Assessment of Marine and Hydrokinetic Energy Technology: Interim Letter Report

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Committee on Marine and Hydrokinetic Energy Technology Assessment; National Research Council

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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.

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*

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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.

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.

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

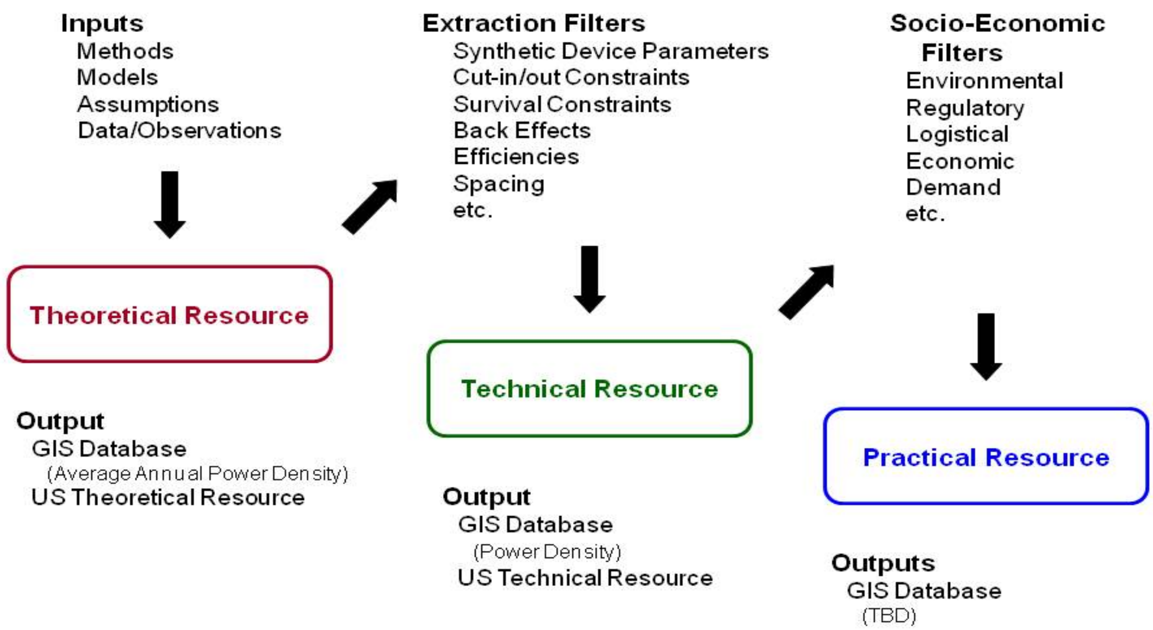

FIGURE 1 Conceptual framework developed by the committee for marine and hydrokinetic resource assessments. NOTE: GIS, Geographic Information System; TBD, to be determined.

(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.

[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.

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.

Tides			
Tidal power density	Power of horizontal tidal currents flowing through a vertical plane of unit area. $P = ½\rho v^3$	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 velocity
f = wave frequency
θ = wave direction
l = length of coastline, depth contour, or other region
v = tidal current velocity
a = tidal amplitude (half of tidal range)
Q_{max} = maximum horizontal tidal volume flux (over tidal cycle)

A determination of the practical resource is beyond the scope of the resource assessment groups' tasks as defined by the DOE. However, 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 ft grid, although the resolution is coarser in a few areas. 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

[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

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.

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 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

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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).

[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.

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 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, **further 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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Attachment A

Statement of Task

MARINE AND HYDROKINETIC ENERGY TECHNOLOGY ASSESSMENT

National Research Council's Board on Energy and Environmental Systems and Ocean Studies Board

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.

Attachment B

Biographies of the Committee Members

Paul Gaffney (NAE), *Chair,* is the president of Monmouth University. A retired Navy vice admiral, he served as president of the National Defense University from 2000 to 2003. Prior to assuming those duties, he was the Chief of Naval Research with responsibility for science and technology investment, a substantial part of which supported basic research in U.S. universities. He was appointed to the U.S. Ocean Policy Commission in July 2001 and served during its full tenure, from 2001 to 2004. President Gaffney's distinguished naval career spanned more than three decades and included duty at sea, overseas, and ashore in executive and command positions. He served in Japan, Vietnam, Spain, and Indonesia and traveled extensively in official capacities. While he was a military officer, his career focused on oceanography. President 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 the Catholic University of America in Washington, D.C. 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. He is a member of the National Academy of Engineering and chair of 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 GE Global Research Center in Niskayuna, New York. His laboratory is in part focused on research and development of hydromechanical devices for GE. In this regard he has participated internally with GE Energy and GE Water and also with numerous external organizations in tracking a wide range of emerging ocean energy technologies. Dr. Beauchamp holds an M.S. degree in numerical methods from the University of Arizona, an M.S. in aeronautics and astronautics from the Massachusetts Institute of Technology, 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. His 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 government activities for the Department of Defense (DOD), Department of Energy, and other government agencies in the areas of advanced materials and alternative energy. Prior to forming ValTech Solutions, LLC, in December 2007, Dr. Browning served as a program manager in the Defense Sciences Office (DSO) at the Defense Advanced Research Projects Agency (DARPA). During her tenure at DARPA, she assumed full responsibility for the strategic planning, operating management, and leadership and development of multiple DOD research and development programs providing innovative technologies in power and energy, radar, telecommunications, and biotechnology for diagnostics, therapeutics, and chemical and biological warfare defense. Specific programs that Dr. Browning managed 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 DSO director 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. When 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 (MRS), and Sigma Xi. Dr. Browning served as co-chair for a 2007 MRS symposium on magnetic materials and was the technical program committee chair for the 2008 Fuel Cell Seminar. She continues to serve on the Technical Program Committee for the Fuel Cell Seminar and Exposition and was appointed a member of the National Materials Advisory Board in 2009. Additionally, she served as a committee member on the recently completed National Research Council report entitled *Seeing Photons: Progress and Limits of Visible and Infrared Sensor Arrays.*

Christopher Garrett (NAS) is the Lansdowne Professor of Ocean Physics at the University of Victoria. His background is in applied mathematics and fluid dynamics. His research emphasis has been primarily 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. His research highlights include the following: discovery of the conservation of wave action, or energy divided by intrinsic frequency, rather than energy; explaining the world’s highest tides in the Bay of Fundy in terms of resonance at 13.3 hours of the Fundy/Maine system; providing simple models for the ubiquitous internal waves in the ocean; unraveling some of the hydraulics of the exchange flow through the Strait of Gibraltar; using the Mediterranean Sea and Red Sea as test basins for learning about air-sea fluxes; and finding simple ways of understanding the complicated fluid dynamics of turbulent, rotating, stratified motions near the sloping sides of ocean basins. He has also contributed to assessments of the oceanic disposal of radioactive and other wastes and to issues of ocean energy, such as the prediction of iceberg trajectory for the Canadian offshore oil industry and the derivation of fundamental limits to tidal power as well as evaluation of its environmental impact. Dr. Garrett holds B.A. and Ph.D. degrees in physical oceanography from the University of Cambridge. He is a member of the National Academy of Sciences.

Annette Grilli is a research assistant professor of ocean engineering at the University of Rhode Island. She earned a Ph.D. in climatology in 2000 from the University of Delaware, an M.S. in physical oceanography from the University of Liège (Belgium) in 1984, a B.S. in geography from the University of Liège in 1983 (summa cum laude), and a B.S. in education from the University of Liège in 1983. Her professional experience started with her service as an assistant in Regional Geography at the University of Liège, working on identifying indices of economic and social crises in rural areas, using multivariate spatial statistical analysis. She then moved to the University of Delaware, earning her Ph.D. in climatology in modeling the albedo of the ocean surface as a function of sea state. While finishing her Ph.D., she worked as a consultant in environmental science and engineering and as 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, technical, and ecological factors. The latter two projects are still active.

J. Andrew Hamilton is a research engineer with the Monterey Bay Aquarium Research Institute. His research interests include the harvesting of ocean wave energy for oceanographic and renewable energy applications, as well as marine hydrodynamics. He 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 is also an associate editor of the *Journal of Renewable and Sustainable Energy,* an American Institute of Physics publication. 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 on the order of 10 m or less. Dr. Ozkan-Haller has special interest in the application of numerical models for predicting 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 at Research and Technology Management, Research and Environmental Affairs, Southern Company. She has 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 energy delivery and use. Her focus now is the defining of 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 Institute of Technology 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 the Electric Power Research Institute 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 and 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 in 1961. He is a member of the National Academy of Engineering. Dr. Rath has received a number of honors and awards, including the Department of Defense 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 Climate Variability and Predictability (CLIVAR) Science Steering Group, and the 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 his Ph.D. in physical oceanography from the University of Rhode Island and his B.S. in physics from Carnegie Mellon University.

James Thomson is an assistant professor of environmental fluid dynamics at the University of Washington. After completing a Ph.D. in Massachusetts Institute of Technology-Woods Hole Oceanographic Institution Joint Program, 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, he 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 the director of the Iowa Institute of Hydraulic Research at the University of Iowa. His research interests are in fish-passage facilities, physical modeling, river hydraulics, hydropower, computational hydraulics, and ice mechanics, including the following: combining hydrodynamic data and biological data of fish response, applying computational fluids 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) Marine Sciences Laboratory. Dr. Yang's primary research focuses on the 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 of Puget Sound and 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 loads. Dr. Yang also has extensive experience in computational fluid dynamics modeling, groundwater modeling, ocean engineering, and river flood and management analysis. Currently, Dr. Yang is leading the model development to assess the impacts of marine and hydrokinetic renewable energy devices on coastal and estuarine systems. He holds an M.S. degree in ocean engineering from the University of Rhode Island and a Ph.D. in physical oceanography from the College of William and Mary.