written information submitted by all five of the resource assessment groups.

Although the wave resource and tidal resource assessment groups will eventually release final reports, their reports were not available for the development of this interim report. Thus, the committee believes that it is important to complete its interim letter report at this point, not only for the letter report's potential impact with respect to the wave resource and tidal resource assessments, but also to provide timely feedback to the other assessment groups. The committee will continue to review the methodologies and assumptions that are used in all five of the assessments, as it completes its study and writes its final report (currently scheduled for completion in the spring of 2012).

In the sections that follow, the committee first describes the motivation for and purpose of this report. It then presents the conceptual framework of the overall MHK resource assessment process that it developed in order to have a consistent, clear set of definitions and a framework for assessing the approaches of the individual groups. The committee's evaluation of the wave resource assessment and of the tidal resource assessment is presented in the next two sections, with conclusions and recommendations in each. A final section on overarching conclusions completes the body of the report.

As elaborated on in the sections that follow, the committee concludes that the overall approach taken by the wave resource and tidal resource assessment groups is a useful contribution to understanding the distribution and possible magnitude of energy sources from waves and tides in U.S. waters. However, the committee has concerns regarding the usefulness of aggregating the analysis to produce a "single number" estimate of the total national or regional theoretical and technical resource base (defined in the section below entitled "Conceptual Framework") for any one of these sources. The committee also has some concerns about the methodologies and assumptions, as detailed in the sections below. For the wave resource assessment, the committee is particularly concerned with the extension of the analysis into shallow depths, where the modeling is most inaccurate. One important issue for the tidal resource assessment is the lack of clarity on how the assessment group will incorporate any sort of technological considerations into its resource assessment. The committee is also concerned about the limited scope of the assessments' validation exercises. These issues are discussed further below.

MOTIVATION FOR AND PURPOSE OF THE INTERIM REPORT

Marine and hydrokinetic resources are increasingly becoming part of energy regulatory, planning, and marketing activities in the United States and elsewhere. In particular, state-based renewable portfolio standards and federal production and investment tax credits have led to an increased interest in the possible deployment of MHK technologies. This interest is reflected in the number of requests for permits for wave, current, tidal, and river-flow generators that have been filed recently with the Federal Energy Regulatory Commission (FERC); at the end of 2010 FERC had issued preliminary permits for 110 projects and had another 12 preliminary permits pending. It should be noted that although permit activity is a measure of the potential interest in MHK resource development, it is not a reliable predictor of the future development of hydrokinetic resources because developers apply for permits before planning the facility or obtaining financing.

In order to assess the overall potential for U.S. MHK resources and technologies, the DOE is funding the following: (1) detailed resource assessments for estimating what the DOE terms the "potential extractable energy" for each resource and (2) projects for generating the technology-related data necessary for estimating the expected performance of the wide variety of technology designs currently under consideration (DOE, 2010; Battey, 2010, 2011). The objective of the DOE's work in the area of MHK resource assessments is to help the DOE prioritize its overall portfolio of future research, increase the understanding of the potential for MHK resource development, and direct MHK device and/or project developers to locations of greatest promise (Battey, 2011). In terms of resource assessments, the Energy Policy Act of 2005 (Public Law 109-58) directed the DOE to estimate the size of the MHK resource base. Earlier estimates (EPRI, 2005, 2007) of the amount of energy that could be extracted from MHK resources are based on limited and possibly inaccurate data regarding the total resource size and on potentially dated assumptions related to the amount of each resource that might ultimately prove extractable. To improve these estimates, the DOE contracted with the five assessment groups referred to above to conduct separate estimates of the extractable energy from five categories of MHK resources: waves, tidal currents, ocean currents, marine temperature gradients, and free-flowing water in rivers and streams (DOE, 2010). Performing these assessments requires that each group estimate the average power density of the resource base, as well as the basic technology characteristics and spatial and temporal constituents that convert power into electricity for that resource. Each assessment group is using distinct methodologies and assumptions. This NRC committee is tasked with evaluating the detailed assessments produced for the DOE, reviewing estimates of extractable energy (typically represented as average terawatt-hours [TWh] per year)[1] and technology specifications, and accurately comparing the results across resource types.

In reviewing the initial methodologies from the five U.S. MHK resource assessment groups contracted by the DOE, the committee observed that the groups all employed different terminology to describe similar results. Thus, besides providing its review comments on each individual assessment, the committee is also taking on the role of providing a forum for comparing and contrasting the approaches taken by the respective assessment groups. To that end, the committee developed the conceptual framework of the overall MHK resource assessment process, presented in the section below, in order to help develop a common set of definitions and approaches.

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[1] Note that terawatt-hours per year can be translated into units of power, such as gigawatts, and used to represent the average power generation over the time period indicated. However, a unit such as terawatt-hours per year (or, as shown in an electricity bill, kilowatt-hours per month) is a standard unit for the electricity sector. Energy units such as kilowatt-hours or terawatt-hours measure the commodity that is generated by power plants and sold to consumers. For example, the Energy Information Agency's table of total electricity generation (see http://www.eia.doe.gov/aer/pdf/pages/sec8_8.pdf) is given in billions of kilowatt-hours per year.

CONCEPTUAL FRAMEWORK

In order to develop its approach to the study task and to review the individual resource assessments, the committee developed a conceptual framework (Figure 1) for visualizing the processes used to develop the assessment results requested by the DOE. This framework establishes a set of three terms—*theoretical resource, technical resource,* and *practical resource*—and their definitions, provided below, to clarify elements of the overall resource assessment process as described by each assessment group and to allow for a comparison of different methods, terminology, and processes among the five assessment groups. The committee recognizes that communities involved with other energy types, such as wind and fossil fuels, use different terms to describe their resource bases (i.e., "resources," "proven reserves"). It has instead chosen to follow emerging trends in terminology for MHK resources as used in the European marine energy community, including the European Marine Energy Centre (EMEC; http://www.emec.org.uk/standards.asp). The EMEC terminology has been submitted to the International Electrotechnical Commission for consideration as the basis of an international standard. In addition to employing terminology used in the European marine energy community, the committee developed Table 1 as a common source of definitions and units used in this report.

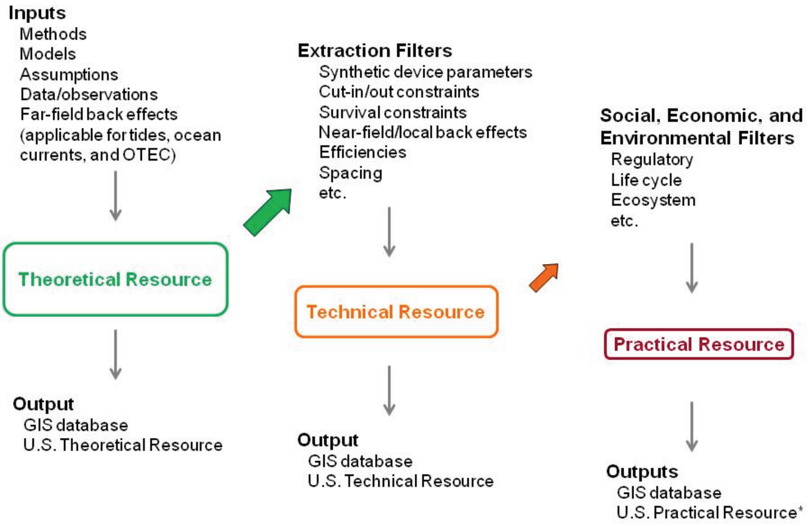

FIGURE 1 Conceptual framework developed by the committee for marine and hydrokinetic resource assessments. NOTE: GIS, Geographic Information System; TBD, to be determined.

TABLE 1 Definitions Used by Department of Energy Marine and Hydrokinetic Resource Assessment Groups and National Research Council (NRC) Committee

Term to be Quantified	Definition	Units	Notes
General			
Energy	The capacity to do work	Joules (J)	
Power	Energy per time	Watts (W) = joules per second	
Resource	Average annual power	Terawatt-hours (TWh) per year (1 TWh/yr = 114 megawatts [MW])	Representing a potential energy resource base for the electricity sector in terawatt-hours.
Waves			
Wave power density (Mei, 1989)	Power of waves per unit crest length based on $P_{vector} = \rho g \, \Sigma \, S(f,\theta)c_g \, df$	Watts per meter	Horizontal energy flux (power density); applies to a single device.
Wave power density (Electric Power Research Institute [EPRI])	Power of waves per unit circle based on $P_{scalar} = \rho g \, \Sigma\Sigma \, S(f,\theta)c_g \, df \, d\theta$	Watts per meter	Horizontal energy flux; applies to a single device.
Total regional wave resource (EPRI)	Based on annual average sum of wave power density along a line defining a region of coastline, such as a bathymetric contour. $P_{coast} = \Sigma \, P_{scalar} \, dl$	Terawatt-hours per year (= 114 MW)	Overestimates the total resource by including energy flux along the line.
Total regional wave resource (recommended by this committee)	Based on annual average sum of wave power density crossing perpendicular to a line defining a region of coastline, such as a bathymetric contour. $P_{coast} = \Sigma \, P_{vector} \cos\theta \, dl$	Terawatt-hours per year (= 114 MW)	Remains approximately constant as waves travel shoreward from deep water.

TABLE 1 Continued

Tides			
Tidal power density	Power of horizontal tidal currents flowing through a vertical plane of unit area. $P = \frac{1}{2}\rho u^3$	Watts per square meter (W/m^2)	Horizontal kinetic energy flux; applies to a single device.
Total regional tidal resource (Garrett and Cummins, 2008)	Based on annual average power available from a tidal bay or channel $P_{max} = 0.22\rho g a Q_{max}$	Terawatt-hours per year (= 114 MW)	Maximum power obtainable with a complete tidal fence; equivalent to a barrage.

NOTE:
List of variables:
ρ = water density
g = gravitational acceleration
S = wave spectrum (sea-surface height variance, per frequency and direction)
c_g = wave group speed
f = wave frequency
θ = wave direction
l = length of coastline, depth contour, or other region
u = tidal current speed
a = tidal amplitude (half of tidal range)
Q_{max} = maximum horizontal tidal volume flux (over tidal cycle)

The *theoretical resource,* shown in the left column of the conceptual framework in Figure 1, is defined as the average annual energy production for each source of hydrokinetic energy. Determining the theoretical resource requires a series of inputs (including methods, models, assumptions, and data and observations) for each source of hydrokinetic energy (e.g., waves, tides). In response to the original DOE request, some, but not all, of the assessment groups have identified paths designed to produce two key outputs for the theoretical resource: (1) overall regional or national numbers for the U.S. theoretical resource, expressed as an average annual energy resource (typically in terawatt-hours per year); and (2) a Geographic Information System (GIS) database that represents the spatial variation in average annual power density in units appropriate for each source (i.e., watts per meter for waves or watts per square meter for tides).

The *technical resource* (center column in Figure 1) is defined as the portion of the theoretical resource that can be captured using a specified technology. For each resource, there are technological constraints that represent how much of the theoretical resource can actually be extracted. The committee conceptualizes these constraints as "extraction filters" consisting of physical and technological constraints, including back effects[2] and technological characteristics associated with one or more energy-extraction devices (representing factors such as device efficiency, device spacing requirements, and cut-in and cut-out parameters).[3] Some of these filters are resource-specific; others are applicable across all of the MHK types. During presentations made to the committee and from its discussion with the DOE and the assessment groups, it became clear that each group offers a different interpretation of what types of constraints need to be included among its extraction filters. However, it is clear to the committee that estimating the technical resource from the theoretical resource requires filters that represent physical and technological constraints associated with energy-extraction devices. Outputs related to the technical resource include an estimate of the energy resource and a GIS representing spatial and temporal variation in the resource associated with various technologies. In the committee's view, the assessment groups determined that reporting the technical resource represented the completion of their projects.

Some of the assessment groups recognized that, beyond the extraction filters, there were additional filters influencing when and where devices could be placed. The *practical resource* (right-hand column in Figure 1), is defined as that portion of the technical resource available after consideration of all other constraints. In the conceptual framework, these constraints are captured in socioeconomic filters. For example, the filters involving logistical and economic considerations include costs of raw materials and maintenance, resources associated with transmission and distribution, electricity demand, and the cost of electricity. Environmental and use constraints include issues relating to a variety of impacts on the environment (e.g., protecting threatened species or ecologically sensitive areas), sea-space conflicts (e.g., involving shipping channels, navigation, protected areas), and multiple- or competing-use issues (e.g., fisheries, viewshed impacts, recreation, national security). Such filters are, by nature, specific to and critical at the local sites where decision making related to marine and hydrokinetic projects will occur.

A determination of the practical resource is beyond the scope of the resource assessment groups' tasks as defined by the DOE. However,

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[2] A *back effect* refers to the modification of an energy resource owing to the presence of an extraction device. In the case of turbines in a river or tidal channel, the back effect is the modification of currents in the whole cross section of the channel, particularly the reduction in the volume flux through the channel.

[3] In some cases, such as for tidal resources or steady currents, the estimation of the theoretical resource requires allowance for back effects.

the committee sees the constraints represented by the socioeconomic filters as being among the most important set of considerations influencing future investments in marine and hydrokinetic energy. The socioeconomic filters are also the most important set of considerations if one is to develop an assessment of what might ultimately be considered the maximum estimate of MHK resources that could be used to generate electricity. An approach for assessing these socioeconomic considerations might be to merge the GIS databases resulting from the theoretical and technical resources with existing spatial information about other economic and ecological uses of the ocean and coast, such as shipping channels and areas associated with critical habitats and species. Although such information would be helpful in highlighting potential multiple-use conflicts, it will not be sufficient for quantifying the practical resource base. The quantification of the practical resource could be done as part the planning processes for site-specific management or for local, state, or regional management.

As discussed below, the wave and tidal resource assessment groups employ different GIS platforms to display their results. Given that one of the DOE's objectives is to be able to compare the various resource types with one another, this lack of coordination among the assessment groups precludes the easy integration of all resource assessments into a single database and seems counterproductive to the ultimate DOE goals. Moreover, this same coordination and consistency would, if present, help the five resource assessment groups develop resource assessments that are easily comparable and that could be easily integrated into a common platform. Given that many of the extraction and the socioeconomic filters might be similar across the assessment groups, coordination would also help in the development of a GIS database useful to policy makers and developers.

The DOE requested that the assessment groups determine the "*maximum practicable, extractable energy*." Although maximum practicable, extractable energy could possibly refer to the practical resource in the conceptual framework shown in Figure 1, discussion with the DOE and the assessment groups led the committee to conclude that the term is instead equivalent to the technical resource in the conceptual framework. It was also made clear that the assessment effort did not include incorporating site-specific information that would be required to define the practical resource base.

Additionally, there is a lack of clarity on the geographic scope for the estimate of maximum practicable, extractable energy. It is unclear from discussions with the DOE and the assessment groups whether the estimate is to be a national, regional, or local resource estimate. The committee finds that the resource estimates, especially the resource base aggregated to a regional or national level, have both limited utility and potential for misuse. Although such estimates might provide broad order-of-magnitude estimates of which resources have the greatest potential, the conceptual framework shown in Figure 1 clearly illustrates that there are many extraction filters needed to determine the technical resource. The assessment groups can only assess a few of these filters, and many of the filters require assumptions about which particular MHK technologies will be used. Moreover, a wide array and diversity of socioeconomic filters ultimately limit only a portion of this technical resource base to be representative of what the maximum practicable, extractable energy might be from MHK resources.

WAVE RESOURCE ASSESSMENT

Introduction

Power in ocean waves originates as wind energy that is transferred to the sea surface when wind blows over large areas of the ocean. The resulting wave field consists of a collection of waves at different frequencies traveling in various directions, typically characterized by a directional wave spectrum. These waves travel efficiently away from the area of generation across the ocean to deliver their power to nearshore areas.

Wave power density is usually characterized as power per length of wave crest; it represents all the energy crossing a vertical plane of unit width per unit time. This vertical plane is oriented along the wave crest and extends from the sea surface down to the seafloor. To capture this orientation, wave power is expressed as a vector quantity, and accurate representation of its magnitude and direction requires the consideration of the full directional wave spectrum. Note that the wave energy conversion devices currently under development are designed to operate at different locations in the water column, and only a portion of this overall wave power may be available to these devices (e.g., devices that respond only to heave motions associated with the waves). As noted in the discussion above of the committee’s conceptual model, the considerations of the amount of power that can be extracted by specific wave power devices are incorporated in the estimation of the technical resource.

Because wave energy travels in a particular direction, care must be taken when interpreting maps that show wave power density as a function of location but do not indicate predominant wave directions. It also must be recognized that if the energy is removed from the wave field at one location, by definition less energy will be available in the shadow of the extraction device. It would not be expected that a second row of wave energy extraction devices would perform the same as the first row of devices that the wave field encountered, because any recovery of the wave field due to additional wind input (if present) would occur over distances much larger than the spacing between rows of wave energy extraction devices that are currently under consideration. This shadowing effect implies that it is erroneous to estimate the theoretical resource as the sum of the wave power density over an area as one might do for solar energy. Note that the magnitude of this shadowing effect is likely to be highly dependent on the specific characteristics of the device (e.g., size, efficiency). Although there are some initial publications with rigorous analytical approaches for quantifying the effect of an arbitrary array of point absorbers devices (e.g., Garnaud and Mei, 2010), shadowing effects due to realistic devices are a topic of active research. The planning of any potential large-scale deployment of wave power devices would require sophisticated, site-specific field and modeling analysis of the devices' interactions with the wave field.

One approach to interpreting wave power density maps correctly is to evaluate the wave energy traveling shoreward across a line parallel to the coastline (perhaps located on a bathymetric contour). This is shown in Table 1 as the "total regional wave resource" assessment recommended by the committee. Provided that the selected line is on the continental shelf, it is reasonable to assume that the winds do not add significant energy to the wave field after the waves cross this line. In this case, the wave power density across such a line provides a reasonable approximation to the theoretical resource that represents the wave energy available to nearshore wave energy devices in a region. To do this estimate properly, wave direction information, in addition to the wave frequency spectrum, must be known.

Description of Wave Resource Estimate

The wave resource assessment group was tasked with producing estimates of the theoretical and technical resource in U.S. coastal regimes. In order to obtain estimates of the theoretical wave resource (left column in Figure 1), the wave resource assessment group utilizes a hindcast of wave conditions that was assembled by the National Oceanic and Atmospheric Administration's (NOAA's) National Center for Environmental Prediction (NCEP) using its wave-generation and -propagation model WAVEWATCH III. The hindcast generally provides wave parameters over a 4′ x 4′ grid, although the resolution is coarser in a few areas (Alaska, for example, is gridded at 4′ x 8′) (Jacobson et al., 2010). Thus the resolution is generally on the order of many kilometers, whereas the shelf bathymetry can vary rapidly over a few hundred meters. The assessment and validation groups first resolve several potential issues related to the available hindcast (i.e., a short data record of only 51 months, a lack of full spectral information at all grid points), and then move on to an estimation of wave power density near the U.S. coastline. To produce maps of wave power density, the assessment group computes a sum of the power density associated with all wave components at a given location, regardless of wave direction. This is equivalent to considering the wave energy flux (power density) impinging on a cylinder of unit diameter that extends over the entire water column. Its estimate of the total theoretical resource is then computed by lining such cylinders along an entire line of interest (e.g., a 50 m depth contour or a 50 nautical mile line) and summing the wave energy flux over all of these cylinders. The several ramifications of this definition are discussed in the next subsection.

To produce an estimate of the technical wave resource (center column, Figure 1), the wave resource assessment group adopts an approach based on analyzing the cumulative probability density function (PDF) of wave power as a function of wave height. For a given threshold operating condition (TOC) and maximum operating condition (MOC), the percentage of the wave power that can be recovered can be estimated as a function of the rated operating condition (ROC). Note that this approach considers several extraction filters (e.g., cut-in/cut-out constraints) and simplifies or neglects others (e.g., efficiencies, back effects, spacing). The group plans to generate cumulative PDFs for the sites along the U.S. coastline and to estimate the technical wave resource using the TOC and MOC values specific to three devices (Archimedes Wave Swing, Pelamis, and Wave Dragon) for various values of the ROCs.

The products of the wave resource assessment will include a database of 51-month time series at 3 hr intervals of wave parameters that can be used to reconstruct the frequency spectra, although directional spreading information is not available. In addition, the group will provide maps of annual and monthly average wave conditions (i.e., wave power density, wave height, period, direction) in a GIS format. It will use ArcIMS, which is also the GIS web-based platform for the maps in National Renewable Energy Laboratory’s Renewable Resource Data Center. Bulk numbers for the total available theoretical wave resource and the total technical resource for different regions and for the entire United States will also be produced.

Comments on Methodology and Presentation of Results

The committee benefited from two presentations by the wave resource assessment group (Jacobson et al., 2010; Hagerman and Jacobson, 2011) and had access to portions of the group’s final report (EPRI, 2010; Virginia Tech University, 2010; EPRI, 2011). The committee therefore reviewed the work of the assessment group on the basis of these materials and identified concerns related to the suitability of the hindcast data set in shallow waters, the approach used to compute the total theoretical resource from the maps of wave power density, the technology assumptions utilized for assessment of the total technical resource, and the lack of a demonstrated GIS tool. These concerns are discussed more fully below.

At a resolution of 4 ft, the WAVEWATCH III simulations cannot capture wave transformation effects due to bathymetric features over shorter spatial scales because the simulations cannot resolve such variability. Yet, these bathymetric effects are known to be important at depths shallower than approximately 50 m (~160 ft) (Komar, 1998). It is important to note that these shallow-water regions may be areas of significant interest to developers of wave-energy-extraction devices. The methodology used precludes providing site-specific information to such developers. Reliable site-specific information in shallow waters can only be produced using results from models with higher spatial resolution that include the consideration of shallow-water physics. The wave resource assessment group acknowledges that its results will not be accurate in the shallower waters of the inner continental shelf, and it states that the shallowest water depths that the group intends to analyze are 50 m (going down to 20 m on the Atlantic coast, where the continental shelf is smoother and less steep). Yet, figures and tables that include results for shallow depths have been repeatedly presented in the materials of the group. Reporting such values is highly misleading and should be avoided.

The wave power density at a given location is estimated by the wave resource assessment group using the concept of wave energy flux impinging on unit diameter cylinders from any direction. The use of the unit cylinder concept results in the loss of the directional information contained in the WAVEWATCH III hindcast database. A consequence of this omission is the consideration only of the magnitude of the vector quantity of wave power density. An example of the potential misinterpretation of the resulting nondirectional (scalar) power density can be illustrated by considering a case of straight-and-parallel depth contours. In this case, the conservation of wave energy flux dictates that the shoreward component of wave power density remains constant across the continental shelf. In addition, wave refraction causes a general decrease in the angle of incidence of the waves, resulting in wave power vectors that are closer to being perpendicular to bathymetric contours as the waves travel toward the shore. The combination of these two processes causes an apparent reduction of the scalar wave power estimate as defined here, even in the absence of any dissipative process (such as bottom friction), despite the fact that the shoreward component of the associated vector will remain unchanged.

The lack of directional information in the wave power density maps also represents a bias toward nondirectional technologies, such as a point absorber technology that is likely to function in the wave field regardless of the wave direction. Yet, many other types of wave energy conversion devices are currently under development, and some of these are strongly influenced by the directional approach of the waves. The wave power estimates generated will not be very useful for the assessment of the behavior of such alternate devices. Reporting the wave power density magnitude as well as direction would alleviate this concern.

The total theoretical resource is estimated by the wave resource assessment group using the concept of wave energy flux impinging on unit diameter cylinders from any direction. Depending on the direction of wave approach and the orientation of the line of interest, there is a distinct possibility that waves passing through one cylinder and into the next cylinder will be counted repeatedly in the aggregate estimate of wave power, resulting in an overestimate of the total theoretical resource. The correct approach would be to acknowledge that the energy flux of waves is a directional quantity and to consider only the component of the wave power density vector that is perpendicular to the line of interest. Hence, rather than summing over a collection of cylinders, a simple line integral should be computed.

At the time of this writing, work is still underway on the determination of the total technical wave resource. Consequently, the following comments are based on the committee's current understanding of the approach and results. It finds that several factors complicate the analysis of the total available technical resource. First, so far the group has only considered the PDF of wave power as a function of wave height. However, the dependence of the wave power on wave period also needs to be considered (and this is acknowledged by the assessment group), since converter efficiency is usually highly sensitive to wave period. However, it is currently unclear what approach the assessment team will adopt in order to address this dependency. It would be desirable to provide the spectral information as output for estimating the potential technical resource for frequency-dependent devices. Further, when multiple devices are considered, an assumed packing density is imposed. Independence of the devices appears to be assumed, and shadowing effects are neglected. Also, it is unclear what assumptions are made regarding device efficiency. Device efficiency will affect how much wave power is available to a second row of devices and will therefore influence the value for the capacity factor and extractable power when arrays of devices are considered.

Finally, because the analysis is currently based on only 51 months of data, the occurrence of extreme events is not captured well, as was shown by the NREL validation group (Scott, 2011). As a result, the cumulative PDF curves might be less accurate in the high-wave height range. It is unclear how this possibly will affect results. It is likely that the long-term power output would be affected minimally because extreme events are likely to exceed the MOC of any devices. However, wave power developers desire sites that can both maximize the potential power output and minimize the cost, with survivability being an essential issue in siting and design analysis. Thus, the use of 51 months of data results in uncertainties in the estimated technical and practical resources. The estimates of the technical resource could be improved by associating it with confidence intervals reflecting these uncertainties.

The 51-month time series of hindcast conditions can be used to deduce information about interannual variability, including some estimate of extreme conditions that devices would have to be able to survive. Currently, the group plans only to provide maps of annual and monthly average wave conditions (i.e., wave power density, wave height, period, direction) in the GIS display. However, it would seem very important to developers of wave energy devices to know more about extreme conditions. Although these extreme events are not well represented by the 51-month time series, some information, along with confidence intervals, can still be extracted. It seems prudent to include such information in the GIS database. Future work, either by developers or by groups carrying out more detailed resource assessments, could include a more rigorous statistical analysis of extreme events by estimating the significant wave height for the upper 95 percent confidence interval of a 50 or 100 return period storm assuming some sort of statistical distribution of the extremes, such as a Gumbel distribution.

The committee was concerned that no demonstration of the GIS tool was possible even though the project is now close to its end date.

Comments on Validation

Several aspects of the wave resource assessment study require validation. First, the ability of the wave resource assessment to produce estimates of monthly or annual mean wave power should be evaluated. Potential inaccuracies in such estimates could result from two primary sources of error: inaccuracies in the WAVEWATCH III simulations, and differences between the full and reconstructed spectra. The accuracy of WAVEWATCH III predictions is relatively well outlined in the scientific literature. In particular, WAVEWATCH III is known to reproduce wave height quite well (Chawla et al., 2009). However, it is unclear how well the reconstructed spectra represent the observed spectra, especially in light of the fact that the spectral reconstruction was optimized at only deepwater stations.

The NREL validation study described to the committee only examines average wave power estimates produced by the assessment study and does not address the validity of the spectral reconstruction (Scott, 2011). Further, the committee found that the validation was generally lacking in rigor; the lack of available data is a limiting factor (only 44 observational locations), and little can be done to address this shortcoming in the short term. Data from the Northeast Regional Association for Coastal Ocean Observing System (NERACOOS, www.neracoos.org), the Scripps Institution of Oceanography's Coastal Data Information Program buoys (http://cdip.ucsd.edu/), and the network of the National Federation of Regional Associations for Coastal and Ocean Observing (http://www/usnfra.org/) could be used to provide additional validation information. Perhaps more importantly, the NREL validation group apparently calculated wave power using a simplified formulation that is only valid in deep water. In contrast, the wave resource assessment group used the full reconstructed spectrum for this estimate. This apparent discrepancy calls into question the validity of the comparison that does not use the full spectra. Finally, the validation effort does not report any statistical measures that would quantify the agreement between observations and estimates. Root-mean-square error values, R^2 statistics, or a number of other standard metrics would be useful.

Conclusions and Recommendations

The maps of wave characteristics produced by the wave resource assessment group could prove useful to developers who are interested in identifying general regions for their particular wave energy conversion devices. Similarly, the approach outlined for the application of the extraction filters and subsequent estimation of the technical resource represents a defensible attempt, albeit limited by the lack of detailed information about the relevant wave energy devices. However, the committee is concerned that presenting an aggregate number for the total regional or national resource bases, whether theoretical or technical resource bases, might be misused if interpreted as representing something close to the practically extractable resource. As noted above, the conceptual framework laid out in Figure 1 indicates that there are numerous extraction filters that must be applied and that site-specific filters will likely dominate the actual development of marine and hydrokinetic resources. Further, the conceptual approach used to estimate the total theoretical resource by the wave resource assessment group is incorrect, and the use of the unit cylinder concept for this purpose is misleading. The associated omission of any consideration of wave direction is problematic.

Finally, the lack of a demonstrated GIS tool is a major concern. This tool can be quite valuable, but it should contain information about mean annual and monthly conditions (i.e., wave height, period, direction) as well as information about expected extreme conditions. In its final report, the committee will also consider how information on the MHK resource base might be overlaid on other ocean uses (e.g., fishing grounds, navigational concerns, recreation areas) to make an assessment of the practical resource base.

Recommendations: The committee recommends that the wave resource assessment group's approach to estimating the theoretical resource base acknowledge that the energy flux (power density) of waves is a directional quantity, and **it recommends that the approach consider only the component of the wave power density vector that is perpendicular to the line of interest.** Hence, as indicated in Table 1, rather than summing over a collection of cylinders, **a simple line integral should be computed. The committee also recommends that strong caveats accompany the estimates of the total theoretical and technical resources.**

The wave resource assessment group should be very cautious in presenting information for shallow-water environments, where its approach is most inaccurate. There has been a recent trend to envision wave energy extraction farther offshore, in deep water, to avoid some ecological and other impacts. However, some potential projects are still seeking shallow-water siting for the closer proximity to transmission and other logistical requirements. Shallow-water sites also generally have lower construction and maintenance costs. Given that the actual placement of devices may occur in such shallow-water areas, **the committee recommends that any siting considerations be accompanied by a modeling effort that resolves the bathymetric variability on the inner shelf and accounts for the physical processes that dominate in shallow waters** (e.g., refraction, diffraction, shoaling, wave dissipation due to bottom friction and wave breaking). The wave resource assessment group should provide to any potential developers and to other users guidance in the application of this assessment in shallow-water areas. For example, some virtual stations could be established where the full directional spectrum would be available for potential users. A developer or coastal engineer could then perform high-resolution simulations and the necessary fieldwork to develop local fields using a shallow-water model such as SWAN combined with an accurate bathymetry.

Additionally, the committee recommends that the wave resource assessment group clearly define the GIS outputs. The full directional wave energy spectrum should be included in order to retrieve the directionality and the time series of the wave parameters, which would allow the GIS data to be used either as input for a more detailed analysis in shallow water or as an informative wave climate geographic tool. Simple summary plots would be convenient to give an overview of the wave climate as wave power roses (diagrams showing the distribution of wave height and direction), probability distribution of wave parameters, wave power monthly average time series, and Gumbel distribution of the extreme events.

TIDAL RESOURCE ASSESSMENT

Introduction

Ocean tides are a response to gravitational forces exerted by the Moon and the Sun. They include the rise and fall of the sea surface and the associated horizontal currents. The potential of tidal power for human use has traditionally led to proposals that envision a barrage across the entrance of a bay that has a large range between low and high tides. A simple operating scheme is to release water trapped behind the barrage at high tide through turbines, generating power as is done in a traditional hydropower facility.

In recent years, considerable attention has been paid to the direct exploitation of tidal currents using in-stream turbines rather than a barrage, in a manner similar to the way that wind turbines work. By way of scale comparison, even a strong current of 3 m/s (~10 ft/s) is equivalent to a hydraulic head of only 0.5 m (~1.6 ft), which is considerably less head than a typical tidal range. As the power produced by a turbine is related to the product of the head and the flow rate, it is clear that capturing tidal currents is considerably less effective than capturing the hydraulic head associated with a modest tidal range.

The upper bound on the power from such an in-stream turbine is shown in Table 1 and is expressed by the Lanchester-Betz limit of $0.3\rho A u^3$, where ρ is water density, u is current speed, and A is the cross-sectional area across the blades (also referred to as the swept area).[4] The Lanchester-Betz limit shows that the turbine power is related to the cube of the current and demonstrates the advantage of deploying turbines in regions of strong current. As an example, if the cross section area A is 100 m^2 (~1,075 ft^2) and the current speed u is 3 m/s, the upper bound on the power from a turbine is 0.8 MW. The average power over a tidal cycle is, of course, considerably less than that obtainable at the maximum current.

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[4] The Lanchester-Betz limit applies to a turbine in an unbounded flow. If a turbine array occupies a significant fraction of the channel cross section, it can create a sufficient blockage and build up a large head, and more power can be obtained. This could ultimately approach the power from a barrage, if the array blocks the entire channel cross section (Garrett and Cummins, 2007).

Project Description

The tidal resource assessment group conducted its tidal energy assessment study by developing a set of models to simulate all U.S. coastal regions and to estimate the maximum tidal energy based on predicted tidal currents (Georgia Tech Research Corporation, 2010; Haas et al., 2010; Georgia Tech Research Corporation, 2011; Haas et al., 2011). The model used in the study was the three-dimensional Regional Ocean Modeling System (ROMS),[5] which is often used in model studies of coastal oceanography and tidal circulation. The model was configured with eight layers and set up for 51 domains, with grid resolutions in the range of 200 to 500 m. Each domain included a section of coast or a particular bay, with offshore boundaries that included part of the adjacent continental shelf. The models were forced at their offshore boundaries by predicted tidal constituents, using the Advanced Circulation Model (ADCIRC) tidal database[6] for the East Coast and Gulf of Mexico regions and the TPXO database[7] for the West Coast region. River inflows and atmospheric forcing (such as wind) were not considered, and stratification and density-induced currents were not simulated. The landward model boundaries and bathymetry were defined using coastline data from NOAA's National Ocean Service and digital sounding data from NOAA's National Geophysical Data Center. The effect of tidal flats was initially evaluated but not considered in the final model runs.

The tidal resource assessment group calibrated the tidal models by adjusting the single friction coefficient to improve the comparison among model results, NOAA predictions of tidal elevation and currents, and limited observations of depth-averaged tidal currents. Model validation performed by the Oak Ridge National Laboratory was done by comparing model predictions with observed tidal elevations and currents at selected stations that were not included in the calibration exercises (ORNL, 2011; Neary et al., 2011). Model skills and error statistics were generated in this validation.

Model output was used (1) to provide an upper bound, $P_{\max}$, of the power available from in-stream turbines for each bay and (2) to create a web-based GIS interface of quantities such as the local average power density (watts per square meter) in a vertical plane perpendicular to the average current at each model grid cell. Visualizations of average power density could, in principle, be used to estimate the power available from a single turbine or a few turbines (an array small enough not to have

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[5] See http://www.myroms.org/; accessed June 21, 2011.

[6] See http://www.unc.edu/ims/ccats/tides/tides.htm; accessed June 21, 2011.

[7] See http://www.esr.org/polar_tide_models/Model_TPXO71.html; accessed June 21, 2011.

a significant back effect on the currents). The tidal resource assessment group used ArcView GIS software. The GIS developed by the group was well designed and executed, and it allowed for downloading of the tidal modeling results for further analysis by a variety of knowledgeable users. Based on the assessment group's last presentation to the committee (Haas et al., 2011), the committee concluded that the resource assessment will not produce estimates of the total theoretical energy resource or incorporate technology characteristics to estimate the technical resource base.

Comments on Methodology

ROMS is a structured-grid, open-source coastal ocean model. It has performed well in the prediction of coastal circulation and tides in a large number of applications (e.g., Warner et al., 2005; Patchen, 2007; NOAA, 2011). Finer grid resolution may be needed to represent bathymetry accurately in high tidal current regions. Increasing the grid resolution in local areas of a ROMS model often results in a significant increase of the total model grid size, owing to the structured-grid framework. In contrast, unstructured-grid models, which have greater flexibility for high grid resolution in complex waterways, could provide an alternative choice, especially for areas of complex geometry with high tidal energy (see, e.g., Patchen, 2007). An evaluation of the effect of grid resolution in high tidal energy regions is necessary for future studies.

The location of the offshore boundary, partway out onto the continental shelf, is adequate for this effort, assuming that only a single turbine or a limited number of turbines is represented. Extension to the shelf edge may be necessary in the future if models are rerun with representations of a large turbine array that would be extensive enough to have a back effect on offshore tides. Estimates of available power may not be accurate without considering the effect of the locations of open boundaries. This question could be evaluated in follow-on studies.

According to the materials provided to the committee, the model tends to reproduce observed tidal elevations well. This is essential for the accurate prediction of the currents, but it may not be sufficient. It is possible for a model to reproduce tidal elevations well but still to have incorrect current patterns. Comparisons between predicted and observed currents indicated that errors associated with predicted currents may be 30 percent or more (Neary et al., 2011). It could be useful to consider more conventional model evaluation skill metrics used in the ocean-modeling field (Warner et al., 2005; Patchen, 2007; NOAA, 2011). Because power is related to the cube of current speed, errors of 100 percent or more occur in the prediction of tidal power density in many model regions. It is unclear whether model calibration through the adjustment of the single friction coefficient is more appropriate than adjustment or improvement of other factors, such as offshore boundary values, model bathymetry, or grid resolution. As noted by the tidal resource assessment group, errors in currents may be a consequence of inadequate model resolution rather than a consequence of an erroneous friction coefficient or uncertain forcing from the open boundary.

Comments on the Estimate of Available Tidal Power

One principal result of the tidal resource assessment is the maximum power, P_{max}, extractable from the tidal currents in a bay. P_{max} is the basis for the theoretical resource shown in the left column of Figure 1. P_{max} would result from the use of a complete "fence" of turbines across the entrance to the bay, but it is not the horizontal kinetic energy flux $0.5\rho u^3$ times the area of the vertical cross section of the entrance to the bay (e.g., Garrett and Cummins, 2007, 2008). Instead, as stated in Table 1 of this letter report, P_{max} is given to a reasonable approximation by

$$P_{max} = 0.22\, g\rho\, a\, Q_{max},$$

where g is gravity, a is tidal amplitude (the height of high tide above mean sea level), and Q_{max} is the maximum volume flux into a bay in the natural state without turbines. P_{max} increases with the tidal amplitude, a, and the surface area of the bay. This result is for a single tidal constituent. If the dominant tide is the twice-a-day lunar tide, P_{max} is equivalent to the provision from each square meter of the bay's surface of $0.3a^2$ W if a is in meters. For example, a tidal amplitude of 1 m (3.28 ft) would require more than 300 square kilometers (over 110 square miles) to produce 100 MW as an absolute maximum. In an area with multiple tidal constituents, the potential power is greater than that available from the dominant tide alone (see, e.g., Garrett and Cummins, 2005). In the assessment, P_{max} was based on all constituents that were extracted for each site. The result makes it clear why serious consideration of tidal power is generally limited to regions with a large tidal range. As reviewed by Garrett and Cummins (2008), this formula for P_{max} is also a reasonable approximation for the power available from a tidal fence across a channel that connects two large systems in which the tides are not significantly affected. In this case, a is the amplitude of the sinusoidal difference in tidal elevation between the two systems.

In the P_{max} scenario, the fence of turbines is effectively acting as a barrage, and therefore P_{max} is essentially the power available when all water entering a bay is forced to flow through the turbines. P_{max} is thus likely to be a considerable overestimate of the practical extractable resource once other considerations, such as the extraction and socioeconomic filters shown in Figure 1, are taken into account.

Lesser but still useful amounts of power could be obtained from turbines that are deployed in regions of strong current without greatly impeding a bay's overall circulation. As mentioned earlier, a single turbine can extract no more than the Lanchester-Betz limit. A total power P requires a volume flux through the cross-sectional area of the turbines of $P/(0.3\rho u^2)$, so that even with a current speed of 3 m/s, the volume flux required for a power of 100 MW is nearly 40,000 m^3/s (~1.4 million ft^3/s). Delivering such a flux would require a large number of turbines (for example, 120 turbines if each had a cross-sectional area of 100 m^2, or 24 turbines with 25 m diameter if full-scale turbines were employed). Many more turbines would be needed for more typical, smaller, average currents. Deploying an extensive array of turbines would impact other marine resource uses, such as other sea-space uses and ecological services, and would necessitate extensive, site-specific planning efforts.

More importantly, a single turbine or a small number of turbines would not significantly affect pre-existing tidal currents, but an array large enough to generate tens of megawatts would have back effects that reduced the current that each individual turbine experienced. In theory, this back effect is allowed for in a complete tidal fence considered in the calculation of $P_{\max}$. However, allowing for the back effects of an in-stream turbine array in a confined region requires further, extensive numerical modeling that was not undertaken in the present tidal resource assessment study and is in its early stages elsewhere (see, e.g., Shapiro, 2011).

Other than for the case of a complete tidal fence, which estimates something close to the theoretical resource base, the tidal resource group's assessment cannot be used to estimate directly the potential power of strong currents in specific bays if more than a few turbines are considered. Nonetheless, an early group presentation to the committee (Haas et al., 2010) attempted to evaluate the technical resource based on P_k, the power that could be obtained if turbines of a specific swept area and efficiency were deployed at a specified spacing in regions satisfying specified minimum average current and minimum water-depth criteria, while making the assumption that any back effects on the currents would be small. This assumption is likely to be false, particularly if P_k is a significant fraction of $P_{\max}$. In that case, the turbines would have an effect on currents throughout the bay, and P_k would be an overestimate of the power available from the turbine array. If P_k is not a significant fraction of $P_{\max}$, circulation in other areas of the bay might not be greatly impacted, but local reductions in the currents would still be likely and could again cause P_k to be an overestimate. The group could consider choosing the lesser of P_k and $P_{\max}$ as an estimate of the technical resource base. However, the committee notes that the tidal resource assessment group abandoned P_k, and thus any evaluation of the technical resource, because of the major uncertainties inherent in specifying parameters (personal communication to the committee from Kevin Haas, Georgia Institute of Technology, March 18, 2011).

Conclusions and Recommendations

The assessment of the tidal resource assessment group is valuable for identifying geographical regions of interest for the further study of potential tidal power. However, although P_{max} may be regarded as an upper bound to the theoretical resource, it is an overestimate of the technical resource because one must assume a complete fence of turbines across the entrance to a bay, a situation that is unlikely to occur. Thus, P_{max} overestimates what is realistically recoverable, and the group does not present a methodology for including the technological and other constraints necessary to estimate the technical resource base.

The power density maps presented by the group are primarily applicable to single turbines or to a limited number of turbines that would not result in major back effects on the currents. Additionally, errors of up to 30 percent for estimating tidal currents translate into potential errors of a factor of more than two in the estimate of potential power. Because the cost of energy for tidal arrays is very sensitive to resource power density, this magnitude of error is quite significant from a project-planning standpoint. The limited number of validation locations and the short length of data periods used lead the committee to question whether the model was properly validated in all 51 model domains, as well as in the vertical structure. Further, the committee is concerned about the potential for misuse of power density maps by end users, as calculating an aggregate number for the theoretical U.S. tidal energy resource is not possible from a grid summation of the horizontal kinetic power densities obtained using the model and GIS results. Summation across a single-channel cross section also does not give a correct estimate of the available power. Moreover, the values for the power across several channel cross sections cannot be added together.

Recommendations: The tidal resource assessment is likely to highlight regions of strong currents, but it includes large uncertainties in its characterization of the resource. Thus, developers would have to perform further fieldwork and modeling, even for planning small projects with only a few turbines. **The committee recommends that follow-on DOE work for key regions should take into account site-specific studies** and existing data from other researchers. If regions are identified in which utility-scale power (greater than 10 MW) is thought to be available, **fur-**

ther modeling will need to include the representation of an extensive array of turbines in order to account for changes in the tidal and current flow regime at local and regional scales. **For particularly large projects, the model domain extent will require expansion**, probably to the edge of the continental shelf (see, e.g., Garrett and Greenberg, 1977).

As will be discussed in the committee's final report, further DOE work on tidal assessments might include additional filters to progress from theoretical resource estimates to estimates of the technical and practical resource bases. Given that the DOE's objective for the resource assessments is to produce estimates of the maximum practicable, extractable energy, it is clear that estimates of the practical resource base need to incorporate additional filters beyond the first column of the committee's conceptual framework (Figure 1). As a way to investigate estimates of maximum practicable, extractable energy, one might consider a region of strong tidal currents in which there is also a large tidal range, such as Cook Inlet. Such an example might consider a comparison of an in-stream tidal power scheme with a tidal power scheme involving a barrage across the head of a bay or involving a lagoon enclosing a coastal area. The reasons for this include the following: (1) as noted above, even a current of 3 m/s is equivalent to a head of only 0.5 m, much less than would be available with a barrage or lagoon; (2) the construction of a lagoon should be much simpler than the installation of a large number of in-stream turbines in a region of strong currents; and (3) it is possible that the overall environmental impact of a lagoon might be less than that of an array of turbines producing the same average power.

OVERARCHING CONCLUSIONS

Use of Resource Assessments

On the basis of the information that it reviewed, the committee concludes that the overall approach taken by the wave resource and tidal resource assessment groups is a useful contribution to the understanding of the distribution and possible magnitude of energy sources from waves and tides in the United States. The models, data sources, and visual display technologies, provided they are conveyed with appropriate caveats and documented assumptions, should aid planners and those interested in potentially developing marine and hydrokinetic energy sources.

The committee has some individual concerns about the methodologies and the communication of these methodologies that are detailed above. Moreover, the committee has a concern regarding the usefulness of aggregating the analysis to produce a "single-number" estimate of the total national or regional theoretical and technical resource base for any one of these energy sources. Based on the information presented to the committee by the wave resource and tidal resource assessment groups, the methods and level of detail in these studies will not be able to provide a defensible estimate of the resources that might be practically extractable from each of the resource types. The committee concludes that developing an estimate of the practical resource would require reaching the bottom of the third column in its conceptual framework (Figure 1). As discussed in the sections reviewing the wave resource and tidal resource assessments, the groups have had varying degrees of success getting to the technical resource base, the bottom of the second column in Figure 1. Although the DOE may desire these overall numbers for some general purposes, such as comparing the sizes of individual MHK resources with one another or comparing the MHK resource base with other renewable resources, a single number is of limited value for understanding the potential contribution of MHK resources to U.S. electricity generation, which must ultimately be assessed from the bottom up on a site-by-site basis. The tapping of wide swaths of ocean or coastal straits and embayments for harvesting a significant portion of their tidal and/or wave energy runs into insurmountable barriers of other ocean uses in addition to technology and materials limits. Furthermore, attempting to develop such a national-level assessment requires that the assessment groups expend effort and resources in locations of lower power density that may divert the groups from doing a thorough assessment in locations with high resource potential. However, the committee recognizes that one of the objectives of this study could be not only to advise developers of areas of high energy, but also to inform decision makers, within a common platform, with an understanding of areas in which there is limited resource potential. Therefore, the assessment groups' confirmation of the spatial variability for wave and tidal resources is useful for a number of interested parties.

The committee's final report will consider types of information that might be needed and follow-up studies that might be done to help estimate the maximum practicable, extractable resource base. Included might be the detailed assessments of specific sites, including investigations where the deployment of MHK devices might be promising and might possibly serve an additional purpose, as well as where the use of MHK resources might serve remote locations with difficult access to other electricity supplies. The final report will also further consider the source and magnitude of the uncertainties in the resource estimates.

Coordination Among GIS Products

A lesser overarching concern than those summarized above is the inconsistency across the implementation of GIS databases for presenting power density results. Continuing the committee's warnings on total resource numbers, the local results and spatial distribution of power densities are agreed to be the primary utility of the resource studies. For this reason, it would be best to have the GIS products coordinated and readily able to be integrated across the resource assessment groups. This was not included in the DOE tasking of the groups and has not been done spontaneously by them. Additionally, there is a concern that the databases will not be maintained after the performance period of the DOE contracts. Finally, the committee concludes that caveats and warnings need to accompany the GIS products so that users are not tempted to sum over, or extrapolate from, the power density maps.

Sincerely,

Paul Gaffney, *Chair*
Committee on Marine and Hydrokinetic Energy Technology Assessment

Attachments
A Statement of Task
B Biographies of the Committee Members

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C

Biographical Sketches

PAUL GAFFNEY (NAE), *Chair,* is president of Monmouth University. He is a retired Navy vice admiral and served as president of the National Defense University from 2000 to 2003. Prior to assuming those duties, Admiral Gaffney was the chief of naval research with responsibility for science and technology investment, a substantial part of which supported basic research in American universities. He was appointed to the U.S. Ocean Policy Commission in July 2001 and served during its full tenure from 2001 to 2004. His distinguished naval career spanned more than three decades, including duty at sea, overseas, and ashore in executive and command positions. Admiral Gaffney served in Japan, Vietnam, Spain, and Indonesia and traveled extensively in official capacities. While a military officer, his career focused on oceanography. Admiral Gaffney is a 1968 graduate of the U.S. Naval Academy. Upon graduation, he was selected for immediate graduate education and received a master's degree in ocean engineering from Catholic University of America. He completed a year as a student and advanced research fellow at the Naval War College, graduating with highest distinction. He completed an M.B.A. at Jacksonville University. The University of South Carolina, Jacksonville University, and Catholic University have awarded him honorary doctorates. He has been recognized with a number of military decorations and the Naval War College's J. William Middendorf Prize for Strategic Research. Admiral Gaffney chairs the federal Ocean Research/Resources Advisory Panel. He is a trustee of Meridian Health and a director of Diamond Offshore Drilling, Inc.

PHILIP BEAUCHAMP manages the Mechanical Systems-Performance Lab at the General Electric Global Research Center in Niskayuna, New York. His laboratory is in part focused on research and development (R&D) of hydromechanical devices for GE. In this regard, he has participated internally with GE Energy and GE Water and with numerous external organizations in tracking a wide range of emerging ocean energy technologies. Dr. Beauchamp holds an M.S. in numerical methods from the University of Arizona, an M.S. in aeronautics and astronautics from the Massachusetts Institute of Technology (MIT), and a Ph.D. in mechanical and aerospace engineering from Boston University.

MICHAEL BECK is a senior scientist with the Global Marine Initiative of the Nature Conservancy and a research associate at the University of California, Santa Cruz. He works in the interface between marine science and policy. Dr. Beck's present work includes research on marine regional planning; the nursery role of nearshore habitats such as kelp forests; tools for ecosystem-based management and land-sea integration; the conservation and restoration of nearshore habitats, including shellfish reefs and beds; and marine proprietary rights, including the lease and ownership of submerged lands. Dr. Beck holds B.A. and M.S. degrees in environmental sciences from the University of Virginia and a Ph.D. in biological sciences from Florida State University.

VALERIE BROWNING is the owner, senior consultant, and subject matter expert for ValTech Solutions, LLC. She serves as a subject matter expert for a number of Department of Defense (DOD), Department of Energy (DOE), and other government activities in the areas of advanced materials and alternative energy. Prior to forming ValTech Solutions in 2007, Dr. Browning served as a program manager in the Defense Sciences Office at the Defense Advanced Research Projects Agency (DARPA). During her tenure at DARPA, she assumed full responsibility for the strategic planning, operating management, leadership, and development of multiple DOD R&D programs providing innovative technologies in power and energy, radar, telecommunications, and biotechnology for diagnostics, therapeutics, and chemical and biological warfare defense. Specific programs managed by Dr. Browning include the MetaMaterials, Palm Power, Direct Thermal to Electric Conversion, Negative Index Materials, Robust Portable Power Systems, and BioMagnetic Interfacing Concepts programs. She also served as the DARPA liaison to the DOD Integrated Product Team on energy security and served as acting director of the Defense Sciences Office prior to her departure from government service. In addition to her time at DARPA, Dr. Browning spent 16 of her 24 years of government service as a research physicist at the Naval Research Laboratory. Her primary areas of research were thermoelectric materials, high-temperature superconductors, and magnetic oxide materials. Upon leaving her government position, Dr. Browning was awarded the Secretary of Defense Award for Outstanding Public Service. She has published more than 40 peer-reviewed manuscripts, including three book chapters. She is active in a number of professional organizations, including the American Physical Society, the Materials Research Society, and Sigma Xi. Dr. Browning served as co-chair for a 2007 Materials Research Society symposium on magnetic materials and was the Technical Program Committee chair for its 2008 Fuel Cell Seminar. She continues to serve on the Technical Program Committee for the Fuel Cell Seminar and Exposition and was appointed as member of the National Materials Advisory Board in 2009. Additionally, she served as a member of the NRC Committee on Developments in Detector Technologies.

CHRIS GARRETT (NAS) is an emeritus professor at the University of Victoria, having been the Lansdowne Professor of Ocean Physics until 2010. His background is in applied mathematics and fluid dynamics. His research emphasis has mostly been on theoretical studies of small-scale processes such as waves, tides, turbulent dispersion and mixing, air–sea interaction, and the dynamics of flows in straits. He has also contributed to assessments of the oceanic disposal of radioactive and other wastes and to issues of ocean energy, such as iceberg trajectory prediction for the Canadian offshore oil industry and deriving fundamental limits to tidal power as well as evaluating its environmental impact. Dr. Garrett holds a B.A. in mathematics and a Ph.D. in geophysical fluid dynamics, both from the University of Cambridge. He is a foreign associate of the National Academy of Sciences.

ANNETTE GRILLI is a research assistant professor of ocean engineering at the University of Rhode Island. Her professional experience started as an assistant in regional geography at the University of Liège (Belgium), working on identifying indices of economic and social crises in rural areas using multivariate spatial statistical analysis. While finishing her Ph.D. in climatology at the University of Delaware, modeling the albedo of the ocean surface as a function of sea state, she worked as a consultant in environmental science and engineering and a research scientist for Applied Science Associates, Inc. (Narragansett, Rhode Island) on various environmental modeling projects. After a few years as research scientist in the Department of Ocean Engineering at the University of Rhode Island, in 2005 Dr. Grilli joined the faculty and has since been working on a variety of ocean renewable energy projects, for example, the siting in Rhode Island of Energetech’s Oscillating Water Column wave energy plant (now

Oceanlinx, Australia); the conceptual development and modeling of point absorber autonomous buoys; and the siting of a wind farm in Rhode Island waters, including siting optimization in terms of resources and technical, and ecological factors. The latter two projects are still active. At the University of Liège, Dr. Grilli earned a B.S. in geography (summa cum laude), a B.S. in education, and an M.S. in physical oceanography. She earned a Ph.D. in climatology from the University of Delaware.

J. ANDREW HAMILTON is a research engineer with the Monterey Bay Aquarium Research Institute. His research interests include ocean wave energy harvesting for oceanographic and renewable energy applications, as well as marine hydrodynamics. Dr. Hamilton is currently developing a free-swimming ocean platform that can harvest energy from the ocean environment to provide at-sea recharging for autonomous vehicles. He has served as an associate editor of the *Journal of Renewable and Sustainable Energy*. Dr. Hamilton holds an M.S. degree in ocean engineering and a Ph.D. in mechanical engineering from the University of California, Berkeley.

TUBA OZKAN-HALLER is an associate professor in the College of Oceanic and Atmospheric Sciences at Oregon State University. Her interests include numerical, field, and analytical investigations of water motions in the nearshore zone, defined by water depth of about 10 m or less. Of special interest is the application of numerical models to predict nearshore circulation as well as the modeling of bathymetric change due to this circulation field. Verification of the results is carried out using field and laboratory data. Dr. Ozkan-Haller holds an M.C.E. and a Ph.D. in civil engineering from the University of Delaware.

ELIZABETH FANNING PHILPOT is a principal research engineer, Research and Technology Management, Research and Environmental Affairs, Southern Company. She managed a variety of research projects in the following strategic areas: energy policy and economic analysis, environmental research, environmental regulation, strategic implementation, energy production, and delivery and use. Now, her focus is defining renewable energy resources within the Southern Company footprint and evaluating renewable energy technologies that might be applicable to the Southern Company. She was the project manager for Southern Company on the Southern Winds project, which was a joint Southern Company–Georgia Tech project looking into the feasibility of offshore wind generation along the Georgia coast. She is currently working on an interim lease application to the Bureau of Ocean Energy Management, Regulation and Enforcement for the placement of an offshore meteorological tower. She also worked with EPRI to define the ocean resources within the Southern Company footprint and to evaluate technologies that might be applicable for the existing resource.

BHAKTA RATH (NAE) is the head of the Materials Science and Component Technology Directorate at the Naval Research Laboratory. In his current position, Dr. Rath manages a multidisciplinary research program to discover and exploit new improved materials, generate new concepts associated with materials behavior, and develop advanced components based on these new and improved materials and concepts. Scientists in this directorate perform theoretical and experimental research to determine the scientific origins of materials behavior and to develop procedures for modifying these materials to meet naval needs for advanced platforms, electronics, sensors, and photonics. Dr. Rath earned an M.S. in metallurgy from Michigan Technological University and received his Ph.D. from the Illinois Institute of Technology. He has received a number of honors and awards, including the DOD Distinguished Civilian Service Award and the National Materials Advancement Award from the Federation of Materials Societies (2001).

RAYMOND SCHMITT is a senior scientist at the Woods Hole Oceanographic Institution, where he has spent most of his career. His research interests include oceanic mixing and microstructure, double-diffusive convection, the thermohaline circulation, oceanic freshwater budgets, the salinity distribution and its measurement, the use of acoustics for imaging fine structure, and the development of instrumentation. He is also interested in the intergenerational problem of sustaining long-term observations for climate. Dr. Schmitt has served on ocean sciences and polar program panels with the National Science Foundation, the Ocean Observing System Development Panel, the CLIVAR Science Steering Group, and the NRC's Ocean Studies Board. He was named a J.S. Guggenheim fellow in 1997 and has authored or co-authored more than 75 publications. Dr. Schmitt earned a Ph.D. in physical oceanography from the University of Rhode Island and a B.S. in physics from Carnegie Mellon University.

JAMES THOMSON is the assistant professor of environmental fluid dynamics at the University of Washington. After completing a Ph.D. in MIT's joint program with the Woods Hole Oceanographic Institution, he joined the University of Washington's Applied Physics Laboratory in 2006. Dr. Thomson studies waves and currents in the coastal ocean, with an emphasis on field measurements and physical processes. As a member of the Northwest National Marine Renewable Energy Center, Dr. Thomson is developing techniques to select and monitor sites for tidal energy development. He was raised on the coast of Maine and worked in the sailing industry there prior to beginning a career in physical oceanography.

LARRY WEBER is a professor of civil and environmental engineering and director of the Iowa Institute of Hydraulic Research-Hydroscience and Engineering at the University of Iowa. His research interests are in fish passage facilities, physical modeling, river hydraulics, hydropower, computational hydraulics, and ice mechanics, including combining hydrodynamic data and biological data of fish response, applying computational fluid dynamics codes to natural river reaches and hydraulic structures, fundamental principles of plunging jets, and combining open channel flows. Dr. Weber holds B.S., M.S., and Ph.D. degrees in civil and environmental engineering from the University of Iowa.

ZHAOQING YANG is a senior research scientist in the Coastal and Watershed Processes Modeling Group of the Pacific Northwest National Laboratory's (PNNL's) Marine Sciences Laboratory. Dr. Yang's primary research focuses on numerical modeling of hydrodynamic and transport processes in estuarine and coastal waters, reservoirs, and river systems. He is currently leading the development of PNNL's high-resolution hydrodynamic and transport model and operational forecast system for Puget Sound and the Northwest Straits. Dr. Yang has conducted many modeling studies on coastal ocean circulation, estuarine tidal dynamics, nearshore wetland restoration, water quality, sediment and fate transport, and effects of climate changes and sea-level rise on nearshore habitat. He also applied three-dimensional hydrodynamic and transport models to simulate the temperature stratification, circulation patterns, and suspended sediment transport in reservoirs and river systems to help the design of a fish collection facility, sediment cleanup decisions, and source control in connection with total maximum daily load. Dr. Yang also has extensive experience in computational fluid dynamics modeling, groundwater modeling, and ocean engineering, river flood, and management analysis. Currently, Dr. Yang is leading the development of a model to assess the impacts of marine and hydrokinetic renewable energy devices on coastal and estuarine systems. Dr. Yang holds an M.S. in ocean engineering from the University of Rhode Island and a Ph.D. in physical oceanography from the College of William and Mary.

D

Presentations and Committee Meetings

FIRST COMMITTEE MEETING
NOVEMBER 15-16, 2010, WASHINGTON, D.C.

Alejandro Moreno, U.S. Department of Energy: Motivation for the Study and DOE's Objectives

Paul Jacobson, Electric Power Research Institute: Presentation on Wave Energy Resource Assessment

Tina Taylor, Electric Power Research Institute; Thomas Ravens, University of Alaska; Laura Martel, Lockheed Martin; and Howard Hansen, Florida Atlantic University: Presentation on In-Stream River and Ocean Thermal Resource Assessments

Kevin Haas, Georgia Tech Research Corporation: Presentation on Tidal Energy Resource Assessment

Kevin Haas, Georgia Tech Research Corporation: Presentation on Ocean Current Research Corporation

SECOND COMMITTEE MEETING
FEBRUARY 8-9, 2011, WASHINGTON, D.C.

Hoyt Battey, U.S. Department of Energy: How DOE Uses Results of Resource Assessments and Further Discussions of DOE's Objectives

Paul Jacobson, Electric Power Research Institute; and George Hagerman, Virginia Polytechnic Institute and State University (Virginia Tech): Follow-Up Presentation on Wave Energy Resource Assessment

Kevin Haas, Georgia Tech Research Corporation: Follow-Up Presentation on Tidal Energy Resource Assessment

Vince Neary, Oak Ridge National Laboratory: Validation of Tidal Resource Assessments

George Scott, National Renewable Energy Laboratory: Validation of Wave Resource Assessment

Tina Taylor, Electric Power Research Institute; and Thomas Ravens, University of Alaska: Presentation on In-Stream River Energy Resource Assessments

THIRD COMMITTEE MEETING
MARCH 15-16, 2011, SEATTLE, WASHINGTON

No open session presentations.

FOURTH COMMITTEE MEETING
SEPTEMBER 27-28, 2011, WOODS HOLE, MASSACHUSETTS

Hoyt Battey and Caitlin Frame, U.S. Department of Energy: Opening Remarks and Discussion of Interim Report

Howard Hanson, Florida Atlantic University: OTEC Presentation

Kevin Haas, Georgia Tech Research Corporation: Ocean Currents Presentation

Keith Cunningham, University of Alaska, Fairbanks; Paul Jacobson, Electric Power Research Institute; and Thomas Ravens, University of Alaska, Anchorage: In-Stream Presentation

Kevin Haas, Georgia Tech Research Corporation: Informal Discussion of Final Tides Assessment between the Committee and Kevin Haas

Paul Jacobson, Electric Power Research Institute; George Hagerman, Virginia Tech; and George Scott, National Renewable Energy Laboratory: Display of Wave GIS and Discussion of Wave Assessment with the Committee

FIFTH COMMITTEE MEETING
DECEMBER 12-13, 2011, IRVINE, CALIFORNIA

Hoyt Battey and Caitlin Frame, U.S. Department of Energy: DOE Presentation

Kevin Haas, Georgia Tech Research Corporation: Ocean Currents Presentation

Howard Hanson, Florida Atlantic University; Matthew Ascari, Lockheed Martin; and Desikan Bharathan, National Renewable Energy Laboratory: OTEC Presentation

Paul Jacobson, Electric Power Research Institute; George Scott, National Renewable Energy Laboratory; and George Hagerman, Virginia Tech: Presentation and Discussion of Final Waves Assessment

Stan Calvert and Hoyt Battey, U.S. Department of Energy: DOE Presentation

Paul Jacobson, Electric Power Research Institute; Keith Cunningham, University of Alaska, Fairbanks; and Thomas Ravens, University of Alaska, Anchorage: In-Stream Presentation

Howard Hanson, Florida Atlantic University; Matthew Ascari, Lockheed Martin; and Desikan Bharathan, National Renewable Energy Laboratory: OTEC Presentation

Kevin Haas, Georgia Tech Research Corporation: Ocean Currents Presentation

SIXTH COMMITTEE MEETING
APRIL 9-10, WASHINGTON, D.C.

Hoyt Battey, U.S. Department of Energy: DOE Presentation

Paul Jacobson, Electric Power Research Institute: In-Stream Presentation

George Scott, National Renewable Energy Laboratory: In-Stream Assessment Presentation

Matthew Ascari, Lockheed Martin: OTEC Presentation

Kevin Haas, Georgia Tech Research Corporation: Ocean Currents Presentation

E

Acronym List

ADCIRC	Advanced Circulation Model
ADCP	acoustic Doppler current profiler
BOEM	Bureau of Ocean Energy Management
DOE	Department of Energy
DOI	Department of the Interior
EGL	energy gradeline
EIA	Energy Information Administration
EMEC	European Marine Energy Centre
ENSO	El Niño/Southern Oscillation
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FERC	Federal Energy Regulatory Commission
FWS	U.S. Department of Fish and Wildlife
GDEM	Generalized Digital Environment Model
GIS	geographic information system
HF	high frequency
HGL	hydraulic gradient line
HYCOM-GLOBAL	Hybrid Coordinate Ocean Model

HYCOM-GOM	Hybrid Coordinate Ocean Model—Gulf of Mexico
IEC	International Electrotechnical Commission
JPL-ROMS	Jet Propulsion Laboratory Regional Ocean Model System
MHK	marine and hydrokinetic (resources)
MOC	maximum operating condition
MODAS	Moderate Resolution Imaging Spectroradiometer
NCOM	Navy Coastal Ocean Model
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
ORPC	Ocean Renewable Power Company
OTEC	ocean thermal energy conversion
PDF	probability density function
ROC	rated operating condition
ROMS	Regional Ocean Modeling System
SOT	statement of task
SST	sea surface temperature
TBD	to be determined
TGE	turbogenerator efficiency
TOC	threshold operating condition
USACE	U.S. Army Corps of Engineers
WSL	water surface line