Marine Energy in the United States: An Overview of Opportunities

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National Renewable Energy Laboratory

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List of Acronyms

CONUS	contiguous U.S. states
DOE	U.S. Department of Energy
EEZ	exclusive economic zone
IEC	International Electrotechnical Commission
kWh	kilowatt hour
GW	gigawatt
MHK	marine and hydrokinetic
MW	megawatt
nmi	nautical mile
NREL	National Renewable Energy Laboratory
NRC	National Research Council
OTEC	ocean thermal energy conversion
PNNL	Pacific Northwest National Laboratory
QTR	2015 Quadrennial Technology Review
Sandia	Sandia National Laboratories
TWh	terawatt hour

Executive Summary

This report provides a concise and consolidated overview of the Unites States' marine energy resources.[1] The results reported herein are primarily based on U.S. Department of Energy (DOE)-funded marine energy resource assessments in the following technology areas: wave, tidal currents, ocean currents, ocean thermal gradients, and river currents (Jacobson, Hagerman, and Scott 2011; Haas et al. 2011; Haas 2013; Ascari et al. 2012). This report also incorporates recent updates and refinements to the U.S. wave and tidal resource assessments performed by several national laboratories (Kilcher, Garcia-Medina, and Yang 2021; Kilcher, Haas, and Muscalus 2021). Many of these refinements were undertaken to address feedback from the National Research Council's evaluation of the original resource assessments (National Research Council 2013). Further, this report refines the analysis published to date by identifying the marine energy resources available in each state or region to the extent practical. In short, this report summarizes the best available data on U.S. marine energy resources at the state, regional, and national scales.

While marine energy technologies are still at the relatively early stages of development, the resource potential is immense and distributed widely across the nation's coastlines and rivers. We use the following definitions to frame the conversation about marine energy resource potentials (International Electrotechnical Commission 2020):

- *Theoretical resource*—the energy available in the resource
- *Technical resource*—the proportion of the theoretical resource that can be captured using existing technology options
- *Practical resource*—the proportion of the technical resource that is available after consideration of external constraints. Where 'external constraints' are the socio-economic, environmental, regulatory, and other competing-use constraints that determine whether a project is viable at a specific site.

In this work, we focus on the *technical resource* within the nation's exclusive economic zone (EEZ)[2] that can be harnessed for large-scale (megawatt- to gigawatt-scale) energy generation. It does not include marine energy resources that may be valuable to many blue economy applications,[3] which often have lower power requirements and can use low-energy marine energy resources that are not sufficiently energetic for large-scale energy generation. Accordingly, some locations where this report indicates there is little or no technical resource

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[1] Marine energy is defined in the Energy Act of 2020 as energy from waves, tides, ocean currents, free-flowing rivers and man-made channels, as well as from differentials in salinity, temperature, and pressure (116th U.S. Congress 2020). Before this bill was enacted, marine energy had often been known as marine and hydrokinetic energy (MHK).

[2] In this report, we use the National Oceanic and Atmospheric Administration definition of the U.S. EEZ (National Oceanic and Atmospheric Administration 2019).

[3] Blue economy applications for marine energy include providing power at sea to support offshore industries, science, and security activities and also meeting the energy and water needs of coastal and rural island communities (LiVecchi et al. 2019).

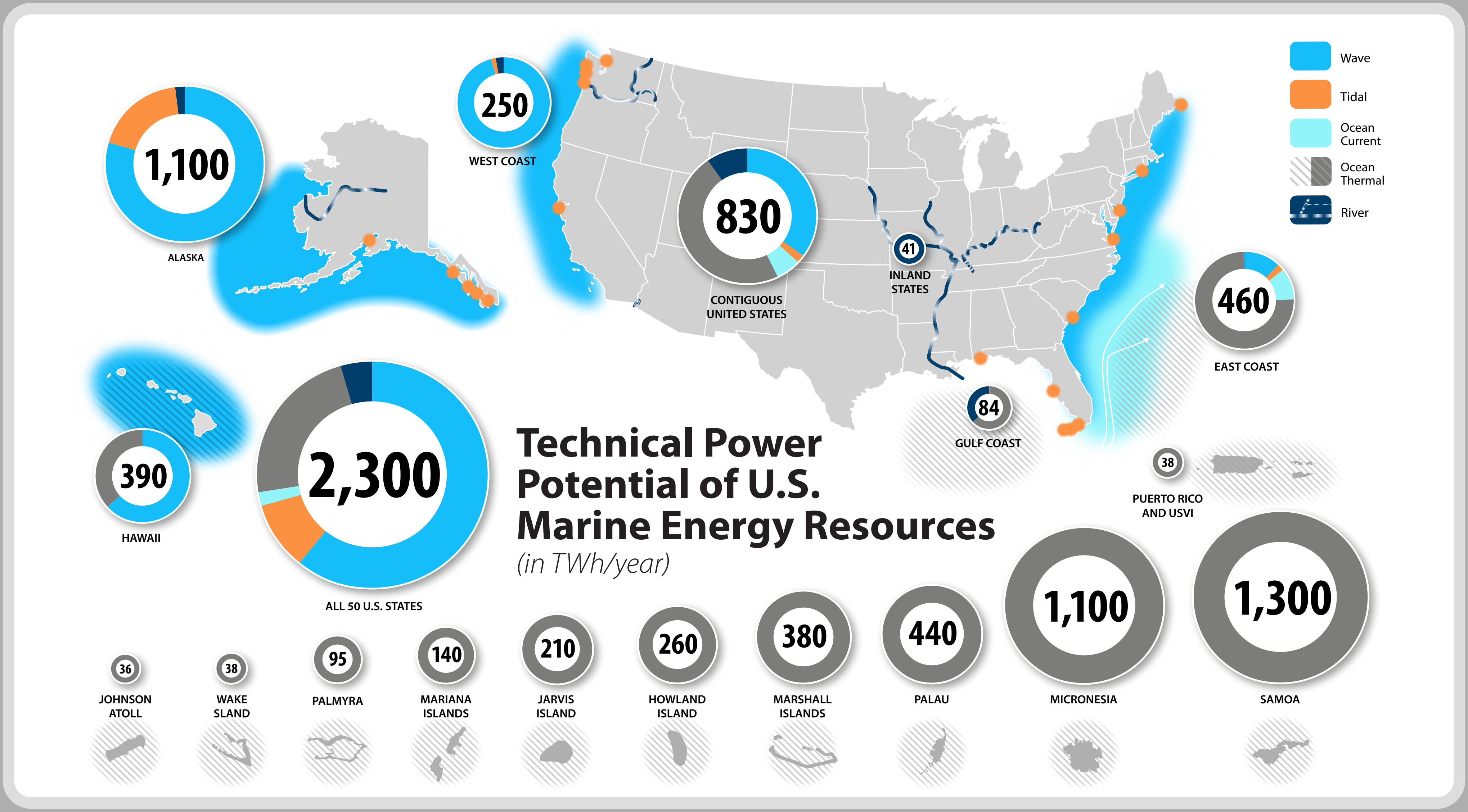
may still have marine energy resources that are sufficient to provide power for blue economy applications.

The total marine energy technical resource in the 50 states is 2,300 TWh/yr, equivalent to 57% of the electricity generated by those states in 2019. The nation's Pacific and Caribbean territories and freely associated states add an additional 4,100 TWh/yr of ocean thermal energy resource. While we do not attempt to forecast the future deployment of marine energy technologies, it is important to note that even if only a small portion of the technical resource potential is captured, marine energy technologies would make significant contributions to our nation's energy needs. For example, utilizing just one-tenth of the technically available marine energy resources in the 50 states would equate to 5.7% of our nation's current electricity generation—enough energy to power 22-million homes (U.S. Energy Information Administration 2020) (Figure ES-1). Assuming this energy could be generated at capacity factors between 30% and 70%, this would translate to between 40 GW and 90 GW of marine energy projects.

Marine energy resources are distributed throughout the United States and provide unique opportunities to different states and regions. Massive quantities of wave energy arrive at our coastlines every year, and this resource is particularly energetic along the nation's Pacific shorelines (California, Oregon, Washington, Alaska, and Hawaii). Tidal energy, perhaps the most predictable renewable energy resource, could play a major role in Alaska's electricity generation and could realistically contribute sizable quantities of power in Washington state and several Atlantic states. Ocean current energy, which is primarily contained in the Gulf Stream, has the potential to provide steady, reliable power to homes in North Carolina, South Carolina, Georgia, and Florida. Ocean thermal energy is another significant opportunity for parts of the Atlantic coast as well as the Gulf Coast states, Hawaii, and U.S. Pacific territories and freely associated states. Finally, the nation's riverine resource can be harnessed without the need for dams or river diversion to provide reliable power throughout the country.

Technical Power Potential of U.S. Marine Energy Resources

(in TWh/year)



U.S. States[a]	Technical Resource (TWh/yr)[b]	Potential Number of Homes Powered[c]	Resource as a Percent of U.S. Electricity Generation (%)[e]
■ Wave (to EEZ)	1,400	130,000,000	34
■ Tidal	220	21,000,000	5.4
■ Ocean Current	49	4,600,000	1.2
■ Ocean Thermal	540	51,000,000	13
■ River	99	9,300,000	2.4
Total	**2,300**	**220,000,000**	**57**

East Coast[a]	Technical Resource (TWh/yr)[b]	Potential Number of Homes Powered[c]	Resource as a Percent of Regional Electricity Generation (%)[d]	Resource as a Percent of U.S. Electricity Generation (%)[e]
■ Wave (to EEZ)	55	5,200,000	6.0	1.3
■ Tidal	10	950,000	1.1	0.24
■ Ocean Current	49	4,600,000	5.3	1.2
■ Ocean Thermal	340	32,000,000	37	8.3
■ River	0.67	63,000	0.07	0.02
Total	**460**	**43,000,000**	**49**	**11**

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*

[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2 of the report.*

[c] *Based on avg. monthly household electricity use of 877 kWh/month—or 10,649 kWh in 2019.*

[e] *Percent based on all 50 U.S. states' electricity generation (4,126.7 TWh) in 2019.*

[d] *Percent based on 924.5 TWh of the East Coast's electricity generation produced in 2019. (ME to FL with 1/2 of FL's generation.)*

Alaska[a]	Technical Resource (TWh/yr)[b]	Potential Number of Homes Powered[c]	Resource as a Percent of Regional Electricity Generation (%)[d]	Resource as a Percent of U.S. Electricity Generation (%)[e]
■ Wave (to EEZ)	890	83,000,000	15,000	21
■ Tidal	210	20,000,000	3,400	5.0
■ Ocean Current	0	0	0	0
■ Ocean Thermal	0	0	0	0
■ River	21	1,900,000	340	0.50
Total	**1,100**	**100,000,000**	**18,000**	**27**

[d]Percent based on 6.1 TWh of Alaska's electricity generation produced in 2019.

Inland U.S. States[a]	Technical Resource (TWh/yr)[b]	Potential Number of Homes Powered[c]	Resource as a Percent of Regional Electricity Generation (%)[d]	Resource as a Percent of U.S. Electricity Generation (%)[e]
■ Wave (to EEZ)				
■ Tidal				
■ Ocean Current				
■ Ocean Thermal				
■ River	41	3,800,000	2.2	0.99
Total	**41**	**3,800,000**	**2.2**	**0.99**

[d]Percent based on 1,901.0 TWh of the inland U.S. states' electricity generation produced in 2019.

West Coast[a]	Technical Resource (TWh/yr)[b]	Potential Number of Homes Powered[c]	Resource as a Percent of Regional Electricity Generation (%)[d]	Resource as a Percent of U.S. Electricity Generation (%)[e]
■ Wave (to EEZ)	240	22,000,000	64	5.7
■ Tidal	4.1	380,000	1.1	0.10
■ Ocean Current	0	0	0	0
■ Ocean Thermal	0	0	0	0
■ River	6.7	630,000	1.8	0.16
Total	**250**	**23,000,000**	**67**	**6.0**

[d]Percent based on 370.5 TWh of the West Coast's electricity generation produced in 2019.

Gulf Coast[a]	Technical Resource (TWh/yr)[b]	Potential Number of Homes Powered[c]	Resource as a Percent of Regional Electricity Generation (%)[d]	Resource as a Percent of U.S. Electricity Generation (%)[e]
■ Wave (to EEZ)	0	0	0	0
■ Tidal	0.37	35,000	0.04	0.01
■ Ocean Current	0	0	0	0
■ Ocean Thermal	53	5,000,000	5.8	1.3
■ River	31	2,900,000	3.3	0.74
Total	**84**	**7,900,000**	**9.2**	**2.0**

[d]Percent based on 914.8 TWh of the Gulf Coast's electricity generation produced in 2019.
(AL, LA, MS, TX, and with 1/2 of FL's generation.)

Hawaii[a]	Technical Resource (TWh/yr)[b]	Potential Number of Homes Powered[c]	Resource as a Percent of Regional Electricity Generation (%)[d]	Resource as a Percent of U.S. Electricity Generation (%)[e]
■ Wave (to EEZ)	250	23,000,000	2,500	6.0
■ Tidal	not assessed			
■ Ocean Current	0	0	0	0
■ Ocean Thermal	140	13,000,000	1,500	3.5
■ River	not assessed			
Total	**390**	**37,000,000**	**4,000**	**9.4**

[d]Percent based on 9.7 TWh of Hawaii's electricity generation produced in 2019.

PR & USVI[a]	Technical Resource (TWh/yr)[b]	Potential Number of Homes Powered[c]	Resource as a Percent of Regional Electricity Generation (%)[d]	Resource as a Percent of U.S. Electricity Generation (%)[e]
■ Wave (to EEZ)	0	0	0	0
■ Tidal	not assessed			
■ Ocean Current	not assessed			
■ Ocean Thermal	38	3,600,000	210	0.92
■ River	not assessed			
Total	**38**	**3,600,000**	**210**	**0.92**

[d]Percent based on 18 TWh of Puerto Rico and the U.S. Virgin Islands' electricity generation produced in 2017.

Pacific Territories and Freely Associated States[a]	Technical Resource (TWh/yr)[b]	Potential Number of Homes Powered[c]	Resource as a Percent of U.S. Electricity Generation (%)[e]
■ Wave (to EEZ)	not assessed		
■ Tidal	not assessed		
■ Ocean Current	not assessed		
■ Ocean Thermal	4,100	380,000,000	98
■ River	not assessed		
Total	**4,100**	**380,000,000**	**98**

[a]All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.
[b]Detailed methodologies for estimating Technical Resource are provided in Section 2 of the report.
[c]Based on avg. monthly household electricity use of 877 kWh/month—or 10,649 kWh in 2019.
[e]Percent based on all 50 U.S. states' electricity generation (4,126.7 TWh) in 2019.

Ocean Thermal in Pacific Territories and Freely Associated States[a]	Technical Resource (TWh/yr)[b]	Potential Number of Homes Powered[c]	Resource as a Percent of U.S. Electricity Generation (%)[e]
Johnson Atoll	36	3,400,000	0.87
Wake Island	38	3,600,000	0.92
Palmyra	95	8,900,000	2.3
Mariana Islands	140	13,000,000	3.3
Jarvis Island	210	20,000,000	5.2
Howland Island	260	25,000,000	6.3
Marshall Islands	380	35,000,000	9.2
Palau	440	41,000,000	11
Micronesia	1,100	110,000,000	27
Samoa	1,300	120,000,000	32
Total	**4,100**	**380,000,000**	**98**

Figure ES-1. Technical power potential of U.S. marine energy resources (in TWh/yr) for the United States, U.S. territories, and freely associated states.

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1 Introduction

This report was written at the request of the U.S. Department of Energy's (DOE's) Water Power Technologies Office to provide a concise and consolidated summary of the location and quantity of utility-scale wave, tidal current, ocean current, ocean thermal, and river hydrokinetic resources. The information presented herein is intended to help improve understanding of the locations and characteristics of the resources and how they might contribute to the future energy portfolio of the United States. This work is based on several DOE-funded resource assessment studies (Haas et al. 2011; Haas 2013; Jacobson, Hagerman, and Scott 2011; Jacobson et al. 2012; Ascari et al. 2012), a review of these studies performed by the National Research Council (National Research Council (NRC) 2013), and work to update and improve resource assessment studies currently underway at the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (Sandia). Accordingly, this report presents the most up-to-date marine energy technically recoverable utility-scale resource data for the United States.

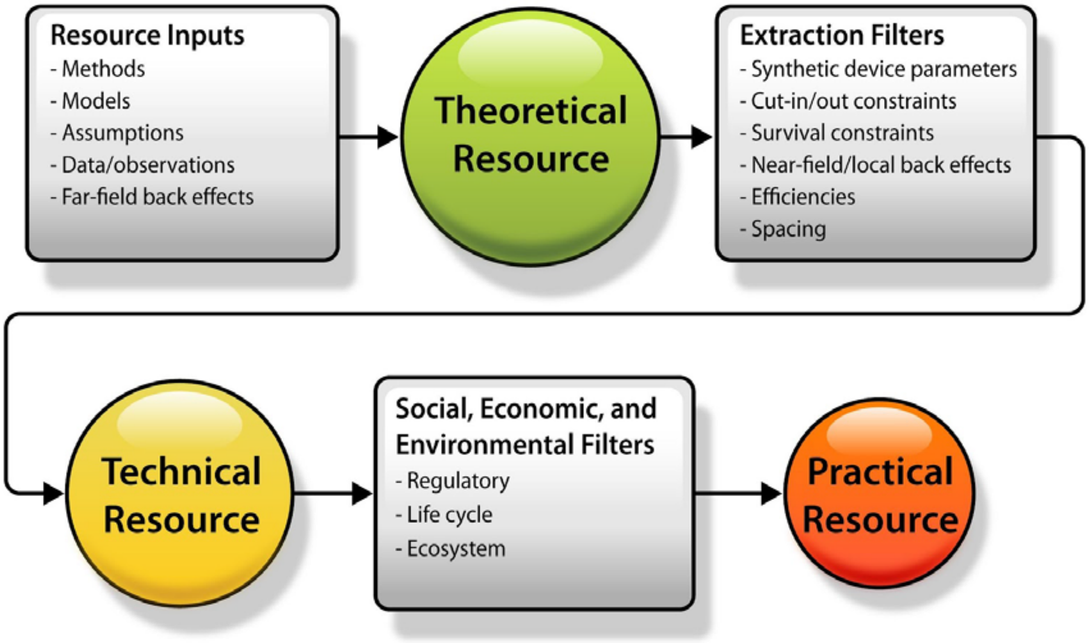
This report focuses on the technically recoverable marine energy resource that can be captured using utility-scale technologies that, when deployed in arrays, can provide megawatts to gigawatts of power and does not independently consider marine energy resources for *Powering the Blue Economy* applications and markets (LiVecchi et al. 2019). Many blue economy uses of marine energy have lower power requirements and can often harness low-energy marine energy resources that are not sufficiently energetic for large-scale energy generation. Accordingly, some locations where this report identifies little or no technical resource may still have sufficient resource potential to power blue economy marine energy technologies. While quantifying marine energy resources for blue economy applications is beyond the scope of this report, including them would increase the overall resource available withing the U.S. exclusive economic zone (EEZ). Further, although *Powering the Blue Economy* power requirements are often small, the value of energy in these markets is typically high, and there is the potential for significant market opportunities and economic benefit in harnessing marine energy for blue economy applications.

Section 2 of this document provides a high-level overview of terminology and methods used to describe and define each marine energy resource type. It also includes a short description of challenges and next steps for each resource type, based primarily on the NRC 2013 report. Sections 3 and 4 provide a description of marine energy resources at the national, state, and regional scales, respectively. Section 5 provides conclusions and a discussion of how to prioritize future research in marine energy resource assessment to support the growth of the industry.

2 Resource Data and Methods

2.1 Terminology and Units

This report follows the resource assessment terminology used and defined by the NRC and the International Electrotechnical Commission Technical Committee 114 (International Electrotechnical Commission 2020), as shown in Figure 1. These definitions are distinct from the definitions used in the assessment of other renewable energy sectors, such as wind and solar. In particular, the definitions of ‘practical’ and ‘technical’ resource used here are closer to the ‘technical’ and ‘gross’ resource definitions, respectively, used in other renewable energy sectors (Lopez et al. 2012; Musial et al. 2016).



Resource Inputs
- Methods
- Models
- Assumptions
- Data/observations
- Far-field back effects

Theoretical Resource

Extraction Filters
- Synthetic device parameters
- Cut-in/out constraints
- Survival constraints
- Near-field/local back effects
- Efficiencies
- Spacing

Technical Resource

Social, Economic, and Environmental Filters
- Regulatory
- Life cycle
- Ecosystem

Practical Resource

Figure 1. Classification of marine energy resource assessment.

Theoretical resource is the “energy available in the resource.” Theoretical resource will always be the largest of theoretical, technical, and practical resource estimates. Estimation of the theoretical resource depends on the accuracy, as well as the temporal and spatial resolution, of the model used.

Technical resource is the “proportion of the theoretical resource that can be captured using existing technology options without consideration of external constraints.” Technical resource will always be smaller than theoretical resource estimates and larger than practical resource estimates. Estimation of the technical resource is a function of the type of technology being modeled and the model’s ability to sufficiently quantify the effect of the technology on the theoretical resource.

Practical resource is the “proportion of the technical resource that is available after consideration of external constraints.” External constraints include, but are not limited to, economic, environmental, and regulatory considerations. Practical resource will always be the smallest of theoretical, technical, and practical resource estimates.

The practical resource for marine energy technologies depends heavily on regulatory constraints, social acceptance, competing uses, and other factors that are highly uncertain and difficult to accurately quantify. As such, consideration of the practical resource is beyond the scope of this report—only estimates of the theoretical and technical resources are presented, with a focus on the technical resource. Throughout this work, wherever the term ‘resource’ is used without a ‘practical’ or ‘theoretical’ qualifier, it refers to the technical resource.

In this report, the marine energy resource is reported in terms of four metrics:

- **Terawatt hours per year (TWh/yr) is the amount of energy the marine energy resource could generate per year.** This metric is valuable because it indicates the average amount of energy the resource can provide per year. 1e12 watts = 1 trillion watts = 1 terawatt.
- **Number of average homes the marine energy resource could power per year.** This metric is a more readily conceptualized indication of how much electricity the resource could produce. In 2019, the average U.S. residential electricity customer consumed 10,649 kilowatt hours (kWh) of energy per year (U.S. Energy Information Administration 2020). One TWh/yr can provide electricity for approximately 94,000 U.S. homes given 2019 consumption rates.
- **Percentage of the region’s electricity generation the marine energy resource could provide.** This metric allows regions to consider the marine energy resource relative to present-day electricity generation (as of 2019). This allows state and regional planners to better consider opportunities to develop marine energy resources, including opportunities for energy export.
- **Percentage of electricity generation by all 50 states that the marine energy resource could provide.** This metric allows regional resources to be compared to the nation’s total generation. This provides a common reference (4,127 TWh/yr in 2019), rather than the metric in the previous bullet, which varies by region (U.S. Energy Information Administration 2020).

2.1.1 Capacity Estimates

In addition to the metrics defined above, it can also be useful to discuss the amount of electrical generation capacity (i.e., the nameplate capacity of devices installed in megawatts (MW)) that would need to be installed to capture the resource, because this is another metric that is more familiar to utility operators, policymakers, and the general public. Where we do estimate capacity in this work (i.e., in Section 5), we do so according to the following equation:

$$Capacity\ [\mathrm{GW}] = \frac{Energy\ Capture\ \left[\frac{\mathrm{TWh}}{\mathrm{yr}}\right]}{Capacity\ Factor} * \frac{1000\ [\mathrm{GW/TW}]}{8760\ [\mathrm{h/yr}]}$$

We use the capacity factor estimates from (Jenne, Yu, and Neary 2015), shown in Table 1. This approach certainly neglects many details of device performance and resource variability. However, a simple analysis of existing marine energy technologies in realistic U.S. resource conditions indicates that these values are at least technically achievable. Therefore, for a technology that is precommercial, we believe this approach is at least reasonable for estimating the *potential scale* of future projects in terms of the resource available. However, the reader should not interpret any statements of capacity as anything more than a first-order estimate of marine energy opportunities in terms of installed capacity and a starting point for more detailed investigation.

Table 1. Capacity Factors for Each Resource Type

Resource Type	Capacity Factor
Wave	30%
Tidal	30%
Ocean-Current	70%
Ocean thermal energy conversion (OTEC)	100%[4]
River	30%

2.2 Ocean Wave Energy

There have been several notable wave resource assessments over the last two decades that have gradually improved the accuracy and spatial coverage of our understanding of the U.S. wave energy opportunity (Jacobson, Hagerman, and Scott 2011; García-Medina, Özkan-Haller, and Ruggiero 2014; Bedard and Hagerman 2004). In this report, the theoretical resource results and data are from a forthcoming manuscript authored by researchers at NREL and PNNL (Kilcher, Garcia-Medina, and Yang 2021). This data set is distinct from the new high-resolution wave hindcasts because the methodology required a more detailed breakdown of the wave field (i.e., directional spectra and wave energy source terms) than is contained in the new high-resolution wave data set generated by PNNL and Sandia (Yang and Neary 2020; Wu et al. 2020; Allahdadi et al. 2019). The forthcoming manuscript builds on the previous DOE-funded resource assessment and resolves several limitations of that work that were identified in an NRC review (Jacobson, Hagerman, and Scott 2011; National Research Council 2013). The forthcoming manuscript improves upon the 2011 methodology in three important ways:

1. It extends the resource area to cover the entire U.S. EEZ

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[4] An OTEC capacity factor was not estimated in Jenne, Yu, and Neary (2015), but the technology is expected to be very consistent, so we utilize a value of 100%.

2. It expands the definition of wave resource to include waves generated by local winds within the EEZ

3. It accounts for wave directionality using a vector line-integral to compute the total wave energy that arrives at the edge of the EEZ.

The wave energy technical resource is calculated from this same data set using the methodology described in Chapter 4.N of DOE's *2015 Quadrennial Technology Review (QTR)* (U.S. Department of Energy 2015). The basis for this methodology is summarized by:

> *If an array consists of an arbitrarily large number of rows, it is theoretically possible to extract almost all incoming wave energy. In practice, however, there will be a point of diminishing returns, where installing additional rows of devices will provide only marginal increases in absorbed energy. Accordingly, there will be a point where deploying additional rows of* [wave energy converters] *is not economically beneficial. To evaluate the technical wave resource, it is assumed that once the resource has been depleted to 8 kW/m as it passes through an array, it is not economical to deploy additional rows. In addition, the analysis assumed that the array has an overall mechanical to electrical conversion efficiency of 90%.*

The equation that defines this method of estimating the technical resource is:

$$\frac{wave\ array\ output}{meter} = \left(\frac{inflow\ energy}{meter} - \frac{outflow\ energy}{meter}\right) * conversion\ efficiency$$

While our work uses the same outflow energy value as in the QTR (8 kW/m), we make two different assumptions that effect the magnitude of the wave energy technical resource. First, we account for wave directionality by using a "bidirectional dot-product" to quantify energy that is propagating both onshore and offshore. In contrast, the QTR did not account for directionality. Second, we change the *conversion efficiency* from 90% to 70%. We made this adjustment because we currently have no operational knowledge of wave array efficiencies, which we believe require a more conservative approach.

We apply this equation to the data sets developed for estimating the theoretical resource at both 10 nautical miles (nmi) from shore (the "inner shelf resource") and at 200 nmi from shore (the resource at the EEZ boundary) to compute the technical resource. These two values provide upper and lower bounds (respectively) on estimates of the United States' technical wave resource, depending on how far from shore it is technically and economically viable to generate wave energy.

The theoretical and technical resources for states along the U.S. West Coast were calculated by breaking the EEZ (i.e., out to 200 nmi from shore) into three sections, separated by extending the borders between the states offshore directly westward (i.e., along lines of constant latitude). On the East Coast, the southeast subregion was separated from the mid-Atlantic subregion by extending the border between North Carolina and Virginia directly eastward. The border between New England and the mid-Atlantic subregions was separated by a line that extends the state-water boundary between New York and Rhode Island to the southeast (i.e., the line connecting 41.419 N, 72.021 W to 36.667 N, 67.670 W separates the two subregions).

2.2.1 Ocean Wave Energy: Challenges and Future Work

The new high-resolution wave hindcast data sets are being made publicly available via cloud-hosting services (Yang and Neary 2020). That data will also be accessible via the MHK Atlas by the end of 2021. The improved resolution of this data set is expected to help project developers identify specific sites that are suitable for specific wave technologies.

More work is needed to delineate the wave resource, which is currently quantified in terms of the entire EEZ by state along the Atlantic and Gulf coasts. This is especially challenging because state boundaries are typically only defined out to 3 nmi from shore (9 nmi in the Gulf), which makes other definitions arbitrary. It was relatively simple to accomplish this on the West Coast, where state coastlines are long and straight, but it is significantly more challenging to do so for East Coast states. Additionally, more work is needed to build consensus around a methodology for estimating the technical resource because divergent approaches exist (Jacobson, Hagerman, and Scott 2011; U.S. Department of Energy 2015).

2.3 Tidal Current Energy

The tidal data reported here comes primarily from the 2011 DOE-funded wave resource assessment (Haas et al. 2011). That work modeled the tides along the entire U.S. coastline, then calculated the power potential at each channel where the tidal flows exceeded 0.5 m/s over an area greater than 0.5 km^2 and with a depth greater than 5 m. The power available at these ‘hot spots’ was estimated in terms of a theoretical limit based on tidal hydraulics (Garrett and Cummins 2005). This approach provides the maximum power that can be extracted from a function of drag added to it. Below this ‘maximum power’ point, more energy can be extracted by adding more turbines. However, above this ‘maximum power’ point, adding more turbines will actually constrict the flow to the point that the array as a whole extracts *less* energy (i.e., it restricts and slows the flow).

The 2011 assessment included a fairly detailed model validation effort based on publicly existing data at the time, but an exhaustive model validation effort for each hot spot is a big challenge. As time has passed, the energy at several locations has been identified to have been underestimated, which has motivated refined modeling efforts (Gunawan, Neary, and Colby 2014). This work utilizes new model data for four locations: Long Island Sound coupled to the New York/New Jersey bight via the East River, a refined model of Portsmouth Harbor (Lower Piscataqua River) on the New Hampshire/Maine border, Cape Cod Canal that connects Buzzards Bay to Cape Cod Bay, and a new model of Delaware Bay (Kilcher, Haas, and Muscalus 2021). All other data presented are from the original 2011 report. In the QTR, the tidal energy technical resource was estimated to be 50%–75% of the theoretical resource. For simplicity and to be conservative, we take the technical resource to be 50% of the theoretical resource estimates provided in Haas et al. (2011).

2.3.1 Tidal Current Energy: Challenges and Future Work

A definitive estimate of the technical potential of tidal energy requires a detailed understanding of the energy dissipated to turbulence in the wake of tidal energy devices. This is because the wake turbulence also contributes to the effective drag in the channel and, thereby, reduces the total amount of energy that can be extracted. Furthermore, the support structures of the turbines also contribute directly to increased channel drag as well as generate wake turbulence. Finally, it seems likely that most tidal arrays will be restricted to operate at a depth where there is zero probability that they pose a risk to vessel traffic. As such, the energy in the surface layer may be more technically challenging to harness.

A more detailed understanding of energy dissipation in turbine wakes, and the associated increase in drag, is required to improve our understanding of the tidal energy technical resource. With an improved understanding of these 'wake losses,' it will be possible to model arrays of turbines to identify optimal energy extraction scenarios. By iterating this process across all of the nation's tidal energy hot spots, it will be possible to obtain a more rigorous estimate of the technical resource potential. This type of iterative approach, where realistic models of turbines are simulated to extract energy and increase drag in tidal circulation models, is also needed to identify whether complex channel geometries (e.g., those in Puget Sound) might be capable of yielding more energy than simple hydraulic models currently indicate (Wang and Yang 2017).

Furthermore, the assumptions in the underlying theory for tidal energy resource assessment are not always relevant to the sites where it was applied (Garrett and Cummins 2005). Many tidally forced regions are far more complicated than 'a single channel connecting two basins.' Instead, these regions are often an interconnected web of channels connecting many basins (e.g., Puget Sound and the San Juan Islands in Washington state). In these geometries, the interactions and phase-lags between channels complicate the application of, and violate several assumptions of, the theoretical approach of Garrett and Cummins. High-resolution models with accurate bathymetry and the ability to simulate turbines in the tidal flow are being used to address these challenges.

The data used here still rely primarily on the filters identified in the original assessment (>0.5 m/s, >0.5 km^2, >5-m depth). However, as new tidal energy technologies emerge—for example, designed to meet the objectives of DOE's *Powering the Blue Economy* initiative—to harness energy at lower flow speeds, or at smaller sites, the tidal energy resource could grow considerably. For example, the existing surface area filter alone omits 66% of sites that were otherwise identified to have strong tidal currents. If this happens, a more detailed assessment of the 'low speed' or 'small site' tidal resource may be worthwhile. Furthermore, new tidal energy technologies that minimize wake losses would also increase the technical resource.

More work is needed to collect measurements that can be used to validate models at potentially promising tidal energy sites—and also to improve the resolution of existing models. The national laboratories have already started this work: New measurements and new models have been made for the Western Passage of Maine and several sites in Puget Sound; measurements are planned in Cook Inlet, Alaska. As these data sets improve our understanding of the tidal energy resource, the data will be made available via the MHK Atlas and will be used to improve national resource estimate totals.

2.4 Ocean Current Energy

The ocean current data used here comes exclusively from the 2013 DOE-funded resource assessment of ocean current energy (Haas 2013). While that work assessed the ocean current resource across the majority of the U.S. coastline, the report focused primarily on the Gulf Stream, because this contains the vast majority of the United States' ocean current resource. Other wind-driven currents (i.e., nontidal currents) in U.S. waters are relatively small (i.e., velocities of ~0.2 m/s or less).

The 2013 report used a simplified ocean circulation model to assess the theoretical potential of the Gulf Stream. This was based on similar principles as the tidal assessment, where power was maximized as a function of drag applied to the current (Gulf Stream). As the drag (number of turbines) increased, a maximum power was identified beyond which the currents slowed such that the total power was reduced. The technical resource was estimated for the Gulf Stream (from Florida to North Carolina within the U.S. EEZ; i.e., including the Florida Current), by assuming a device efficiency of 30%.

2.4.1 Ocean Current Energy: Challenges and Future Work

There already exists a wide range in the theoretical resource estimates for the Gulf Stream (from 1 GW to >200 GW). This wide range is related to the challenges of accurately modeling the dynamics of the Gulf Stream under the influence of large-scale energy extraction. At some point, experts agree that the Gulf Stream would likely shift its course around arrays of turbines that extracted large amounts of energy, though the levels of energy extraction necessary to cause any of these shifts are unknown.

The details of predicting this 'inflection point' are complex. Understanding where, when, and under what conditions the current will divert around an array is critical to estimating a project's economic viability. This problem spans nearly all oceanic spatial scales: the north Atlantic Ocean itself (i.e., the wind-driven gyre circulation) to the turbulence and stratification along the southeastern United States that controls the drag in the Gulf Stream. Furthermore, though the Gulf Stream is known to play an important role in the global heat budget, the climatic and geologic implications of extracting energy from the Gulf Stream are not yet clearly understood (Minobe et al. 2008; Palter 2015; Nunn et al. 2007).

Several recent works have begun to investigate and explore the processes and challenges to energy extraction in the Gulf Stream. This includes modeling studies that account for energy extraction by arrays of turbines in the Florida Current (Haas et al. 2017) as well as detailed modeling and measurement efforts offshore of North Carolina (Lowcher et al. 2017; Muglia, Seim, and Taylor 2020; Bane et al. 2017). We believe the next step would be to take a more coordinated and comprehensive approach to answering these questions. That is, though the challenge of doing so is great, it would be wise to take a more detailed look at the Gulf Stream system before pursuing large- or even medium-scale energy extraction opportunities. Fortunately, thanks largely to the growing trove of high-quality measurements of the Gulf Stream, the improvement in unstructured grid circulation models, and the expanding power of computational resources, there is a real opportunity to improve our understanding of ocean-current energy extraction.

2.5 Ocean Thermal Energy Conversion (OTEC)

The ocean thermal data used here comes exclusively from the 2012 DOE-funded resource assessment of ocean thermal energy (Ascari et al. 2012). That work provides a global assessment of OTEC (electricity generation) via a detailed analysis based on a specific OTEC technology and a two-year HYbrid Coordinate Ocean Model (HYCOM) simulation of ocean temperature and currents. This work takes the technical resource estimates directly from Ascari et al. (2012).

The Ascari report also discussed the opportunity to use seawater for cooling and provided a map that shows locations where 8°C water is less than 300 meters from the surface, but the potential electricity savings that can be attributed to this resource was not quantified. This opportunity may be worth more investigation in locations such as the U.S. West Coast and Hawaii, where summer cooling loads are sizable and cold water is available near the surface.

2.5.1 Ocean Thermal Energy: Challenges and Future Work

As pointed out by the NRC 2013 review, the OTEC resource assessment could be significantly improved by a longer-duration simulation (at least a decade) and by accounting for seasonality of the resource. Future assessments should also explore the opportunity in terms of a broader mix of available technology options (rather than just one). Furthermore, a more detailed investigation of the influence of OTEC water discharge on circulation patterns in the vicinity of the plant is needed to quantify the resource magnitude and to understand other impacts of OTEC on the ocean (e.g., ocean chemistry and biological changes caused by bringing deep—potentially nutrient-rich—waters to the surface).

2.6 River Current Energy

The river data reported here comes exclusively from the 2012 DOE-funded river resource assessment (Jacobson et al. 2012). This data is a collection of more than 71,000 river segments throughout the United States and is available on the MHK Atlas. The theoretically available power for each segment was calculated according to the standard hydrologic engineering equation based on the river volume flow, Q, and the head, H:

$$P = \gamma \cdot Q \cdot H \quad .$$

Where γ is the specific weight of water. Volume flux (Q) and elevation drop (H) of each river segment were used to calculate the theoretically available power. The data for this analysis, for the contiguous United States (CONUS), was calculated from the NHDPlus GIS database containing discharge rates and channel slope information for discrete river segments. The data for Alaska was calculated using a combination of resources, including the Idaho National Laboratory's Virtual Hydropower Prospector, Google Earth, and U.S. Geological Survey stream gages. Segments with flow rates less than 1,000 cubic feet per second were omitted from the analysis, as were stream segments with existing hydroelectric plants or nonpowered dams.

The technical resource was calculated based on a recovery factor for each segment that depended on water velocity and depth during low flow conditions, maximum device packing density, device efficiency, flow statistics, channel slope, and feedback effects between turbine presence and hydraulic head. There were 31% of segments that had a non-zero recovery factor 0. This work takes the technical resource estimates directly from Jacobson et al. (2012).

NREL took the data from this resource assessment, which was not previously organized by state, and grouped it by state. This was done using a simple geographic analysis to identify the state in which each segment was contained. Where a segment was on or near a border between states, the power in that segment was divided equally between those states. We utilized the Natural Earth database, “first order admin” data layer for state boundaries.[5] Because state borders are known to follow rivers—but, often, there was not a perfect match between the river segment data and the borders data—we utilized a 5-km buffer to identify overlap between rivers and borders; that is, any river segment that was within 5 km of the border was identified to be on the border and, therefore, the power in that segment was shared between those states.

It is also important to note that the riverine resource quantified here overlaps with the theoretical potential of conventional hydropower. In other words, this energy could be extracted via conventional hydropower (dams) or marine energy turbines that do not require dams or other flow confinement structures—but not with both technologies simultaneously.

2.6.1 River Current Energy: Challenges and Future Work

The assessment of river hydrokinetic resources in terms of the standard hydrologic power equation was an important first step and was probably the only defensible methodology that could be applied nationwide with data that was available at the time. However, the method of quantifying the technical resource is not consistent with the methodology proposed for quantifying river resource by the International Electrotechnical Commission (IEC) resource assessment technical specification (International Electrotechnical Commission 2019). In particular, while the theoretically extractable energy is certainly limited by the hydrologic equation (Section 2.6), and the technical resource methodology was a good first attempt based on the data available, the uncertainty in the technical resource assessment is large.

The IEC technical specification provides a methodology that yields much more accuracy, but it is based on detailed knowledge of the river bathymetry and requires significant computational resources. However, applying this methodology nationally is a very big challenge because the bathymetry needed does not exist uniformly at the resolution necessary. Therefore, it seems more reasonable that project developers use local knowledge and/or the existing resource assessment data (on the MHK Atlas) to identify potential sites of interest and proceed with site-specific assessments. As we gain a clearer understanding of the important considerations for these projects through the iterative experience of siting and installing them (e.g., sedimentation and river meandering, turbine wakes, competing uses of rivers, etc.), an improved methodology for estimating the technical resource may become apparent. Until then, it seems prudent to simply acknowledge the large uncertainty in the nation’s river resource and focus instead on conducting rigorous and thorough site assessments and developing technologies that can operate at those sites.

3 U.S. Marine Energy Resources

The total technical marine energy resource for the CONUS, extending to the EEZ, is calculated to be 830 TWh/yr, equivalent to the power needs of 78-million homes[6]—or 20% of the total electricity generation by U.S. states in 2019[7] (Table 2a). The two largest marine energy resources for the CONUS are ocean thermal and wave resources, with 400 and 290 TWh/yr, respectively.

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[5] www.naturalearthdata.com

[6] In 2019, the average annual electricity consumption for a U.S. residential utility customer was 10,649 kWh, an average of about 877 kWh per month: https://www.eia.gov/tools/faqs/faq.php?id=97&t=3

[7] Net Generation by state by type of producer by energy source: https://www.eia.gov/electricity/data/state/

The river current resource in the CONUS is 79 TWh/yr, the ocean current resource is 49 TWh/yr, and the tidal current resource is 15 TWh/yr (all with the various uncertainties noted in the section above). The top five tidal sites in the CONUS include one location each in Washington, Delaware/New Jersey, Maine, New York, and California.

When Alaska and Hawaii are included, the total technical marine energy resource increases to 2,300 TWh/yr, equivalent to the power needs of 220-million homes, or 57% of the total electricity generation by U.S. states in 2019 (Table 2b). This increase is largely attributable to the substantial wave and tidal resources in Alaska.

Finally, when the U.S territories and freely associated states in the Pacific and Caribbean are included, the total technical marine energy resource is 6,400 TWh/yr—equivalent to the power needs of 600-million homes, or 160% of the total electricity generation by U.S. states in 2019 (Table 2c).

Because resource assessments for the five marine energy resource types (wave, tidal currents, ocean currents, OTEC, and river currents) have not been completed for all U.S. states, territories, and freely associated states, the technical resources here underestimate the full marine energy resources contained within all U.S. land and EEZ extents.

Table 2a. Theoretical and Technical Marine Energy Resources for the CONUS[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
CONUS Marine Energy Resources				
Wave (EEZ)	860	290	27,000,000	7.1
Wave (to 10 nmi)	540	190	18,000,000	4.7
Tidal	29	15	1,400,000	0.35
Top 5 Tidal Sites Ranked by Power				
Admiralty Inlet Entrance, WA	4.0	2.0	190,000	0.05
Delaware Bay, DE/NJ	2.8	1.4	130,000	0.03
E of Cross Island, ME	2.4	1.2	110,000	0.03
Fishers Island Sound Central Entrance, NY	2.1	1.1	100,000	0.03
San Francisco Bay Entrance, CA	1.6	0.78	73,000	0.02
Ocean Current	160	49	4,600,000	1.2
Ocean Thermal	not reported	400	37,000,000	9.6
River	1,100	79	7,400,000	1.9
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	2,100	830	78,000,000	20
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	1,800	730	69,000,000	18

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*

[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

Table 2b. Theoretical and Technical Marine Energy Resources for All U.S. States[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
US States Marine Energy Resources				
Wave (EEZ)	3,300	1,400	130,000,000	34
Wave (to 10 nmi)	1,800	770	72,000,000	19
Tidal	440	220	21,000,000	5.4
Top 5 Tidal Sites Ranked by Power				
Cook Inlet, AK	160	80	7,500,000	1.9
Chatham Strait, AK	110	53	5,000,000	1.3
Clarence Strait, AK	36	18	1,700,000	0.44
Summer Strait, AK	23	12	1,100,000	0.28
N of Inian Islands, AK	22	11	1,100,000	0.27
Ocean Current	160	49	4,600,000	1.2
Ocean Thermal	not reported	540	51,000,000	13
River	1,300	99	9,300,000	2.4
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	5,200	2,300	220,000,000	57
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	3,800	1,700	160,000,000	41

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*

[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

Table 2c. Theoretical and Technical Marine Energy Resources for All U.S. States, Territories, and Freely Associated States[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
US States, Territories, and Freely Associated States Marine Energy Resources				
Wave (EEZ)	3,300	1,400	130,000,000	34
Wave (to 10 nmi)	1,900	770	72,000,000	19
Tidal	440	220	21,000,000	5.4
Top 5 Tidal Sites Ranked by Power				
Cook Inlet, AK	160	80	7,500,000	1.9
Chatham Strait, AK	110	53	5,000,000	1.3
Clarence Strait, AK	36	18	1,700,000	0.44
Summer Strait, AK	23	12	1,100,000	0.28
N of Inian Islands, AK	22	11	1,100,000	0.27
Ocean Current	160	49	4,600,000	1.2
Ocean Thermal	not reported	4,600	440,000,000	110
River	1,300	99	9,300,000	2.4
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	5,200	6,400	600,000,000	160
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	3,800	5,800	540,000,000	140

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*
[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

4 Marine Energy Resources by State/Region

Marine energy theoretical and technical resources are reported by region in Table 3–Table 10.

4.1 West Coast

West Coast marine energy resources are reported by state and by regional totals (Tables 3a–3d).

In California, the marine energy technical resource total extending to the EEZ is 140 TWh/yr, equivalent to the power needs of 13-million homes, 69% of California's 2019 net electricity generation, or 3.4% of the total electricity generation by U.S. states in 2019 (Table 3a). The wave resource accounts for nearly all of the state's marine energy resource (140 TWh/yr total). The tidal resource in the San Francisco Bay entrance has the potential to power an additional 73,000 homes and is the fifth-largest tidal resource in the CONUS.

In Oregon, the marine energy technical resource total extending to the EEZ is 95 TWh/yr, equivalent to the power needs of 8.9-million homes, which is 1.5 times Oregon's 2019 net electricity generation, or 2.3% of the total electricity generation by U.S. states in 2019 (Table 3b). The wave resource accounts for 93 TWh/yr of the 95 TWh/yr total and could allow Oregon to be a net exporter of wave-powered electricity.

In Washington, the marine energy technical resource total that extends to the EEZ is 12 TWh/yr, which is small due to the method used to calculate the wave resource, because wave energy that propagates southward from the Canadian EEZ does not count toward the U.S. total. However, if we assume that Canada does not extract this energy before it propagates into U.S. waters, then there is significantly more wave energy available in Washington. For example, if the wave resource to 10 nmi is used instead of the wave resource to the EEZ limit, Washington's marine energy technical resource total is 43 TWh/yr, equivalent to the power needs of 4-million homes, 40% of Washington's 2019 net electricity generation, or 1.0% of the total electricity generation by U.S. states in 2019 (Table 3c). Admiralty Inlet is a particularly energetic site.

Overall, the West Coast Region's marine energy technical resource total extending to the EEZ is 250 TWh/yr, equivalent to the power needs of 23-million homes, 67% of the West Coast's 2019 net electricity generation, or 6.0% of the total electricity generation by U.S. states in 2019 (Table 3d). The wave resource accounts for 240 TWh/yr of the 250 TWh/yr total. The tidal sites and river hydrokinetics of the West Coast have the potential to power 1-million homes. There are no ocean current or OTEC resources along the West Coast.

Table 3a. Theoretical and Technical West Coast Marine Energy Resources for California[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation in CA (201.8 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
California Marine Energy Resources					
Wave (EEZ)	320	140	13,000,000	69	3.4
Wave (to 10 nmi)	220	91	8,500,000	45	2.2
Tidal	1.8	0.89	84,000	0.44	0.02
Top 5 Tidal Sites Ranked by Power					
San Francisco Bay Entrance, CA	1.6	0.78	73,000	0.39	0.02
Humboldt Bay, CA	0.12	0.06	5,800	0.03	0.00
Heckman Island, CA	0.05	0.03	2,500	0.01	0.00
San Diego Bay, CA	0.03	0.01	1,200	0.01	0.00
Tomales Bay, CA	0.03	0.01	1,200	0.01	0.00
Ocean Current	0	0	0	0	0
Ocean Thermal	not reported	0	0	0	0
River	51	0.55	52,000	0.27	0.01
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	370	140	13,000,000	69	3.4
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	270	92	8,700,000	46	2.2

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*

[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

Table 3b. Theoretical and Technical West Coast Marine Energy Resources for Oregon[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation in OR (62.3 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
Oregon Marine Energy Resources					
Wave (EEZ)	170	93	8,700,000	150	2.2
Wave (to 10 nmi)	130	68	6,400,000	110	1.6
Tidal	0.42	0.21	20,000	0.34	0.01
Top 5 Tidal Sites Ranked by Power					
Coos Bay Entrance, OR	0.18	0.09	8,200	0.14	0.00
Tillamook Bay Entrance, OR	0.06	0.03	2,900	0.05	0.00
Bandon, OR	0.04	0.02	2,100	0.04	0.00
Yaquina Bay Entrance, OR	0.04	0.02	2,100	0.04	0.00
Winchester Bay Entrance, OR	0.04	0.02	1,600	0.03	0.00
Ocean Current	0	0	0	0	0
Ocean Thermal	not reported	0	0	0	0
River	76	2.2	200,000	3.5	0.05
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	250	95	8,900,000	150	2.3
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	210	70	6,600,000	110	1.7

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*
[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2*

Table 3c. Theoretical and Technical West Coast Marine Energy Resources for Washington[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation in WA (106.5 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
Washington Marine Energy Resources					
Wave (EEZ)	13	5.4	510,000	5.1	0.13
Wave (to 10 nmi)	69	36	3,400,000	34	0.87
Tidal	6.0	3.0	280,000	2.8	0.07
Top 5 Tidal Sites Ranked by Power					
Admiralty Inlet Entrance, WA	4.0	2.0	190,000	1.9	0.05
Willapa Bay, WA	0.80	0.40	37,000	0.37	0.01
Columbia River, WA	0.61	0.31	29,000	0.29	0.01
Grays Harbor, WA	0.53	0.27	25,000	0.25	0.01
n/a	0				
Ocean Current	0	0	0	0	0
Ocean Thermal	not reported	0	0	0	0
River	66	4.0	370,000	3.7	0.10
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	85	12	1,200,000	12	0.30
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	140	43	4,000,000	40	1.0

[a] All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.
[b] Detailed methodologies for estimating Technical Resource are provided in Section 2.

Table 3d. Theoretical and Technical West Coast Marine Energy Resources for the U.S. West Coast (CA, OR, WA) [a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation in CA, OR, WA (370.5 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
West Coast (CA, OR, WA) Marine Energy Resources					
Wave (EEZ)	500	240	22,000,000	64	5.7
Wave (to 10 nmi)	420	190	18,000,000	52	4.7
Tidal	8.2	4.1	380,000	1.1	0.10
Top 5 Tidal Sites Ranked by Power					
Admiralty Inlet Entrance, WA	4.0	2.0	190,000	0.54	0.05
San Francisco Bay Entrance, CA	1.6	0.78	73,000	0.21	0.02
Willapa Bay, WA	0.80	0.40	37,000	0.11	0.01
Columbia River, WA	0.61	0.31	29,000	0.08	0.01
Grays Harbor, WA	0.53	0.27	25,000	0.07	0.01
Ocean Current	0	0	0	0	0
Ocean Thermal	not reported	0	0	0	0
River	190	6.7	630,000	1.8	0.16
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	710	250	23,000,000	67	6.0
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	620	200	19,000,000	55	5.0

[a] All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.

[b] Detailed methodologies for estimating Technical Resource are provided in Section 2.

4.2 East Coast

The East Coast marine energy resources are reported by subregional (New England, Mid-Atlantic, Southeast) and regional totals (Tables 4a–4d).

The New England Coast subregion includes states from Maine to Connecticut. In New England, the marine energy technical resource total extending to the EEZ is 24 TWh/yr, equivalent to the power needs of 2.3-million homes, 25% of the subregion’s 2019 net electricity generation, or 0.59% of the total electricity generation by U.S. states in 2019 (Table 4a). The wave resource accounts for 21 TWh/yr of the 24 TWh/yr total. The five largest tidal resources in the subregion are located in Maine, including the area east of Cross Island, which is the third-largest tidal site by power in the CONUS. The total technical resource of all tidal sites in this subregion is 3.3 TWh/yr, providing the potential to power 310,000 homes.

The Mid-Atlantic subregion includes states from New York to Virginia. In the Mid-Atlantic Coast, the marine energy technical resource total extending to the EEZ is 16 TWh/yr, equivalent to the power needs of 1.5-million homes, 4.8% of the subregion's 2019 net electricity generation, or 0.40% of the total electricity generation by U.S. states in 2019 (Table 4b). The wave resource accounts for 12 TWh/yr of the 16 TWh/yr total. The top five tidal sites by power in the Mid-Atlantic include two locations between Long Island and Fishers Island, New York; Delaware Bay, Delaware/New Jersey; Chesapeake Bay, Virginia; and Toms Cove, Maryland—and have the potential to power 309,000 homes. All of the tidal sites in this subregion have a total technical resource of 3.8 TWh/yr, which could power 360,000 homes.

The Southeastern Coast subregion includes states from North Carolina to Florida. In the Southeastern Coast subregion, the marine energy technical resource total extending to the EEZ is 74 TWh/yr, equivalent to the power needs of 7-million homes, 15% of the subregion's 2019 net electricity generation, or 1.8% of the total electricity generation by U.S. states in 2019 (Table 4c). The largest marine energy resource is the ocean current resource with 49 TWh/yr of technical resource, followed by 22 TWh/yr in wave resource. The top five tidal sites by power in the Southeastern Coast subregion include two locations in South Carolina and three in Georgia. The technical resource of all of the tidal sites in this subregion is 3.0 TWh/yr, enough to power 280,000 homes. To date, the Southeastern Coast subregion is the only area with resources in all five marine energy resource types. While the OTEC report by Ascari et al. (2012) only reports the total OTEC resource within the EEZ for the East Coast, the report states, " … mean net power of 80 MW is achievable as far north as 36 degrees, offshore from North Carolina where the Gulf Stream breaks from the U.S. coast into the Atlantic Ocean."

Overall, the East Coast Region's marine energy technical resource total extending to the EEZ is 460 TWh/yr, equivalent to the power needs of 43-million homes, 49% of the East Coast's 2019 net electricity generation, or 11% of the total electricity generation by U.S. states in 2019 (Table 4d). The ocean thermal resource accounts for 340 TWh/yr of the total marine energy resource.

The wave resource at the edge of the EEZ is 55 TWh/yr. Much of this energy is in waves that are generated within the EEZ by westerly winds and are propagating offshore. On the inner-shelf (10 nmi from shore) the theoretical resource does not exceed the 8 kW/m threshold (in the annual average) described in Section 2.2 and, therefore, the technical wave resource is zero. Alternate methodologies for estimating the technical resource, especially a method focused on small-scale wave energy for blue economy applications, could certainly identify viable wave resources here. For example, if the 'outflow energy' in Section 2.2 was lowered from 8 kW/m to 5 kW/m, the East Coast's 10-nmi technical resource would be 3.8 TWh/yr.

The ocean current resource of 49 TWh/yr in the Gulf Stream is the only such resource in the United States and is the equivalent to powering 4.6-million homes. The top five tidal sites by power include Delaware Bay, Delaware/New Jersey; east of Cross Island, Maine; Fishers Island Sound Central entrance, New York ('The Race'); Chesapeake Bay entrance, Virginia; and Port Royal Sound, South Carolina. All of the tidal sites along the East Coast have a technical resource of 10 TWh/yr.

Table 4a. Theoretical and Technical East Coast Marine Energy Resources for the New England Coast Subregion[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation in ME, NH, MA, RI, CT (97.7 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
New England (Maine–Connecticut) Marine Energy Resources					
Wave (EEZ)	80	21	2,000,000	21	0.51
Wave (to 10 nmi)	34	0	0	0	0
Tidal	6.6	3.3	310,000	3.4	0.08
Top 5 New England (ME–CT) Tidal Sites Ranked by Power					
E of Cross Island, ME	2.4	1.2	110,000	1.2	0.03
S of Eastport, ME	0.93	0.46	44,000	0.48	0.01
Btwn Southwest Breaker & Green Islands, ME	0.60	0.30	28,000	0.30	0.01
Btwn East Sister & Crow Islands, ME	0.53	0.27	25,000	0.27	0.01
NE of Roque Island, ME	0.28	0.14	13,000	0.14	0.00
Ocean Current	0	0	0	0	0
Ocean Thermal	not reported				
River	13	0.12	11,000	0.12	0.00
River Resource by State					
Connecticut	0.93	0.04	3,500	0.04	0.00
Maine	9.4	0.05	4,400	0.05	0.00
Massachusetts	1.3	0.03	2,600	0.03	0.00
New Hampshire	1.8	0.01	690	0.01	0.00
Rhode Island	0.00	0	0	0	0
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	100	24	2,300,000	25	0.59
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	54	3.4	320,000	3.5	0.08

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*
[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

Table 4b. Theoretical and Technical East Coast Marine Energy Resources for the Mid-Atlantic Subregion[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation in NY, NJ, DE, MD, VA (344.0 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
Mid-Atlantic (New York–Virginia) Marine Energy Resources					
Wave (EEZ)	67	12	1,200,000	3.6	0.30
Wave (to 10 nmi)	23	0	0	0	0
Tidal	7.6	3.8	360,000	1.1	0.09
Top 5 Mid-Atlantic (NY–VA) Tidal Sites Ranked by Power					
Fishers Island Sound Central Entrance, NY	2.1	1.1	100,000	0.31	0.03
Delaware Bay, DE/NJ	2.8	1.4	130,000	0.40	0.03
Chesapeake Bay Entrance, VA	1.1	0.57	53,000	0.17	0.01
Toms Cove, MD	0.29	0.14	14,000	0.04	0.00
Fishers Island Sound Southern Entrance, NY	0.25	0.12	12,000	0.04	0.00
Ocean Current	0	0	0	0	0
Ocean Thermal	not reported				
River	20	0.17	16,000	0.05	0.00
River Resource by State					
Delaware	0.09	0.01	610	0.00	0.00
Maryland	2.0	0.04	4,100	0.01	0.00
New Jersey	1.7	0.03	2,900	0.01	0.00
New York	8.7	0.06	5,100	0.02	0.00
Virginia	7.5	0.03	3,200	0.01	0.00
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	95	16	1,500,000	4.8	0.40
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	51	4.0	370,000	1.2	0.10

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*

[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

Table 4c. Theoretical and Technical East Coast Marine Energy Resources for the Southeastern Coast Subregion[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation in NC, SC, GA, 1/2 FL (482.8 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
Southeast (North Carolina–Florida) Marine Energy Resources					
Wave (EEZ)	140	22	2,000,000	4.5	0.53
Wave (to 10 nmi)	40	0	0	0	0
Tidal	6.0	3.0	280,000	0.62	0.07
Top 5 Southeast Coast (NC–FL) Tidal Sites Ranked by Power					
Port Royal Sound, SC	0.95	0.48	45,000	0.10	0.01
Saint Helena Sound, SC	0.89	0.45	42,000	0.09	0.01
Sapelo Sound, GA	0.41	0.21	19,000	0.04	0.00
St Catherines Sound, GA	0.39	0.19	18,000	0.04	0.00
Cumberland Sound Entrance, GA	0.27	0.14	13,000	0.03	0.00
Ocean Current	160	49	4,600,000	10	1.2
Ocean Thermal					not reported
River	24	0.38	36,000	0.08	0.01
River Resource by State					
Florida	3.1	0.10	9,500	0.02	0.00
Georgia	8.5	0.11	10,000	0.02	0.00
North Carolina	5.9	0.02	2,000	0.00	0.00
South Carolina	6.6	0.15	14,000	0.03	0.00
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	330	74	7,000,000	15	1.8
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	230	52	4,900,000	11	1.3

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*
[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

Table 4d. Theoretical and Technical East Coast Marine Energy Resources for the East Coast Region[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation in ME to FL as listed above (924.5 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
East Coast (Maine–Florida) Marine Energy Resources					
Wave (EEZ)	280	55	5,200,000	6.0	1.3
Wave (to 10 nmi)	98	0	0	0	0
Tidal	20	10	950,000	1.1	0.24
Top 5 East Coast Tidal Sites Ranked by Power					
Delaware Bay, DE/NJ	2.8	1.4	130,000	0.15	0.03
E of Cross Island, ME	2.4	1.2	110,000	0.13	0.03
Fishers Island Sound Central Entrance, NY	2.1	1.1	100,000	0.12	0.03
Chesapeake Bay Entrance, VA	1.1	0.57	53,000	0.06	0.01
Port Royal Sound, SC	0.95	0.48	45,000	0.05	0.01
Ocean Current	160	49	4,600,000	5.3	1.2
Ocean Thermal	not reported	340	32,000,000	37	8.3
River	57	0.67	63,000	0.07	0.02
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	520	460	43,000,000	49	11
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	800	400	38,000,000	43	9.7

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*
[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

4.3 Gulf Coast

The Gulf of Mexico Coast marine energy resources are reported by regional total (Table 5).

The Gulf Coast Region's marine energy technical resource total extending to the EEZ is 84 TWh/yr, equivalent to the power needs of 7.9-million homes, 9.2% of the Gulf Coast's 2019 net electricity generation, or 2.0% of the total electricity generation by U.S. states in 2019. The ocean thermal resource accounts for 53 TWh/yr of the total marine energy resource, and the river hydrokinetic resource contributes 31 TWh/yr. The top five tidal sites by power along the Gulf Coast include four locations in the Florida Keys and one in Pelican Bay, Alabama. Combined, the tidal sites in this subregion have a total technical resource of 0.37 TWh/yr, equivalent to the power needed by 35,000 homes. There are no wave or ocean current technical resources in this region. There is a theoretical wave resource in the Gulf, but in the annual-average, this resource does not exceed the 8-kW/m threshold described in Section 2.2 and, therefore, the technical wave resource is zero. Alternate methodologies for estimating the technical resource, especially a method focused on small-scale wave energy for blue economy applications, could certainly identify viable wave resources.

Table 5. Theoretical and Technical Gulf of Mexico Coast Marine Energy Resources[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation (914.8 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
Gulf Coast Marine Energy Resources					
Wave (EEZ)	69	0	0	0	0
Wave (to 10 nmi)	27	0	0	0	0
Tidal	0.74	0.37	35,000	0.04	0.01
Top 5 Tidal Sites Ranked by Power					
Btwn Boca Grande & Gull Keys, FL	0.25	0.12	12,000	0.01	0.00
W of Pigeon Key, FL	0.14	0.07	6,600	0.01	0.00
N of Egmont Key, FL	0.11	0.06	5,300	0.01	0.00
E of Key West, FL	0.11	0.05	4,900	0.01	0.00
Pelican Bay, AL	0.06	0.03	2,900	0.00	0.00
Ocean Current	0	0	0	0	0
Ocean Thermal	not reported	53	5,000,000	5.8	1.3
River	170	31	2,900,000	3.3	0.74
River Resource by State					
Alabama	15	0.81	76,000	0.09	0.02
Louisiana	75	17	1,600,000	1.9	0.42
Mississippi	56	12	1,200,000	1.4	0.30
Texas	29	0.26	24,000	0.03	0.01
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	240	84	7,900,000	9.2	2.0
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	200	84	7,900,000	9.2	2.0

[a] All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.
[b] Detailed methodologies for estimating Technical Resource are provided in Section 2.

4.4 Alaska

Alaska's marine energy resources are reported by state total (Table 6).

Alaska's marine energy technical resource total extending to the EEZ is 1,100 TWh/yr, equivalent to the power needs of 100-million homes, which is 180 times Alaska's 2019 net electricity generation, or 27% of the total electricity generation by U.S. states in 2019. The wave resource accounts for 890 TWh/yr and is 62% of the U.S. wave resource. Alaska's tidal resource of 210 TWh/yr represents 93% of the U.S. tidal resource. The top two tidal sites by power, Cook

Inlet and Chatham Straight, account for 64% of Alaska's total tidal resource and are relatively close to Anchorage and Juneau, respectively. The state's river hydrokinetic resource of 21 TWh/yr is equivalent to the power needed by 1.9-million homes. There are no ocean current or ocean thermal resources in this region.

Table 6. Theoretical and Technical Alaska Marine Energy Resources[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation (6.1 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
Alaska Marine Energy Resources					
Wave (EEZ)	2,000	890	83,000,000	15,000	21
Wave (to 10 nmi)	1,200	540	50,000,000	8,800	13
Tidal	420	210	20,000,000	3,400	5.0
Top 10 Tidal Sites Ranked by Power					
Cook Inlet	160	80	7,500,000	1,300	1.9
Chatham Strait	110	53	5,000,000	860	1.3
Clarence Strait	36	18	1,700,000	290	0.44
Summer Strait	23	12	1,100,000	190	0.28
N of Inian Islands	22	11	1,100,000	180	0.27
Btwn Seguam and Amlia Islands	10	5.1	480,000	84	0.12
Btwn Sundstrom and Sitkinak Islands	5.5	2.8	260,000	45	0.07
NE of Warren Island	4.7	2.3	220,000	38	0.06
Btwn Unalga and Kavalga Islands	3.8	1.9	180,000	31	0.05
Btwn Kagalaska and Adak Islands	3.7	1.9	170,000	30	0.05
Ocean Current	0	0	0	0	0
Ocean Thermal	0	0	0	0	0
River	240	21	1,900,000	340	0.50
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	2,700	1,100	100,000,000	18,000	27
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	1,800	770	72,000,000	13,000	19

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*
[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

4.5 Hawaii

Hawaii's marine energy resources are reported by state total (Table 7).

Hawaii's marine energy technical resource total extending to the EEZ is 390 TWh/yr, equivalent to the power needs of 37-million homes, 4,000% of the region's 2019 net electricity generation, or 9.4% of the total electricity generation by U.S. states in 2019. The wave resource accounts for 250 TWh/yr, and the ocean thermal resource accounts for the remaining 140 TWh/yr. There is no ocean current resource in Hawaii, and tidal current and river current resources have not been assessed.

Table 7. Theoretical and Technical Hawaii Marine Energy Resources[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation (9.7 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
Hawaii Marine Energy Resources					
Wave (EEZ)	380	250	23,000,000	2,500	6.0
Wave (to 10 nmi)	120	36	3,400,000	370	0.87
Tidal					not assessed
Ocean Current	0	0	0	0	0
Ocean Thermal	not reported	140	13,000,000	1,500	3.5
River					not assessed
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	380	390	37,000,000	4,000	9.4
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	120	180	17,000,000	1,800	4.3

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*
[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

4.6 Puerto Rico and the U.S. Virgin Islands

Puerto Rico and the U.S. Virgin Islands' marine energy resources are reported by state total (Table 8).

Puerto Rico and the U.S. Virgin Islands' marine energy technical resource total extending to the EEZ is 38 TWh/yr, equivalent to the power needs of 3.6-million homes, 210% of the region's 2019 net electricity generation, or 0.92% of the total electricity generation by U.S. states in 2019. The ocean thermal resource accounts for all of the identified marine energy resources because there is no technical wave resource in this region; tidal current, ocean current, and river current resources have not been assessed. There is a theoretical wave resource available for these U.S. Territories, but in the annual-average, this resource does not exceed the 8-kW/m threshold described in Section 2.2 and, therefore, the technical wave resource is zero. Alternate methodologies for estimating the technical resource, especially a method focused on small-scale wave energy for blue economy applications, could certainly identify viable wave resources here.

Table 8. Theoretical and Technical Puerto Rico and U.S. Virgin Islands Marine Energy Resources[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2017 Regional Electricity Generation (18 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
Puerto Rico & US Virgin Islands Marine Energy Resources					
Wave (EEZ)	16	0	0	0	0
Wave (to 10 nmi)	18	0	0	0	0
Tidal	not assessed				
Ocean Current	not assessed				
Ocean Thermal	not reported	38	3,600,000	210	0.92
River	not assessed				
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)	16	38	3,600,000	210	0.92
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)	18	38	3,600,000	210	0.92

[a] All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.
[b] Detailed methodologies for estimating Technical Resource are provided in Section 2.

4.7 Pacific Territories and Freely Associated States

The U.S. Pacific territories and freely associated states' marine energy resources are reported by regional total (Table 9).

Only ocean thermal resources have been assessed for U.S. Pacific territories and freely associated states. The technical ocean thermal resource of this region contributes 63% of the total marine energy resource for all U.S. states, territories, and freely associated states, with a resource equivalent to power 380-million homes and meet 98% of the U.S. states' 2019 net electricity generation. Several of these territories and freely associated states are uninhabited and, those that are inhabited, often have limited electrical infrastructure compared to other U.S. states, territories, and freely associated states. Incorporating OTEC and/or seawater for cooling into the U.S. Pacific territories and freely associated states could vastly improve the lives of residents and provide strategic energy sources for trans-Pacific ship refueling needs if OTEC were used to power hydrogen or similar fuel generation and storage.

Though the wave energy resource of the U.S. Pacific territories and freely associated states has not been quantified in detail, there is anecdotal evidence that a significant wave resource exists at many of these sites. For example, a wave buoy near American Samoa has measured an average wave resource of more than 20 kW/m over the last 3 years, and buoys in Guam and the Northern Mariana Islands have registered a wave resource of 16 kW/m to 18 kW/m.[8] PNNL is in the process of running a high-resolution wave model of this region, and an assessment of the total wave resource available there will be conducted as soon as the model runs are complete. The wave resource for this region will, therefore, be included in future work similar to this one.

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[8] Data from CDIP, Scripps Institution of Oceanography. Buoy numbers 189, 196, and 197.

Table 9. Theoretical and Technical Pacific Territories and Freely Associated States Marine Energy Resources[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation (N/A) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
Pacific Territories and Freely Associated States Marine Energy Resources					
Wave (EEZ)	not assessed				
Wave (to 10 nmi)	not assessed				
Tidal	not assessed				
Ocean Current	not assessed				
Ocean Thermal	not reported	4,100	380,000,000		98
Resource by Locale					
Johnson Atoll	not reported	36	3,400,000		0.87
Wake Island	not reported	38	3,600,000		0.92
Palmyra	not reported	95	8,900,000		2.3
Mariana Islands	not reported	140	13,000,000		3.3
Jarvis Island	not reported	210	20,000,000		5.2
Howland Island	not reported	260	25,000,000		6.3
Marshall Island	not reported	380	35,000,000		9.2
Palau	not reported	440	41,000,000		11
Micronesia	not reported	1,100	110,000,000		27
Samoa	not reported	1,300	120,000,000		32
River	not assessed				
Total (Wave to EEZ + Tidal + Ocean Current + Ocean Thermal + River)		4,100	380,000,000		98
Total (Wave to 10 nmi + Tidal + Ocean Current + Ocean Thermal + River)		4,100	380,000,000		98

[a] *All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.*
[b] *Detailed methodologies for estimating Technical Resource are provided in Section 2.*

4.8 Inland States

The U.S. inland states' marine energy resources are reported by state and regional totals (Table 10).

Inland U.S. states have 41 TWh/yr of technical river hydrokinetic resource, equivalent to the power needs of 3.8-million homes and 0.99% of the total electricity generation by U.S. states in 2019. While each inland state has some river hydrokinetic resource, most of the resource is along the lower Mississippi and Ohio river basins.

Table 10. Theoretical and Technical River Hydrokinetic Energy Resources in Inland States[a]

	Theoretical Resource (TWh/yr)	Technical Resource[b] (TWh/yr)	Technical Resource as Potential Number of Homes Powered	Technical Resource as Percent of 2019 Regional Electricity Generation (1901.0 TWh) (%)	Technical Resource as Percent of US Electricity Generation (4126.7 TWh) (%)
Inland States Marine Energy Resource					
River					
River Resource by State Ranked by Technical Resource					
Arkansas	52	10	950,000	0.53	0.25
Missouri	50	7.5	710,000	0.40	0.18
Tennessee	34	5.4	500,000	0.28	0.13
Kentucky	27	4.1	390,000	0.22	0.10
Illinois	26	3.4	320,000	0.18	0.08
Arizona	53	1.3	120,000	0.07	0.03
Montana	72	1.3	120,000	0.07	0.03
Nebraska	28	1.1	110,000	0.06	0.03
Indiana	10	1.0	97,000	0.05	0.02
Idaho	76	0.88	83,000	0.05	0.02
Iowa	10.0	0.75	70,000	0.04	0.02
Ohio	8.5	0.59	56,000	0.03	0.01
South Dakota	7.0	0.58	54,000	0.03	0.01
North Dakota	6.0	0.52	49,000	0.03	0.01
Kansas	17	0.51	48,000	0.03	0.01
Pennsylvania	24	0.50	47,000	0.03	0.01
Utah	24	0.40	37,000	0.02	0.01
West Virginia	17	0.32	30,000	0.02	0.01
Oklahoma	11	0.18	17,000	0.01	0.00
Wisconsin	5.5	0.14	13,000	0.01	0.00
Minnesota	5.4	0.10	9,500	0.01	0.00
Nevada	5.4	0.08	7,500	0.00	0.00
Colorado	32	0.06	5,200	0.00	0.00
Wyoming	27	0.03	2,800	0.00	0.00
Vermont	0.95	0.01	750	0.00	0.00
New Mexico	12	0.00	9.6	0.00	0.00
Michigan	1.3	0.00	0.24	0.00	0.00
Total (River)	640	41	3,800,000	2.2	0.99

[a] All values are listed to two significant figures; therefore, totals shown may not equal the sum of values.
[b] Detailed methodologies for estimating Technical Resource are provided in Section 2.

5 Conclusion

This report provides an overview of the U.S. marine energy resource magnitude and the methods used to estimate them. The total marine energy resource in the 50 states is 2,300 TWh/yr, equivalent to 57% of the electricity generated by those states in 2019. The nation's Pacific and Caribbean territories and freely associated states add an additional 4,100 TWh/yr of OTEC resource. These numbers are based on DOE-sponsored marine energy resource assessments published between 2011 and 2013 (Haas et al. 2011; Haas 2013; Jacobson et al. 2012; Jacobson, Hagerman, and Scott 2011; Ascari et al. 2012) and recent updates (Kilcher, Garcia-Medina, and Yang 2021; Kilcher, Haas, and Muscalus 2021) to the resource assessment studies from NREL, Sandia, and PNNL.

This report shows that the nation's marine energy resources are large and geographically diverse. These resources are particularly attractive because early research indicates that they are more predictable than other renewable energy resources, which may be particularly valuable to future energy markets as variable renewables play an increasing role in the nation's energy mix.

However, to realize this future, more work is needed to improve the accuracy of the technical resource estimates presented here. This starts by improving the accuracy and resolution of the underlying resource data sets. Along these lines, DOE has supported the development of a new high-resolution wave resource data set (Yang and Neary 2020). A similar effort is needed for tidal and ocean-current energy. These data sets must be validated with measurements to be reliable, especially in regions where models identify promising sites. Existing public measurements should be used for validation as much as possible but, where existing measurement data is lacking or is of insufficient quality, targeted measurement efforts are needed.

These DOE-sponsored marine energy resource assessments were performed with utility-scale projects in mind. As such, the resource data reported here do not fully capture the many distributed, smaller-scale resources available (which are a major focus of DOE's new *Powering the Blue Economy* initiative); thus, this summary may represent an underestimate of the total marine energy resource that is potentially available (LiVecchi et al. 2019).

The U.S. wave energy resource is large (1,400 TWh/yr), and the vast majority of this energy is delivered directly to the nation's shorelines where it can be utilized on land. The U.S. West Coast is a particularly attractive region for wave energy because the resource reaches the shoreline (240 TWh/yr), where it can be readily utilized. Harnessing 10% of the West Coast resource (24 TWh/yr) at a capacity factor of 30% would require installing approximately 9 GW[9] of wave energy capacity. Hawaii is also an attractive early market for wave energy (250 TWh/yr total and 36 TWh/yr at 10 nmi) because it has high energy prices and aggressive renewable portfolio standards. Installing 1 GW of capacity in Hawaii, again assuming a 30% capacity

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[9] These discussions of capacity are meant to provide context to the resource estimates so that policymakers, utility operators, and the general public have a better understanding of how and where marine energy might meaningfully contribute to our nation's energy supply. The methodology for estimating capacity is described in Section 2.1.1.

factor, could deliver 27% of the state's energy needs while harnessing just 7% of the state's near-land (10 nmi) resource.

Though the nation's tidal energy resource is smaller than the wave resource (220 TWh/yr), the technology is, in general, closer to commercialization. It is also a highly predictable form of renewable energy, and many sites are adjacent to markets that could utilize the power available. Most notable among these sites is Cook Inlet, Alaska, which possesses 36% of the nation's resource and is adjacent to the state's Railbelt electricity grid that provides power to more than two-thirds of the state's population (Energy Information Administration 2019). Installing 1 GW of tidal energy capacity[9] in Cook Inlet, at a capacity factor of 30%, would harness just 3% of the resource and deliver approximately half of the Railbelt's current electricity generation (43% of the state's 2019 generation).

Ocean current energy (49 TWh/yr) could provide clean reliable power to the Atlantic southeastern states. Florida has a particularly attractive opportunity in the Florida Current, which is part of the Gulf Stream. The Florida Current is attractive because the flow, which squeezes between the coastline around Miami and the shallow shoals of the Bahamas, is both relatively close to shore and highly energetic (depth-averaged current speeds approaching 2 m/s). Installing 1 GW of capacity in the Gulf Stream, at an assumed capacity factor of 70%, would harness 12% of the resource and power the equivalent of more than 550,000 homes.

Although the OTEC resource is immense (4,600 TWh/yr across the United States, its territories, and freely associated states), it is distributed across the nation's vast EEZ. That is, only a very small fraction of this resource (much less than 1%) is located near land where it can be utilized in the near term. However, if energy storage technologies become sufficiently inexpensive, it does raise the possibility that OTEC—and other marine energy resources that are distant from load centers (e.g., wave energy along Alaska's Aleutian Island chain)—become viable sources of energy. Harnessing 1% of this resource, assuming a capacity factor of 100%, would mean installing 5.3 GW of OTEC capacity[9]—energy sufficient to power more than 4-million homes.

The nation's riverine hydrokinetic resource is attractive because it could provide a clean and reliable source of power to communities or other infrastructure along the nation's riverbanks and waterways. This is a particularly interesting opportunity for remote Alaskan communities, many of which are located along rivers and typically rely on expensive diesel to power their electrical grids. The community of Igiugig is testing a river hydrokinetic device to reduce their use of diesel power (U.S. Department of Energy 2019). Furthermore, many of the same technologies that are developed for tidal and ocean-current energy can also be configured to generate power from rivers.

Finally, it is important to keep in mind that—as is the case for other renewable resource types—the technical and theoretical resource totals for marine energy are much larger than the practical resource:

> *It is the practical resource that will ultimately determine the potential contribution of an [marine energy] 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. (National Research Council 2013)*

Industry leaders and researchers at national laboratories and universities within the marine energy sector have begun the work of site-specific analysis at many early-market sites.

The task of actually developing those plans or quantifying the practical resource in detail is challenging without commercial technologies. This is because regulators and other stakeholders need detailed technology and project plans to understand the risks and impacts to other ocean uses. Having said that, and in lieu of more detailed analysis, we simply note that a practical resource of just 10% of the estimated technical resource for the 50 states would equate to roughly 5.7% of the total 2019 U.S. electricity generation—enough to power 22-million homes. Assuming the capacity factor of these installations is between 30% and 70%, this would mean a total installed marine energy capacity between 40 GW and 90 GW.

Marine energy resources are predictable sources of renewable energy. They are distributed broadly across the world's oceans, along its coastlines, and throughout the world's rivers. As the demand for renewable energy technologies continues to grow, marine energy resources have the potential to contribute meaningfully to the U.S. and world energy supply.

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