Marine Hydrokinetic Energy Site Identification and Ranking Methodology Part II: Tidal Energy

Levi Kilcher, Robert Thresher, and
Heidi Tinnesand

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Technical Report
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October 2016

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Prepared under Task No. WA152001

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Abbreviations and Acronyms

DOE	U.S. Department of Energy
kW	kilowatts
kWh	kilowatt-hour
LCOE	levelized cost of energy
MHK	marine hydrokinetic
MW	megawatt
TPD	tidal power density

Executive Summary

Marine hydrokinetic energy is a promising and growing piece of the renewable energy sector that offers high predictability and additional energy sources for a diversified energy economy. This report investigates the market opportunities for tidal energy along the U.S. coastlines. It is part one of a two-part investigation into the United States' two largest marine hydrokinetic resources (wave and tidal).

Tidal energy technology is still an emerging form of renewable energy for which large-scale grid-connected project costs are currently poorly defined. Ideally, device designers would like to know the resource conditions at economical project sites so they can optimize device designs. On the other hand, project developers need detailed device cost data to identify sites where projects are economical. That is, device design and siting are, to some extent, a coupled problem. This work describes a methodology for identifying likely deployment locations based on a set of criteria that tidal energy experts in industry, academia, and national laboratories agree are likely to be important factors for all technology types.

The methodology is a multi-criteria decision analysis that uses six criteria to identify likely deployment locations:

- Resource density (tidal power density)
- Market size
- Energy price (an estimate of avoided energy cost in the market)
- Range to resource
- Shipping cost
- Water depth.

Data for each criterion were collected from a range of sources, including the National Renewable Energy Laboratory's MHK Atlas (http://maps.nrel.gov/mhk_atlas) and the U.S. Energy Information Administration (http://eia.gov).

This work groups the data for the six criterion into sites where tidal power density is >0.5 kilowatts (kW)/m^2. The definition of "sites" in this work is more specific than the "locales" defined in the companion wave study (Kilcher and Thresher 2016). This study is able to focus on sites because a) tidal energy density is more spatially localized compared to wave energy, which facilitates a more specific analysis, and b) there has been relatively less published work in identifying U.S. tidal energy sites, and so the specificity of this analysis adds unique information to our understanding. The scores are aggregated using a simple product method that includes a weighting factor for each criterion.

This work presents two weighting scenarios: a long-term scenario that does not include energy price (weighted zero) and a short-term scenario that does include energy price. The aggregated scores are then used to produce ranked-lists of likely deployment sites. Results from the short-term scenario indicate locations where tidal energy is likely to be deployed in the near term. The long-term scenario looks beyond the next two decades to a time when the industry has matured and the costs of tidal energy approach parity with other technologies. At that time energy price is expected to be a less-critical project siting criteria. In addition, there may be a higher priority placed on low-carbon electricity generation. In that scenario, the predictability of tidal energy is

likely to have significant value in terms of decreased grid-integration costs and increased resilience by diversification.

The majority of the U.S. tidal energy resource is found in the following regions: 1) the southern coastline of Alaska; 2) sections of the northeastern coast, especially Maine and Massachusetts; 3) Puget Sound, Washington. Top sites in these regions—the Western Passage in Maine, Tacoma Narrows in Washington, and Cook Inlet in Alaska—rank consistently in the top five for both the short-term and long-term scenarios. Outside of these regions, there are several sites—including San Francisco Bay, the Florida Keys, and the estuaries of many U.S. rivers—that may become economical in the long-term, especially if technology emerges that is capable of efficiently harnessing energy from low-velocity sites. In the short-term scenario, sites surrounding Nantucket Sound, Massachusetts (i.e., south of Cape Cod) are also particularly attractive.

The site ranking presented here should not be interpreted as a definitive description of the most economical sites for tidal energy generation. Several factors that will affect tidal project costs and siting have not been considered here—including regulatory constraints, conflicting uses, political support, seasonal resource variability, turbulence intensity, and distance to ports of varied capability—because consistent data are unavailable or technology-independent scoring could not be identified. Furthermore, the accuracy of the modeled resource data utilized here has been shown to under-predict the tidal power density and total power compared to measurements at several sites. We utilize the model data because it provides a consistent data source for the entire U.S. coastline. A more detailed investigation of the source of the model-measurement discrepancy is left for future work.

As the industry continues to mature and converge around a subset of device archetypes with well-defined costs, resource estimates become more accurate, and new data sources emerge, more precise investigations of project siting may dramatically change the site-ranking results. That is, these results should not be interpreted as an indication of a project site's potential economic viability. Instead, these results provide a high-level guide that points to, but does not definitively indicate, the regions where markets and resource are likely to support commercial tidal energy projects.

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1 Introduction

As electricity demand continues to grow and the impacts of climate change are realized, there is increasing awareness of the need for carbon-free renewable energy sources. Established renewables such as wind and solar have the potential to meet a large portion of the United States' energy demand, but at those scales they face technical challenges such as energy storage and grid integration, and societal challenges such as land use and environmental impact concerns. Wave and tidal energy (marine hydrokinetic, or MHK energy) do not have the same challenges because they are more predictable and located at sea, and are therefore well-positioned to provide a significant fraction of the nation's energy needs.

This report is the second in a two-part series on methods for identifying and ranking commercial MHK deployment locations. This document is focused on tidal energy site identification, and its companion focuses on wave energy site identification (Kilcher and Thresher 2016). Each of these reports utilizes publically available data for the U.S. coastline to provide a high-level assessment of the potential for MHK deployment in the United States.

1.1 Background

Tidal energy is currently at a critical middle stage of technology development. A respected body of literature exists that describes the essential physics, classifies design types, and quantifies the resource potential (Garrett and Cummins 2008; Haas et al. 2011; Khan et al. 2009). Several devices have performed full- and mid-scale prototype demonstrations that have supplied electricity to the power grid. In collaboration with regional organizations and universities, the U.S. Department of Energy (DOE) has established marine renewable energy centers to "facilitate the development of marine renewable energy technologies via research, education, and outreach." DOE asked its national laboratories to establish technological baselines, contribute to international standards, develop resource characterization methodologies, investigate environmental impacts, perform component tests, develop device simulation tools, estimate energy conversion costs, and identify cost-reduction pathways.

The next steps for tidal technology development are continued device refinement and development of commercial-scale arrays with capacities greater than 10 megawatts (MW). These larger arrays are expected to greatly reduce costs relative to demonstration projects and start the path toward cost parity with other sources of low-carbon generation through standardization, learning by doing, and economies of scale.

1.2 Approach

The objective of this work is to provide a consistent methodology for assessing tidal energy opportunities along the entire U.S. coastline. Across this domain, a wide range of factors contributes to project viability, including resource characteristics, market conditions, regulatory requirements, manufacturing capacity, ports availability, and operations and maintenance. The diverse mix of these factors, their complex relationships, and the evolving state of tidal energy technology add to the challenge of identifying the most likely deployment sites. It is useful to undertake this study for the purpose of long-term planning and strategic investment in the most viable sites.

This work focuses on identifying and ranking sites independent of the technology or site-specific details while still maintaining quantitative scoring criteria that produce meaningful rankings of tidal energy opportunities. It does not consider the permitting, alternate-use, or zoning considerations that may be important at a site, nor does it consider existing commercial tidal energy project development and permitting efforts. The intent is to facilitate discussion on tidal energy opportunities with stakeholders and provide context for more detailed site-specific investigations by project developers and other organizations. Throughout this analysis, considerable effort is made to consider the sites in a consistent, inclusive, and judicious manner. The methodology is designed to rank sites based on high-level technical and economic factors that are important to current and future tidal energy technology and project development. In general, the analysis is designed to favor sites with potential for larger projects as economies of scale are expected to be an important driver in the adoption of this technology. On the other hand, the scoring is intended to include sites with small markets that have highly favorable site conditions, which may be valuable as early commercial projects.

Toward this end, this work presents two sets of results: 1) a long-term scenario and 2) a short-term scenario. The short-term scenario includes the site's energy price as a scoring criterion. This is important in the short term because tidal energy is still relatively expensive compared to other types of generation, and therefore sites with higher energy prices will be more attractive to project developers. The long-term scenario does not include energy price. This is based on the expectation that tidal energy costs will approach parity with other forms of generation over the next ten to twenty years. In that case, energy price will become a less-critical factor in project siting. In addition, there may be a higher priority placed on low-carbon electricity generation. The short- and long-term scenarios, therefore, provide complimentary perspectives that identify market opportunities and suggest how those opportunities might evolve as the technology matures over the next decade.

2 Methodology and Data

This section provides a detailed description of the data and methods used in this report. All coastal states and U.S. territories are included in the analysis. The analysis is organized into "hot spot" sites, where tidal power density (TPD) is > 0.5 kilowatts (kW)/m^2 (Figure 1). These sites are typically locations where tidal flows accelerate through a narrow inlet or channel that connects two larger water bodies. The acceleration of the flow creates localized high velocities that are tidal energy "hot spots." The majority of the U.S. tidal energy resource is found in the following regions: 1) the southern coastline of Alaska; 2) sections of the northeastern coast, especially Maine and Massachusetts; 3) Puget Sound, Washington. There are also several sites scattered along the remainder of the U.S. east and west coasts, including the San Francisco Bay, the Florida Keys, and the estuaries of many U.S. rivers.

Hot spots were also identified in DOE's regional resource assessment (Haas et al. 2011). These "hot spots" were identified as sites where the average kinetic tidal power density is greater than 0.5 kW/m^2 (the same metric NREL used in this analysis), water depth is more than 5 m, and surface area is larger than 0.5 km^2. The list of sites in these new NREL reports are different, however, because the Haas et al. (2011) study was limited to the primary inlets of closed basins, while this work considers all sub-channels of a tidal basin (e.g., within Puget Sound). This modified approach is the result of different objectives: Haas et al. (2011) sought to estimate total available resource, and therefore consideration of sub-channels within a basin would have led to double-counting. This work, on the other hand, is designed to identify promising sites, and it therefore considers all possible locations within a region.

The methodology utilized to identify promising sites uses a subset of the criteria that might be used in a site-specific feasibility study (International Electrotechnical Commission 2015). A feasibility study, however, will often consider a wider range of criteria then used here (e.g., regulatory requirements, permitting requirements, interconnection requirements, political support, seafloor composition details, etc.). Many of these factors are difficult to quantify, or public data are not uniformly available to make consistent comparisons. The purpose of this work is to take a higher-level perspective that assists in identifying sites that should be considered for more detailed investigation.

The definition of "sites" in this work is more specific than the "locales" defined in the companion wave study (Kilcher and Thresher 2016). This study focuses on sites because a) tidal energy density is more spatially localized compared to wave energy, which facilitates a more specific analysis, and b) there has been relatively less published work in identifying U.S. tidal energy sites, so the specificity of this analysis adds unique information to our understanding.

Based on reviews of previous work, a search of publically available data, and a survey of industry experts, we selected the following list of criteria to estimate suitability for early deployment of marine energy technology:

- Resource density
- Market size
- Range to resource

- Water depth
- Shipping cost
- Energy price (short-term scenario only).

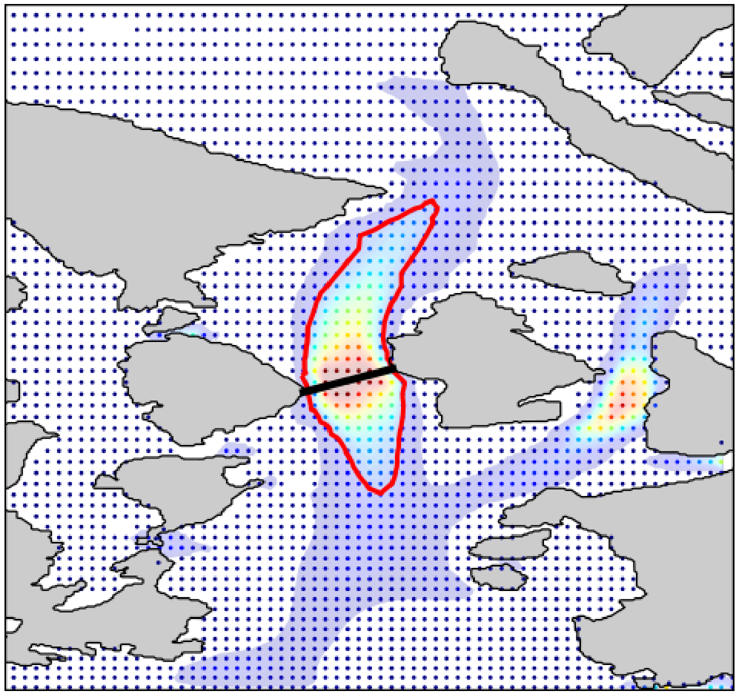

Figure 1. Map highlighting Rosario Strait, Washington, in Puget Sound.

Dots indicate grid points of the MHK Atlas dataset (Haas et al. 2011). Cool colors (blue) indicate low TPD and hot colors (red) high TPD. The red line indicates the region in Rosario Channel where TPD > $\mathbf{0.5}$ kW/m^2 (area = 27 km^2). The black line indicates the cross-channel transect, where $\boldsymbol{Q}_{\text{max}}$ = $\mathbf{153,000}$ m^3/s, $\boldsymbol{a} = \mathbf{0.9}$m, and $\boldsymbol{P} = \mathbf{420}$ MW.

We utilize a Multi-Criteria Decision Analysis framework to score each of these criteria, create a composite score, and generate rankings of tidal sites (Van Cleve et al. 2013; Wang et al. 2009). Resource density and market size criteria are indicators for the technical and commercial viability of a project. Higher resource density and larger markets are likely to be more attractive to project developers, and these criteria are therefore scored positively. The shipping cost, distance to resource, and water depth criteria are indicators for total project cost. Sites with larger costs are considered less attractive, and these criteria are therefore scored negatively.

Each of these metrics are scored on a scale from 0 to 10 and assigned a weight to set the relative importance of each criterion. In this work we combine these scores using a product method in which the composite score is computed as,

$$S = \prod_i s_i^{w_i} \quad . \qquad (1)$$

Where s_i and w_i are the scores and weights, respectively, for each of the criteria. Note that the total composite score for a site, S, is between 0 and 10 if the weights are normalized such that,

$\sum_i w_i = 1$ (Wang et al. 2009). The data and software tools (Python package and scripts) used to score and rank sites in this analysis are available for download from the MHK Data Repository (submission id 154).

These composite scores are used to rank sites in terms of their suitability for early tidal technology deployment. The remainder of this section details the data sources and scoring rationale for each of the six criteria s_i. The long-term scoring model does not include the site's market energy price as a scoring criterion. This is done based on the assumption that tidal energy technologies will eventually become cost-competitive with other renewables and traditional forms of generation. In that case, the market price of energy is believed to be a less important driver of deployment compared to the other factors considered in this long-term model. The short-term model takes energy price into consideration as an important early market factor. The results from each of these methodologies are presented in a later section.

2.1 Resource Density

TPD is the annual average energy flux at a point in the water column in the waterway's existing state (e.g. without the presence of turbines),

$$\mathrm{TPD} = \langle \frac{1}{2} \rho U^3 \rangle$$

Here ρ is the density of seawater (nominally 1020 kg/m^3), and U is the tidal current speed. The angle brackets denote an average over the year.

As turbines are added to a tidal channel, they will alter the state of the channel (most likely increasing the total drag), and therefore alter (most likely reduce) the total TPD of it (Garrett and Cummins 2005). For this reason, TPD cannot be used for detailed estimates of total available power or for detailed project feasibility or array design studies (International Electrotechnical Commission 2015). It is useful, however, for high-level comparisons of potential tidal project sites as an indication of the relative energetics of those sites, which is how it is utilized herein.

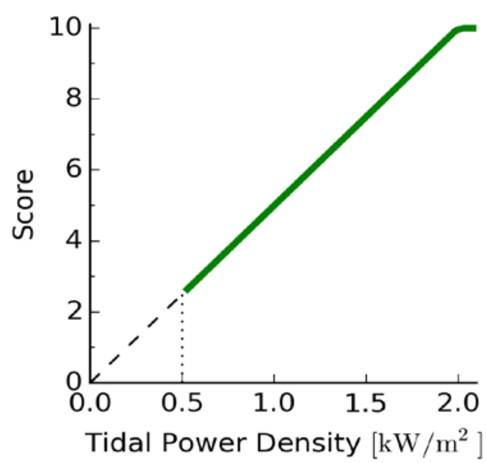

Figure 2. Resource scores for tidal energy

TPD data are taken from the DOE's regional resource assessment effort by Georgia Tech and Oak Ridge National Laboratory (Haas et al. 2011). The TPD estimates from these models are known to have significant discrepancies with measurements because of coarse model resolution and other physics that are unresolved by the models—such as turbulence. Despite these limitations, these models are used herein because they provide the most consistent TPD data for the entire U.S. coastline. As models are refined and new data emerge, it may be important to assess the implications to the results presented here.

The TPD values are scored linearly from 0 to 10 representing the range from 0 to 2 kW/m^2, above which all values are scored 10 (Figure 2). TPD values below 0.5 kW/m represent very weak sites and, as such, are excluded from the analysis. The authors selected a threshold value of 0.5 kW/m^2 based on prior work in this area and from industry feedback (Cleve et al. 2013; Haas et al. 2011). Industry input suggested that sites with energy densities below this value are unlikely to be economically viable. The upper value is set at 2 kW/m^2 because it is representative of the most energetic tidal sites in the United States and is the upper limit used by Van Cleve et al. (2013). This resource scoring function is agnostic to technology-specific details, emphasizes the value of a more energetic resource, and excludes sites with a very low resource.

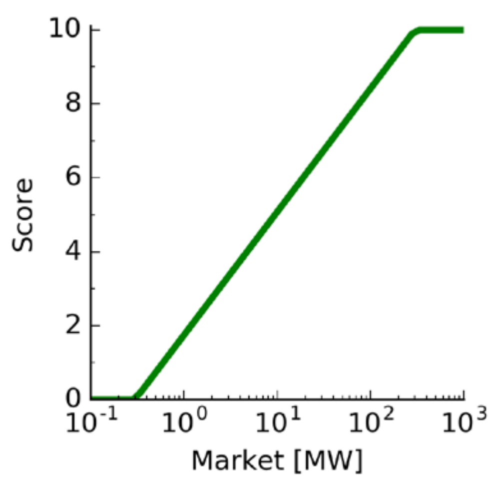

Figure 3. Market scores increase logarithmically from 300 kW to 300 MW.

2.2 Market Size

Tidal energy market size is the maximum amount of tidal energy that can be sold at a given site. This is limited by two site factors: 1) the maximum potential demand for tidal energy, and 2) the total tidal energy available. Therefore, market size is calculated as the smaller of the two quantities demand and total resource.

2.2.1 Demand

Site-specific estimates of maximum potential demand for tidal energy do not currently exist and depend on a range of highly uncertain economic and political factors. Instead, the current electrical load on the grid adjacent to the site is used as a *proxy* for maximum potential demand. This is based on the assumption that sites with larger electric grids will be capable of supporting larger tidal projects, which are attractive for economy of scale benefits and could lead to a reduction in the levelized cost of energy (LCOE).

This approach is reasonable because the uncertainty associated with using this proxy is small compared to the range of loads considered here. For example, a 600-kW rural Alaskan village is unlikely to suddenly create infrastructure that will generate demand for 50 MW of tidal generation capacity. Furthermore, the ranking is based on the relative attractiveness of U.S. MHK sites, and load is a reasonable proxy for relative demand of any economical energy source.

We compiled load data from the following sources:

- Rural Alaskan communities: Alaska Energy Authority's Power Cost Equalization Program report (Alaska Energy Authority 2014)
- All other U.S. states: U.S. Energy Information Administration (*Retail Sales of Electricity* 2013).

2.2.2 Total Tidal Resource

Total available tidal energy is estimated from data available in the MHK Atlas (Haas et al. 2011). At each site, the narrowest cross-channel transect was selected (Figure 1, thick black line), and the tidal energy flux through this transect was computed as:

$$P = \gamma \cdot \rho \cdot g \cdot a \cdot Q_{\max} \tag{1}$$

Where $\gamma = 0.22$ is a dimensionless constant, $\rho = 1024\text{kg/m}^3$ is the density of seawater, $g = 9.81\text{m/s}^2$ is gravity, a is the amplitude of the tidal water level constituent, and $Q_{\max}$ is the maximum tidal volume flux through the channel (Garrett and Cummins 2005, 2008; Haas et al. 2011). $Q_{\max}$ is estimated by integrating the component of the tidal velocity that is normal to the channel cross-section. Note that according to Equation (1), P is independent of the orientation and exact location of the channel cross-section.

Equation (1) was formulated to estimate total available tidal energy at inlets to closed basins, but it is not formulated for other geometries, such as straits between islands (e.g., Figure 1). In these geometries, the back-pressure generated by the tidal turbines can redirect some portion of the tidal volume-flux through parallel channels or around the island. Haas et al. (2011) have accounted for this by applying (1) to groups of channels that link the same basins. That approach, however, is insufficient for the purposes of this work—which is to compare specific channels—and does not account for sub-channels (and sub-basins) inside of a larger basin.

Furthermore, Equation (1) is based on the assumption that the tidal height difference between the two ends of a channel (i.e., the head through the channel) is unaffected by the flow through it. This will be true for large surface-area basins with large tidal-height forcing (compared to the volume that flows through the channel each tidal cycle) or basins that are fed by different channels. However, for small surface-area basins or basins fed by alternate channels (1) may under- or over-estimate the total available resource.

Succinct formulations, similar to (1), do not currently exist for arbitrary geometries. Therefore—having acknowledged the limitations of (1) and still seeing it as a useful estimate of total theoretical power—this work utilizes Equation (1) to estimate total available resource for all channel geometries. More accurate estimates of total available power on a per-site basis will require a deployment scenario analysis employing basin-scale numerical simulations, as detailed in the tidal power resource assessment technical specification (International Electrotechnical Commission 2015).

2.2.3 Market Size: Summary and Scoring

In summary, we compute the total available resource at each site and compare this to the potential demand (load) for tidal energy at that site. The smaller of the two values is taken as an estimate of market size.

Sites with larger markets are likely to be capable of supporting larger projects, which is highly attractive to tidal project developers. On the other hand, it is likely that larger grids will have lower contributions from these sources, as a fraction of their load, when compared to small power grids surrounded by abundant resource. To account for these factors and the range of market sizes considered here, we score market size logarithmically from 300 kW to 300 MW (Figure 3). This function captures the logarithmic distribution of the markets considered in this analysis and produces a scoring that is more sensitive for small markets (e.g., <10 MW) and less sensitive for the large markets that are all assumed to be capable of generating demand for tidal energy deployments.

The 300-kW threshold is assumed herein to be the minimum market size for tidal energy projects to be economical. This is based on the idea that several project development activities—such as permitting, operations, installation, and grid-integration—will have fixed minimum costs that cannot be recovered by very small tidal energy projects. While the 300-kW value is rather arbitrary, it is chosen as a balance between a) screening out very small markets that are unlikely to support tidal project development with existing technologies and b) including small, high energy-price markets that may serve as early adopters of these technologies.

2.3 Range

Range is the distance from each resource point to the nearest power grid feature (in kilometers). The range scores are chosen according to the following criteria: 1) Sites that are within 1 km of the transmission grid are assigned a maximum score of 10, and 2) From 1 to 20 km, scores decrease linearly to emphasize the importance of transmission costs to project viability. Resource estimates farther than 20 km from the grid are considered to have prohibitively high transmission costs and are therefore assigned a score of 0 and excluded from the analysis (Figure 4).

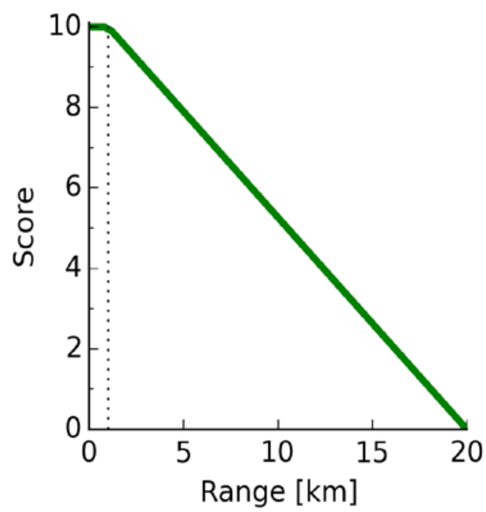

Figure 4. Scoring for distance between site and transmission substation (range)

2.4 Water Depth

Water depth (bathymetry) data were taken from the publically available National Oceanic and Atmospheric Administration Geophysical Data Center, which is a compilation of the U.S. National Ocean Service Hydrographic Database, the U.S. Geological Survey, the Monterey Bay Aquarium Research Institute, the U.S. Army Corps of Engineers, and various other academic institutions.

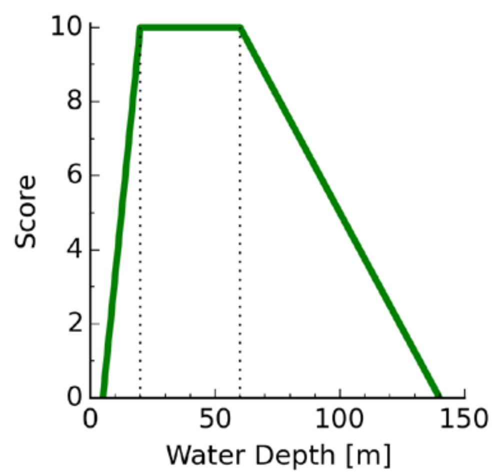

Figure 5. Water depth scores for tidal energy

Water-depth scores are taken from Van Cleve et al. (2013) and simplified into a piecewise linear model according to the following criteria:

- Sites shallower than 5 m are too shallow for inclusion in this analysis.
- Sites between 20 and 60 m are ideal for some type of tidal device (score: 10).
- Sites deeper than 150 m are too deep for economical tidal energy conversion.

Between 5 and 20 m, and 60 and 150 m, scores change linearly (Figure 5).

2.5 Shipping Cost

Shipping costs are estimated in units of U.S. dollars per metric-tonne using a simple shipping-distance model (USD/tonne). The model is designed to account for the challenge and added cost of developing, manufacturing or transporting, installing, operating, and maintaining a tidal energy facility at locations that are distant from the contiguous United States where the technology is expected to originate. The model calculates costs from Seattle, Washington, or Portland, Maine. The cost model used is,

$$C_s = r \cdot D_i + C_i$$

Where C_s is the total shipping cost to the site, C_i is the cost to ship to the regional "intermediate port," r is the "regional shipping rate" in USD per tonne per mile, and D_i is the distance between the intermediate port and the site in miles. Values for r and C_i (Table 1) for each region were estimated from publically available shipping cost data (SeaRates.com 2015). Coastal states within the contiguous 48 states are assumed to have low shipping costs.

Table 1. Origin Port, Intermediate Port, and Parameters of the Shipping Cost Model for Each Region

Region	Origin Port	Intermediate Port	r (USD/tonne/mile)	C_i (USD/tonne)
New England	Portland, ME	--	0.08	0
Alaska Southeast	Seattle, WA	--	0.10	0
Alaska	Seattle, WA	Anchorage, AK	0.12	84
Alaska Bering Sea	Seattle, WA	Dutch Harbor, AK	0.15	180

The shipping costs are given a maximum score for shipping costs below 60 USD/tonne (Figure 6). This value serves as an estimate of the intra-contiguous U.S. shipping costs that all projects will bear. That is, it accounts for the uncertainty in the intra-contiguous U.S. shipping costs that are considered low enough to receive high scores. Above 60 USD/tonne, the scores decrease linearly to account for the added costs associated with developing and operating these projects at remote locations. Shipping costs above 500 USD/tonne are considered prohibitively expensive and are assigned a score of zero.

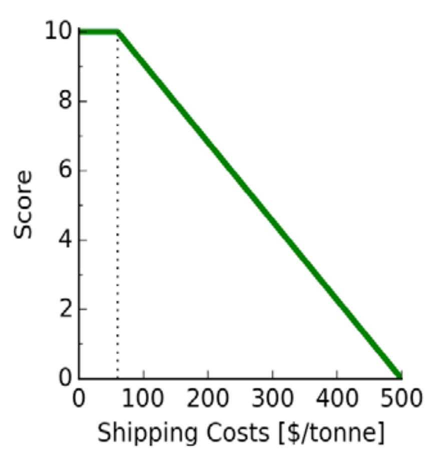

Figure 6. Shipping cost scores

2.6 Energy Price

Energy price is an estimate of the price a utility could pay a power producer for electricity in today's market. This is frequently conceptualized as the avoided cost of energy. Given existing infrastructure, avoided cost is the value of the next unit additional of electricity produced. It is therefore the maximum a utility could pay a power provider for electricity without subsidizing that electricity or raising rates. While this approach does not account for market growth or mechanisms that raise the value or increase demand for tidal energy (e.g., subsidies or renewable portfolio standards), it does provide a reasonable estimate of the value of tidal energy in the existing marketplace in the near future.

For small island nations and rural communities in Alaska, this work uses fuel cost per unit of energy (USD/kilowatt-hour, or kWh) as an estimate of the energy price. This is justified because fuel costs account for the vast majority of avoidable costs in these markets. In larger markets (continental United States and Hawaii), the industrial rate is used as a proxy for energy price. This is justified because industrial (i.e., bulk) rates are typically only minimally higher than avoided costs.

The markets considered here have a wide range of energy prices: from a few cents to more than $0.50 per kilowatt-hour. Energy price is scored linearly from a score of 0 at $0.00 up to 10 at a cost of $0.50/kWh (Figure 7). This linear increase captures the increasing attractiveness of a project as the price of electricity increases in the market. The upper bound is set to $0.50/kWh because costs above that are probably unsustainable (other renewables could enter the market at that cost, or the price is artificially high).

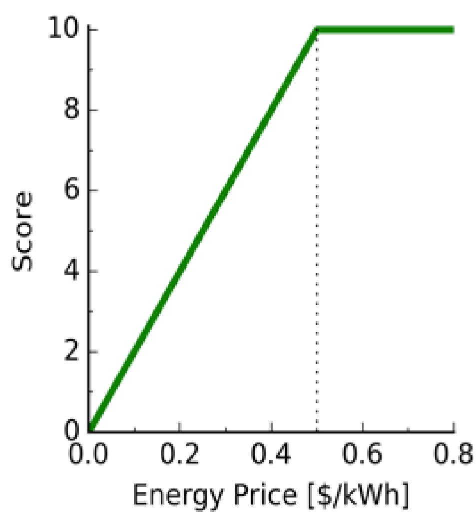

Figure 7. Energy cost scores

3 Results

This section presents the results of two analyses for identifying tidal "hot spots:" a long-term model that does not consider the current cost of electricity and a short-term model that does.

3.1 Long-Term Model

This model identifies 36 U.S. sites that have the load (>300 kW), TPD (>0.5 kW/m^2), area (>0.5 km^2), distance to transmission (<20 km), and depth (>5 m, <140 m) characteristics to be included in this analysis. The list of sites is distinct from the regional resource assessment (Haas et al. 2011) for two reasons. First, the introduction of additional screening criteria—distance to transmission, depth, and load—significantly reduces the number of sites. Second, the regional study focuses on estimating *total tidal energy* and therefore treats a complex tidal basin as a single resource point in order to avoid "double counting" (e.g., Admiralty Inlet is the only point in Puget Sound). This work, on the other hand, focuses on identifying *sites* that have favorable conditions for MHK development, and therefore includes more than one site at many of the "hot spots" of tidal energy, thereby extending the list of sites considered.

Energy price is excluded (i.e., assigned a weight of zero) from the long-term model for two reasons. First, as the technology matures in the next decade, tidal energy costs will approach parity with other renewables. In that case, the importance of energy price in determining site attractiveness decreases relative to market size and resource details. Second, energy price is likely to fluctuate considerably over the next several decades. In particular, as markets evolve, renewable portfolio standards approach deadlines, and other incentives emerge, the energy price landscape for tidal energy may change dramatically. In this model, the other five scoring criteria are assigned a weight of 1/5.

The winnowing of sites by the screening criteria reduces the number of sites much more than the "site focus" adds to it, so the total number of sites considered here (36) is much smaller than that identified in the regional assessment (>200). Many sites, especially on the East Coast, are screened due to shallow water depth (<10 m). Several more sites—mostly in Alaska—are screened because they are very far from transmission infrastructure (>20 km). While the reduction in number of sites may be dramatic, many of the most energetic sites—such as Cook Inlet and those in Puget Sound and Maine—are retained here. Furthermore, identifying a short list of the most viable sites is intended to help DOE and the tidal industry focus resources so the technology can mature more rapidly and, as the technology matures, expand its market to sites with less ideal characteristics.

The Western Passage between Eastport, Maine, and Deer Island, New Brunswick, is the top-ranking site in this analysis. This site has a very high TPD of nearly 3 kW/m^2, a market large enough to consume all 190 MW that the resource may be capable of yielding, and a short transmission distance of about 1 km. The water depth at this site is also ideal for existing tidal energy technologies. The second- and third-ranking sites, Tacoma Narrows and Rosario Strait, are both in Puget Sound, Washington. These sites also have high TPD, markets of several hundred megawatts, nearby grid infrastructure, and ideal water depths. The top-three sites are all in the contiguous United States and therefore have low shipping costs.

The fourth site is Cook Inlet, Alaska, which Haas et al. (2011) showed is the largest tidal energy resource in the country. This is the only tidal site in this country with a market greater than 100 MW that is limited by demand. A project in Cook Inlet could theoretically power the entire Railbelt power grid (the primary grid that powers Anchorage, Fairbanks, and Alaska's south-central region). The highest energy density sites in Cook Inlet—offshore of Nikiski, Alaska—are only a few kilometers from substations on that grid.

The next two sites, Bellingham Channel and San Juan Channel, are in Puget Sound and have good TPD (approximately 2 kW/m^2) but have smaller total tidal resource and are farther from the grid than the earlier mentioned Puget Sound sites. The next two sites are both in Massachusetts adjacent to Martha's Vineyard: Vineyard Sound to the north and Muskeget Channel to the east of the island. Vineyard Sound is nearer to transmission features, while Muskeget Channel has somewhat higher TPD. Portsmouth Harbor on the border of Maine and New Hampshire is another viable tidal energy site, though the water depth is small and the resource is limited to less than 20 MW.

Back in Puget Sound, at Friday Harbor the strait between San Juan Island and Shaw Island rounds out the top ten sites with a large total resource but somewhat lower TPD (<1 kW/m^2). Between Kodiak Island and Whale Island, Alaska, is a very energetic site with a TPD >3.5 kW/m^2. Power generated at this site could be delivered to the Kodiak power grid via the community of Port Lions, which is 9 km from the site. Back in Puget Sound, Admiralty Inlet has a massive total resource of 720 MW. The TPD estimate of 0.9 kW/m^2 from the regional assessment is much lower than the >2.5 kW/m^2 estimate from real measurements at this site (Thomson et al. 2012).

The mouth of San Francisco Bay ranks 13th and is the highest-ranking West Coast site outside of Puget Sound. It does not rank higher primarily because it possesses a modest TPD of 0.75 kW/m^2. The same is true for the west entrance to Long Island Sound— aka "The Race"—where tidal velocities are modest compared to higher-ranking sites. Spieden Channel and Dana Passage in Puget Sound rank 15th and 16th, respectively. They both have a noteworthy TPD, large total resource (>40 MW), but large distance to transmission. Dana Passage and Rich Passage (18th) are both rather shallow.

The mouth of St. Mary's River (17th) at the border of Georgia and Florida has a modest TPD and a limited total resource of 13 MW. It is the highest-ranking site in the southern United States. The mouth of the Columbia River (19th) at the border of Oregon and Washington has a decent TPD of 1.7 kW/m^2. The eastern entrance to Nantucket Sound (20th), north of Nantucket Island, has locations where TPD is 2 kW/m^2. Woods Hole Passage (21st) has low TPD and a small total resource of 3.2 MW. The remaining sites all have one or more of the following characteristics: a) low TPD (<1 kW/m^2), b) small markets (<12 MW), c) very shallow (<15 m). The lowest-scoring sites are very far from the grid they would power, with a range that approaches 20 km.

Table 2. Ranking of Tidal Energy Sites for the Long-Term Scoring Model (Each Category Weighted Equally).

Darker greens indicate higher scores in each category. “L” and “R” in the market column indicate whether the site is primarily load or resource limited. Each scoring criterion is weighted equally (1/5) to compute the total score.

		State	Lat	Lon	Resource [kW/m^2]	Market [MW]		Range [km]	Shipping [$/ton]	Depth [m]	Score
1	Western Passage	ME	44.92	-66.99	3.0	190	R	1.1	0	35	9.8
2	Tacoma Narrows	WA	47.28	-122.55	2.0	210	R	1.4	0	33	9.8
3	Rosario Strait	WA	48.58	-122.75	2.2	420	R	3.5	0	50	9.7
4	Cook Inlet	AK	60.79	-151.26	2.1	500	L	2.5	91	41	9.7
5	Bellingham Channel	WA	48.56	-122.67	2.0	130	R	4.0	0	24	9.4
6	San Juan Channel	WA	48.46	-122.95	2.0	160	R	7.0	0	56	9.1
7	Vineyard Sound	MA	41.48	-70.64	1.7	84	R	5.1	0	23	8.8
8	Muskeget Channel	MA	41.35	-70.37	2.4	89	R	8.3	0	23	8.7
9	Portsmouth Harbor	ME,NH	43.08	-70.75	1.7	18	R	1.1	0	17	8.4
10	Friday Harbor	WA	48.54	-122.98	1.0	170	R	3.5	0	48	8.3
11	Admiralty Inlet	WA	48.14	-122.70	0.9	720	R	6.6	0	48	7.9
12	Kodiak	AK	57.79	-152.41	3.6	16	L	9.3	114	27	7.8
13	San Francisco Bay	CA	37.82	-122.48	0.7	170	R	4.8	0	32	7.7
14	Long Island Sound	NY	41.22	-72.07	0.7	250	R	5.7	0	22	7.7
15	Spieden Channel	WA	48.63	-123.12	1.4	160	R	12.7	0	30	7.5
16	Dana Passage	WA	47.17	-122.86	1.9	47	R	10.6	0	13	7.2
17	St. Mary's River	GA,FL	30.71	-81.45	0.8	13	R	3.1	0	18	7.0
18	Columbia River	OR,WA	46.25	-124.02	1.8	80	R	13.0	0	14	6.9
19	Rich Passage	WA	47.59	-122.56	2.0	16	R	3.8	0	10	6.8
20	Nantucket Sound	MA	41.51	-69.97	2.0	260	R	17.4	0	20	6.6
21	Cobscook Falls	ME	44.88	-67.13	1.1	13	R	7.3	0	11	5.9
22	Coos Bay	OR	43.35	-124.34	1.4	9.2	R	3.0	0	8	5.8
23	New Channel	WA	48.66	-123.14	0.8	100	R	16.4	0	33	5.7
24	Woods Hole Passage	MA	41.52	-70.68	0.6	3.2	R	7.2	0	18	5.7
25	Hatteras Inlet	NC	35.19	-75.76	1.4	6.2	R	5.8	0	9	5.6
26	Key West	FL	24.56	-81.83	0.8	14	R	2.4	0	9	5.5
27	Seven Mile Bridge	FL	24.70	-81.15	0.9	27	R	4.5	0	8	5.4
28	Guemes Channel	WA	48.52	-122.62	1.4	16	R	1.5	0	7	5.4
29	Quicks Hole	MA	41.44	-70.84	1.2	11	R	15.9	0	14	5.3
30	Dillingham	AK	59.04	-158.46	1.4	2.1	L	6.6	250	12	5.2
31	Spanish Harbors	FL	24.65	-81.29	0.7	7.9	R	6.1	0	9	5.0
32	Turtle River	GA	30.98	-81.52	0.5	10	R	4.8	0	8	4.7
33	East River	NY	40.78	-73.94	1.0	7.5	R	1.3	0	7	4.7
34	Ocracoke Inlet	NC	35.07	-76.02	0.7	7.5	R	11.4	0	8	4.3
35	Craig	AK	55.48	-133.15	1.7	1.3	L	19.0	71	14	3.5
36	Charlotte Harbor	FL	26.71	-82.26	1.0	8.7	R	19.6	0	13	3.0

3.2 Short-Term Model

The short-term model adds the energy price scoring criterion. In this model, all six criteria described in the methodology section are weighted equally (1/6). Tidal energy technology is relatively new, and estimates of its costs are higher compared to other renewable and conventional generation sources. At the present time, the LCOE of tidal technologies is high compared to conventional generation sources and mature renewables such as wind and solar. Throughout the tidal energy industry and the DOE, there is broad agreement that accelerated deployment is critical to generating the knowledge that is needed to engineer a new generation of low-cost technologies. This strategy follows from experience in the early years of the wind energy industry (1970s and 1980s), in which aggressive deployment in locations with favorable market conditions led to technological breakthroughs that lowered LCOE and thereby expanded the marketability of wind energy.

To inform a similar trajectory for tidal energy, the short-term model includes energy price as a scoring criterion to identify locations where tidal energy is more likely to compete with existing generation sources over the next 10 to 20 years.

Including energy cost as a scoring criterion produces changes in site ranking (Table 3). Relative to the ranking in Table 2, the sites in Puget Sound moved down in comparison to other top-ranking sites because Washington has relatively low energy costs. From this perspective, the Western Passage of northeastern Maine and Cook Inlet, Alaska, are definitively top-ranking sites, with markets of several hundred megawatts and relatively high energy costs. Note also that several small Alaskan sites rose dramatically in the rankings due to their very high energy costs. Kodiak, Alaska, is a particularly attractive small-market site. It has an energetic resource, energy costs of $0.18/kWh, and a transmission distance of approximately 9.3 km. More work is needed to identify whether local market opportunities create sufficient demand elasticity to attract a project developer. Similar investigations may also be worthwhile for other small Alaskan communities.

It is difficult to determine where the first economical tidal energy project will be installed; the top 20 or so sites in Table 3 are all potentially viable. Ultimately, the installation location will depend heavily on factors that are not considered in this analysis, including technology type, permitting barriers, local leadership, and stakeholder support. This analysis is meant to provide a broad context for discussing these issues and to point to the regions worth considering. More work is needed in each of these regions to better identify deployment barriers, refine resource estimates, and provide project design tools. It may be valuable to utilize small, high-cost markets to demonstrate success and generate knowledge. These successes will serve as stepping stones to larger-scale markets, including the U.S. West Coast.

Table 3. Ranking of Tidal Energy Sites for the Short-term Scoring Model (Each Category Weighted Equally).

Table colors are the same as in Table 2. Each scoring criterion is weighted equally (1/6) to compute the total score. The right column indicates the rank change (blue: up, red: down) relative to the long-term model (Table 2).

		State	Lat	Lon	Resource [kW/m^2]	Market [MW]	Energy Cost [$/kWh]	Range [km]	Shipping [$/ton]	Depth [m]	Score	Rank Change
1	Cook Inlet	AK	60.79	-151.26	2.1	500 L	0.16	2.5	91	41	8.0	3
2	Western Passage	ME	44.92	-66.99	3.0	190 R	0.14	1.1	0	35	8.0	-1
3	Vineyard Sound	MA	41.48	-70.64	1.7	84 R	0.16	5.1	0	23	7.4	4
4	Muskeget Channel	MA	41.35	-70.37	2.4	89 R	0.16	8.3	0	23	7.4	4
5	Tacoma Narrows	WA	47.28	-122.55	2.0	210 R	0.09	1.4	0	33	7.4	-3
6	Rosario Strait	WA	48.58	-122.75	2.2	420 R	0.09	3.5	0	50	7.3	-3
7	Bellingham Channel	WA	48.56	-122.67	2.0	130 R	0.09	4.0	0	24	7.1	-2
8	Portsmouth Harbor	ME,NH	43.08	-70.75	1.7	18 R	0.15	1.1	0	17	7.1	1
9	San Juan Channel	WA	48.46	-122.95	2.0	160 R	0.09	7.0	0	56	6.9	-3
10	Kodiak	AK	57.79	-152.41	3.6	16 L	0.18	9.3	114	27	6.8	2
11	Long Island Sound	NY	41.22	-72.07	0.7	250 R	0.19	5.7	0	22	6.8	3
12	San Francisco Bay	CA	37.82	-122.48	0.7	170 R	0.16	4.8	0	32	6.7	1
13	Friday Harbor	WA	48.54	-122.98	1.0	170 R	0.09	3.5	0	48	6.4	-3
14	Admiralty Inlet	WA	48.14	-122.70	0.9	720 R	0.09	6.6	0	48	6.2	-3
15	Spieden Channel	WA	48.63	-123.12	1.4	160 R	0.09	12.7	0	30	5.9	0
16	Nantucket Sound	MA	41.51	-69.97	2.0	260 R	0.16	17.4	0	20	5.9	4
17	St. Mary's River	GA,FL	30.71	-81.45	0.8	13 R	0.11	3.1	0	18	5.8	0
18	Dana Passage	WA	47.17	-122.86	1.9	47 R	0.09	10.6	0	13	5.7	-2
19	Columbia River	OR,WA	46.25	-124.02	1.8	80 R	0.09	13.0	0	14	5.6	-1
20	Rich Passage	WA	47.59	-122.56	2.0	16 R	0.09	3.8	0	10	5.4	-1
21	Cobscook Falls	ME	44.88	-67.13	1.1	13 R	0.14	7.3	0	11	5.2	0
22	Dillingham	AK	59.04	-158.46	1.4	2.1 L	0.27	6.6	250	12	5.2	8
23	Woods Hole Passage	MA	41.52	-70.68	0.6	3.2 R	0.16	7.2	0	18	5.2	1
24	Coos Bay	OR	43.35	-124.34	1.4	9.2 R	0.10	3.0	0	8	4.9	-2
25	Quicks Hole	MA	41.44	-70.84	1.2	11 R	0.16	15.9	0	14	4.8	4
26	Hatteras Inlet	NC	35.19	-75.76	1.4	6.2 R	0.11	5.8	0	9	4.8	-1
27	Key West	FL	24.56	-81.83	0.8	14 R	0.11	2.4	0	9	4.7	-1
28	New Channel	WA	48.66	-123.14	0.8	100 R	0.09	16.4	0	33	4.7	-5
29	Seven Mile Bridge	FL	24.70	-81.15	0.9	27 R	0.11	4.5	0	8	4.7	-2
30	East River	NY	40.78	-73.94	1.0	7.5 R	0.19	1.3	0	7	4.5	3
31	Guemes Channel	WA	48.52	-122.62	1.4	16 R	0.09	1.5	0	7	4.5	-3
32	Spanish Harbors	FL	24.65	-81.29	0.7	7.9 R	0.11	6.1	0	9	4.4	-1
33	Turtle River	GA	30.98	-81.52	0.5	10 R	0.11	4.8	0	8	4.2	-1
34	Ocracoke Inlet	NC	35.07	-76.02	0.7	7.5 R	0.11	11.4	0	8	3.8	0
35	Craig	AK	55.48	-133.15	1.7	1.3 L	0.07	19.0	71	14	3.0	0
36	Charlotte Harbor	FL	26.71	-82.26	1.0	8.7 R	0.11	19.6	0	13	2.9	0

4 Discussion

Ideally, the task of identifying and ranking viable tidal energy sites would combine detailed tidal energy project cost data with site data and market forecasts to quantify the economic value of potential projects. However, the tidal energy industry is still emerging, and most of the existing cost data are for prototypes, the data for which have very little commercial-scale relevance. Furthermore, as renewable portfolio standard deadlines approach, other incentives are introduced, and energy markets evolve in general, the economics of tidal energy will change on regional and sub-regional scales.

In the context of these uncertainties, this work proposes a methodology for assessing project viability in terms of scoring functions that capture many of the major factors that experts have identified to be important to tidal energy project development. Higher scores suggest higher project viability. The scoring functions, weighting, and aggregation method are designed to emphasize site-identification criteria that are important to all device designs. Some factors that many experts believe to be important— such as turbulence intensity, permitting requirements, conflicting-use concerns, and distance to ports—are not included in this analysis because consistent data are unavailable or technology-agnostic scoring could not be identified.

Given the limitations of existing data, the results presented here are not definitive (Tables 2 and 3). Adding criteria, changing the weightings, or altering the scoring functions will change the results. The East River, for example, will rank considerably higher if the 'range' weighting were increased and a permitting criteria were included. As markets evolve and new data become available, it will be valuable to refine this analysis toward a net-present-value or LCOE analysis. In the meantime, these results do provide a valuable guide to where tidal energy development is likely to take place in the United States. Given the importance of the criteria identified herein, it is very unlikely that reasonable changes to the methodology will produce a dramatic re-ordering of the results. The remainder of this section describes regional opportunities and challenges in further detail.

4.1 Puget Sound

The narrow, branching channels of Puget Sound, Washington, are a wealth of tidal energy "hot spots," most of which have the benefit of being near the transmission infrastructure that powers the greater Seattle area. Many of these sites also have ideal depths for tidal energy deployment (20 to 60 m). A significant challenge in this area, however, is the low cost of energy that is largely provided by hydroelectricity along the Columbia River. This was made apparent when the Snohomish Public Utility District halted the tidal energy project it had been pursuing just 6 months after the Federal Energy Regulatory Commission issued a pilot project license. The project was halted due to the high cost of the pilot project. As costs of tidal technology continue to drop, it will be interesting to see whether tidal technology can be justified in this region.

4.2 Alaska

Alaska possesses more than 90% of the nation's total tidal energy resource (Haas et al. 2011), and the constriction between the east and west foreland of Cook Inlet is the largest tidal resource in the country. This site also has the distinct advantage of being directly adjacent to the state's primary power grid, which has an average generation of roughly 600 MW. Alaska also has relatively high energy costs (see Table 3). These factors make Cook Inlet a highly attractive site for tidal energy development in both the short and long term. This location is also the site of significant oil and gas development, indicating that there is industrial infrastructure and local ocean engineering knowledge to support tidal technology deployment. As oil and gas production continues to decline here, rising energy prices may make tidal energy even more attractive. Because many of the rivers feeding into Cook Inlet are glacial, the impact of glacial silt on bearing components is a concern for tidal projects there. Recent research at the University of Alaska Anchorage indicates that advanced bearing and seal technologies could help to reduce this risk (Bromaghin et al. 2014). This and other challenges of the Alaskan environment will need further investigation, but Cook Inlet is a world-class tidal energy site worthy of continued exploration.

The remainder of Alaska's tidal energy resource is located in remote parts of the state, where it is "stranded" from grid infrastructure and consumers who could utilize the power (Johnson et al. 2012). If technologies are identified that can economically deliver this power to market, these resources may one day be utilized for human productivity. Until then, there are a few small towns and communities in Alaska that could benefit from development of the tidal energy resources nearby; most notable are Port Lions, False Pass, Akutan, and Atka. These sites all have TPD greater than 1.5 kW/m^2. False Pass, with the lowest TPD in the group, has been measured to have much larger TPD, >3 kW/m^2. Measurements at the other sites are needed to refine their TPD estimates. The remaining Alaskan tidal sites are either very shallow (Dillingham) or very far from transmission infrastructure (Craig, Gustavus, Adak, Hydaburg).

4.3 Northeastern United States

In the northeastern United States, Maine and Massachusetts possess the best opportunities for tidal energy. The Western Passage between Maine and New Brunswick is the highest-ranking site in the long-term analysis, with 190 MW of available power. This location presents an opportunity for international collaboration with Canada. Most of the power at this site would probably be utilized in Maine because there is more immediate infrastructure on that side of the border. The Massachusetts sites, Vineyard Sound and Muskeget Channel, have significant markets (>160 MW combined), and the relatively high energy prices in this area may be capable of supporting early MHK technology (see Table 3). Furthermore, tidal energy projects may find significant public support in this region because they provide renewable energy from infrastructure that is out of sight and below the sea surface (as opposed to offshore wind).

"The Race" of Long Island Sound has a large total resource, but it is unclear at this early stage whether the relatively low energy density of 0.7 kW/m^2 is high enough to be economical. As more tidal projects are developed and the economics of tidal energy are better understood, these kinds of low-energy-density sites may become viable, especially if tidal devices are designed for these conditions. This kind of technological development would certainly expand the tidal energy market.

Other sites in the northeastern United States, including Cobscook Falls, Portsmouth Harbor, Woods Hole Passage, and the East River of New York, are attractive locations with smaller total resource. However, these sites occupy only a few grid points in the underlying data, and further investigation—including more detailed modeling and direct measurements—may increase their total resource estimates. Direct measurements in the East River, for example, suggest that data in the regional-level resource assessment underestimates the energy density by a factor of 10 (Gunawan et al. 2014; Haas et al. 2011). The regional-scale models were designed to estimate total resource for the U.S. coastline, but these results suggest that more work is needed to quantify the resource at the small-area, highly-energetic “hot spots” of tidal energy. Even in Admiralty Inlet, where the regional model has several hundred grid points, that model under-predicted resource density by at least a factor of 3 (Thomson et al. 2012). These results indicate that higher-fidelity models and real measurements are needed to improve the accuracy of the U.S. tidal energy resource estimate.

4.4 U.S. West Coast

The largest tidal energy site on the U.S. West Coast south of Puget Sound is San Francisco Bay. This is another example of a site with relatively low TPD. There are 170 MW of power available here, but it remains to be seen whether this type of low-TPD resource can be economically converted to electricity. The Columbia River has much higher energy density and 80 MW of available power, but it is somewhat far from transmission and is likely to have depth and permitting limitations as the channel is actively dredged for shipping purposes.

5 Conclusions

Tidal energy is concentrated at channels and straits where tidal flows are constricted. The majority of the United States' tidal energy resource is located in a handful of regions where complex coastlines create the constrictions that focus energy in the tides, most notably in New England, Puget Sound, and Alaska. This work builds on the national resource assessment of Haas et al. (2011) to establish a methodology for identifying and ranking sites based on site characteristics that are important to project development. This methodology is used to identify a shortlist of the most promising tidal energy sites in the United States.

The Western Passage between Eastport and New Brunswick, Maine; several sites in Puget Sound; Cook Inlet, Alaska; and straits adjacent to Martha's Vineyard, Massachusetts, are all top-tier tidal energy sites that could produce well over a gigawatt of power. Several other sites scattered along the East and West Coasts of the United States also have significant total resource, but many of these require either a) low-energy-density technology, or b) significant new transmission infrastructure (>15 km) to deliver the power to market.

The existing national tidal energy resource assessment did well to establish a first estimate of total resource potential and identify regional tidal energy "hot spots" (Haas et al. 2011). However, TPD measurements at several tidal energy sites are consistently higher—by a factor of 2 or more—than those in the national assessment. This suggests that a) the tidal resource density and total power available at several other sites (including those in Table 2) are likely to be biased low, and b) state, regional, and national totals are likely to be biased low. The East River (New York) and Admiralty Inlet (Washington) are two locations where regional resource models have been shown to be dramatically underestimate the total compared to measurements. Due to these discrepancies, the estimates of resource density and market size (especially for resource-limited markets) should not be interpreted as definitive estimates. Developers interested in developing specific project sites should generate their own estimates of a site's market opportunity according to IEC technical specifications, rather than relying on the data used here (International Electrotechnical Commission 2015).

Improving the accuracy of existing regional resource totals would require refined numerical models that support simulation of tidal energy extraction to account for the "back pressure" effect so that reliable estimates of total resource can be calculated for arbitrary geometries. Many of the "hot spots" identified here have existing measurements that could be utilized to validate the refined models. Sites that do not have sufficient data for model validation may require new measurements. The site ranking presented here (Tables 2 and 3) could be used to help prioritize these measurement activities. As models at an increasing number of sites are refined, it will be possible to revise estimates of national totals. These revisions may reorder the site-ranking results presented in Section 3.

Several U.S. and international companies are beginning to deploy grid-connected tidal energy projects. This report is designed to help identify the locations that are most likely for commercial development of tidal energy over the next 10 to 20 years. While the U.S. market for tidal energy is often seen as relatively limited compared to established renewables and wave energy, its predictability offers significant value. As tidal energy technology continues to become more economical, our understanding of the U.S. resource is refined, and storage technologies become available, the tidal energy market could expand significantly from that which is identified here.

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