Deployment Effects of Marine Renewable Energy Technologies

Tidal Energy Scenarios

Prepared by RE Vision Consulting, LLC on behalf of the U.S. Department of Energy

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1. Introduction

Given proper care in siting, design, deployment, operation and maintenance, marine and hydrokinetic technologies could become one of the more environmentally benign sources of electricity generation. In order to accelerate the adoption of these emerging hydrokinetic and marine energy technologies, navigational and environmental concerns must be identified and addressed. All developing hydrokinetic projects involve a wide variety of stakeholders. One of the key issues that site developers face as they engage with this range of stakeholders is that many of the possible conflicts (e.g., shipping and fishing) and environmental issues are not well-understood, due to a lack of technical certainty.

In September 2008, re vision consulting, LLC was selected by the Department of Energy (DoE) to apply a scenario-based approach to the emerging wave and tidal technology sectors in order to evaluate the impact of these technologies on the marine environment and potentially conflicting uses.

The project's scope of work includes the establishment of baseline scenarios for wave and tidal power conversion at potential future deployment sites. The scenarios will capture variations in technical approaches and deployment scales to properly identify and characterize environmental impacts and navigational effects. The goal of the project is to provide all stakeholders with an improved understanding of the potential effects of these emerging technologies and focus all stakeholders onto the critical issues that need to be addressed.

This groundwork will also help in streamlining siting and associated permitting processes, which are considered key hurdles for the industry's development in the U.S. today. Re vision is coordinating its efforts with two other project teams funded by DoE which are focused on regulatory and navigational issues. The results of this study are structured into three reports:

1. Wave power scenario description
2. Tidal power scenario description
3. Framework for Identifying Key Environmental Concerns

This is the second report in the sequence and describes the results of conceptual feasibility studies of tidal power plants deployed in Tacoma Narrows, Washington. The Narrows contain many of the same competing stakeholder interactions identified at other tidal power sites and serves as a representative case study.

Tidal power remains at an early stage of development. As such, a wide range of different technologies are being pursued by different manufacturers. In order to properly characterize impacts, it is useful to characterize the range of technologies that could be deployed at the site of interest. An industry survey informs the process of selecting representative tidal power devices. The selection criteria is that such devices are at an advanced stage of development to reduce technical uncertainties and that enough data are available from the manufacturers to inform the conceptual design process of this study. Further, an attempt is made to cover the range of different technologies under development to capture variations in potential environmental effects. Table 1.1 summarizes the selected tidal power technologies. A number of other developers are also at an advanced stage of development including Verdant Power, which has demonstrated an array of turbines in the East River of New York, Clean Current, which has demonstrated a device off Race Rocks, BC, and OpenHydro, which has demonstrated a device at the European Marine Energy Test Center and is on the verge of deploying a larger device in the Bay of Fundy. MCT demonstrated their device both at Devon (UK) and Strangford Narrows (Northern Ireland). Furthermore OpenHydro, CleanCurrent, and MCT are the three devices being installed at the Minas Passage (Canada).

Table 1.1 – Selected tidal power technologies

	Marine Current Turbines SeaGen	**Lunar Energy RTT**	**SMD TidEl**
Rotor	Dual rotor, horizontal axis: variable pitch aerofoil	Horizontal axis: fixed pitch, symmetric aerofoil Ducted	Dual rotor, horizontal axis: fixed pitch, asymmetric aerofoil
Power train	Gearbox speed increaser	Hydraulic	Gearbox speed increaser
Mooring	Rigid: pile	Rigid: tubular truss	Compliant: cable
Foundation	Penetrating pile	Gravity base	Gravity base

Environmental effects will largely scale with the size of tidal power development. In many cases, the effects of a single device may not be measurable, while larger scale device arrays may have cumulative impacts that differ significantly from smaller scale deployments. In order to characterize these effects, scenarios are established at three deployment scales which nominally represent (1) a small pilot deployment, (2) an early, small commercial deployment, and (3) a large commercial scale plant. For the three technologies and scales at the selected site, this results in a total of nine deployment scenarios outlined in the report.

It is important to understand that for the purpose of this study was to establish baseline scenarios based on device data that was provided by the manufacturer. In reality, devices will need to be optimized to specific site conditions. This may include making quite dramatic design changes such as using a different foundation concept. No such optimization has been carried out and this report should therefore not be used to compare techno-economic parameters such as performance.

The report is structured into three sections. Section 2 describes the physical and biological environment of Tacoma Narrows, including the hydrokinetic resource and possible far-field environmental effects resulting from kinetic power conversion. Section 3 provides an overview of tidal power devices and details about each of the three devices being evaluated, including operational procedures for installation, maintenance, and decommissioning. Section 4 describes the nine scenarios under consideration.

For consistency, mostly metric units are used in this report. We realize that different stakeholders may be used to different units and not be familiar with the metric system. Some of the often units and conversion factors are included below for reference.

Linear

1 meter(m) = 3.28feet (ft)

1 kilometer = 0.62 miles (mi) = 0.54 nautical miles (Nm)

Area

1 square meter (m^2) = 10.76 square feet (sqft)

1 square kilometer (km^2)= 0.386 square miles (mi^2) = 0.292 square nautical miles (Nm^2) = 247 acres

Volume

1 cubic meter (m^3) = 35.3 cubic feet (ft^3) = 264 Gallons

2. Site Description

Tacoma Narrows is a constricted channel connecting the deep, Main Basin of Puget Sound to the inlets and smaller basins of the South Sound, as shown in Figure 2.1 and Figure 2.2. The passage is approximately 9 km long and 1.5 km wide. Water depth averages 40m, though portions of the channel are as deep as 80m.

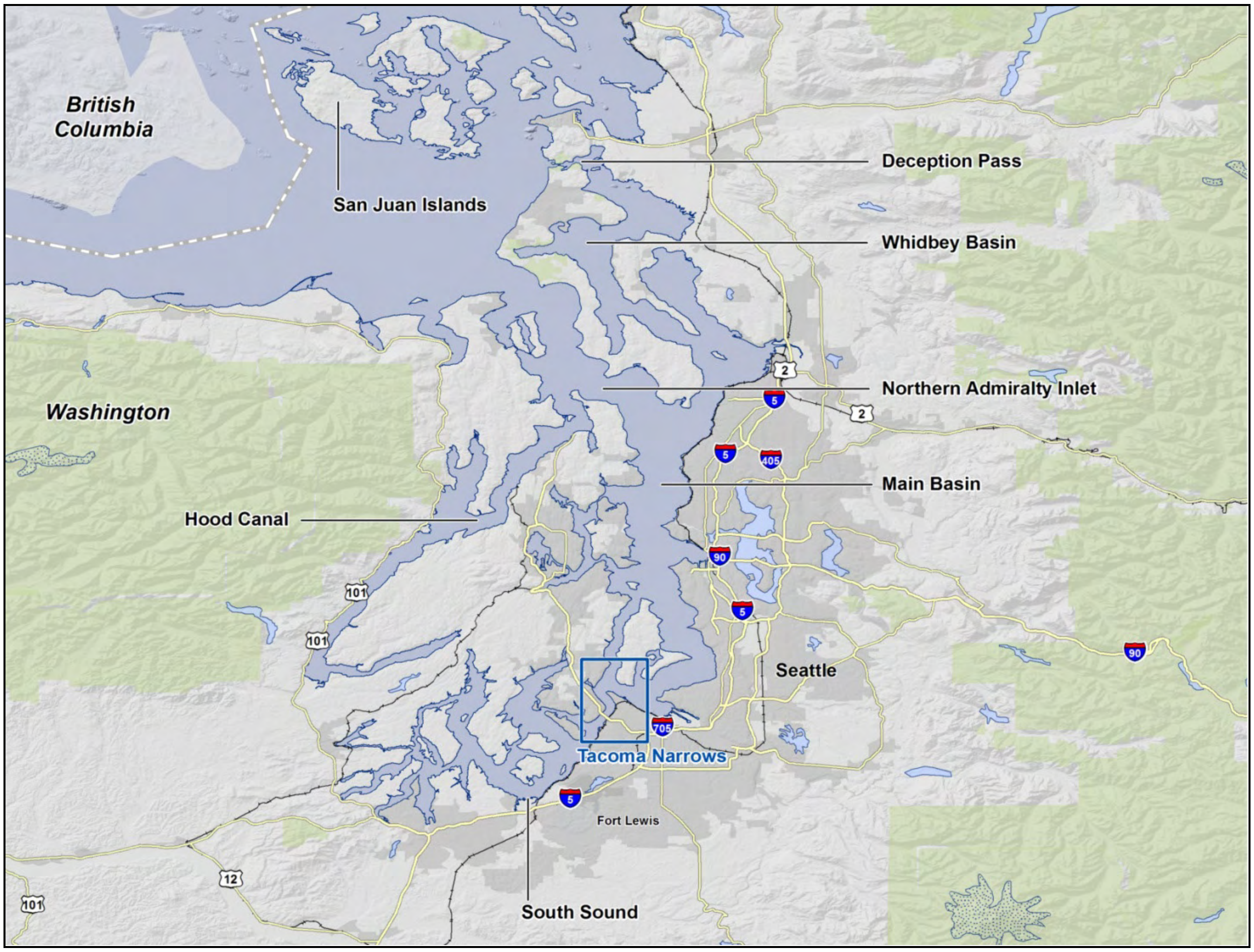


Figure 2.1 – Puget Sound, Washington (Tacoma Narrows highlighted)

Figure 2.2 – Tacoma Narrows detail

The strength of the currents in the Narrows is well-documented by a feasibility study by the Electric Power Research Institute (Polagye et al. 2006) and follow-on activities by Tacoma Power (Hamner 2007). Currents are fastest at the midpoint of the channel in the vicinity of Point Evans, but the kinetic resource is significant at points to the north and south. Tacoma Power relinquished its preliminary permit for the site in early 2009 and the site is not presently under active development.

In recent years, there have been growing concerns about hypoxic (low oxygen) and anoxic (no oxygen) conditions in the inlets of the South Sound (Edwards et al. 2007). Because the entirety of the tidal exchange into the South Sound is through Tacoma Narrows, it is important that in-stream energy development does not significantly reduce the exchange of water between the Main Basin and South

Sound. There are also a number of endangered aquatic species present in Tacoma Narrows including southern resident killer whales (Devine Tarbell & Associates 2006).

Tacoma Narrows has significant infrastructure and a number of existing uses. South of Point Evans, the two spans of the Tacoma Narrows Bridge connect mainland Washington to the Kitsap Peninsula. At Point Evans, two 115 kV transmission lines cross overhead. A passenger and freight railway line runs along the eastern bank. All shipping traffic bound for the Port of Olympia passes through the Narrows and there is a marker light off Point Evans. The original Tacoma Narrows Bridge (on the bottom of the Narrows following wind induced vibration and resonance which caused catastrophic failure) is now a large artificial reef popular with recreation divers. While the Narrows does not support any commercial fisheries, a number of native tribes maintain treaty fishing rights.

Any tidal energy project in Tacoma Narrows must balance resource considerations against environmental concerns and existing users.

2.1 Physical Environment

In order to evaluate the merits of an in-stream energy project in Tacoma Narrows, the physical environment must be characterized in a number of ways. This includes information about tidal currents, the seabed, infrastructure (both within the Narrows and on shore), electrical interconnection, shipping, other recreational and commercial uses, and proximity to port facilities.

2.1.1 Currents

Tacoma Narrows is well-known for its intense currents and the Coast Pilot warns mariners of currents exceeding 5 knots (2.6 m/s) (Coast Pilot, Volume 7). Qualitatively, currents are strongest along the central axis of the Narrows. At the northern end, the sharp turn at Point Defiance generates a strong vertical motion, which overturns the water column on entrance to the Narrows. As a consequence of flow separation around Point Defiance, currents on the western side of the north end of the Narrows are almost always flooding and almost always ebbing on the eastern side. Smaller eddies also set up to the lee of Point Evans –south on flood and to the north on ebb. Areas with strong eddy motion are unsuitable for tidal current development because of both the strong turbulence and low power density. Towards the southern end of Tacoma Narrows, the resource is more uniformly distributed across the channel.

While kinetic power density is one of the most common metrics used to describe resource intensity at a tidal energy site, other metrics may have substantial operational implications. The following section describes these metrics in detail and presents results based on 2007 velocity surveys undertaken in

Tacoma Narrows. An overview of the metrics which may be used to characterize the in-stream resource is given, and representative data from one of the three measurement sites presented. Additional sources of velocity data, and their role in site assessment, are discussed more fully in Section 2.3.

Velocity data for Tacoma Narrows were collected by Evans-Hamilton, Inc. using acoustic Doppler current profilers (ADCPs) deployed at three locations in Tacoma Narrows in 2007 (Figure 2.11). These provide long-term measurements of the water column velocity at a particular location. For these surveys, the temporal resolution is 15 minutes and vertical resolution 1 meter. Information from site 2 is presented here. Spatial variations throughout Tacoma Narrows are discussed in Section 2.3. A summary image showing the velocity magnitude (speed) during the instrument deployment is shown in Figure 2.3. A number of trends are qualitatively observed:

1. The strength of the currents decreases with water depth as a consequence of frictional resistance by the seabed
2. The strength of the currents varies periodically during the deployment period on a 14 day neap (weak) – spring (strong) cycle. Spring tides occur around days 13 and 27.
3. During spring tides, there is a pronounced diurnal inequality – a strong tidal exchange followed by a weak one. This is a defining feature of mixed, mainly semidiurnal tidal regimes.

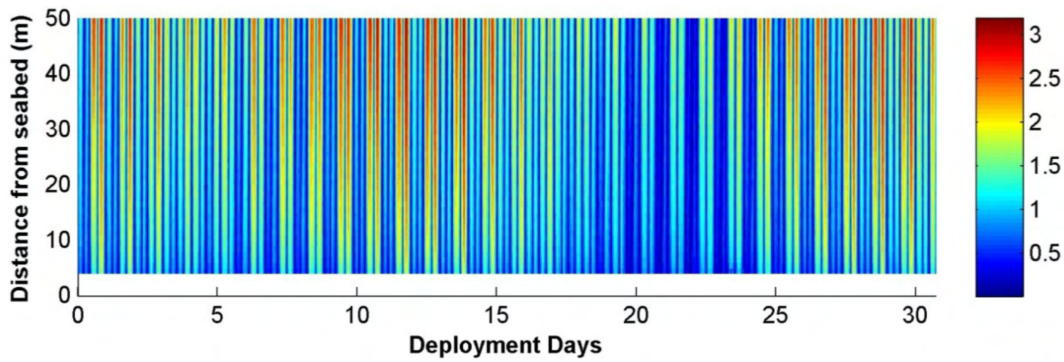


Figure 2.3 – Velocity magnitude (m/s) in Tacoma Narrows (July 2 – August 2, 2007, Site 2)

During spring tides, current speeds exceed 3 m/s, but during neap tides may not even reach 2m/s. The kinetic resource varies with the cube of velocity;

$$K = \frac{1}{2}\rho u^3, \tag{2.1}$$

where K is the kinetic power density (W/m^2), ρ is the density of seawater (kg/m^3), and u is the horizontal velocity magnitude (m/s). Because of this dependence, the kinetic resource varies greatly in time, as shown in Figure 2.4. The effect of diurnal inequality is magnified when considered in terms of power density.

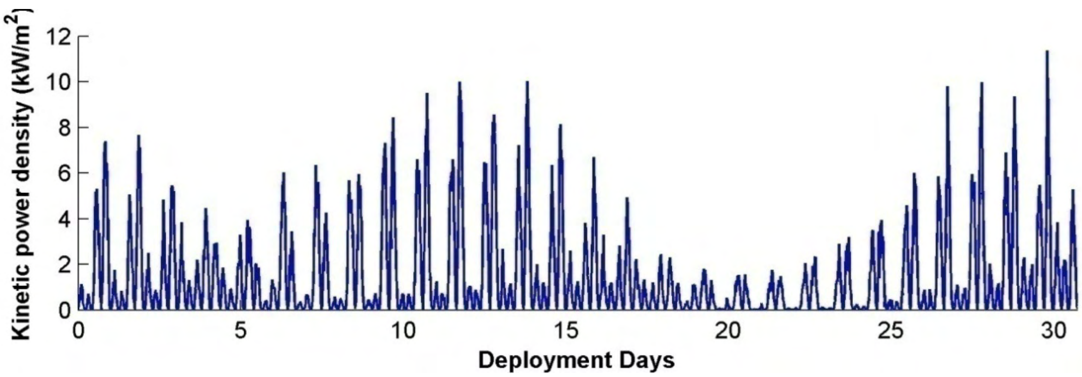


Figure 2.4 – Kinetic power density (kW/m^2) in Tacoma Narrows (July 2 – August 2, 2007, Site 2). Values reported 25m above the seabed.

It is also possible to describe the resource in more quantitative terms, using a methodology developed by the Northwest National Marine Renewable Energy Center (Gooch et al. 2009). Most metrics are reported for ebb, flood, and a composite tidal cycle to provide information about ebb/flood asymmetry and overall conditions. Additionally, statistics are not generally reported for conditions around slack water ($u < 0.5$ m/s) as the direction of currents may change rapidly, but are of little operational importance for tidal energy devices. In general, tidal energy devices do not convert power at speeds less than 0.5 m/s (1 knot). The set of metrics which may be quantified from the available data are described below.

(1) Current Strength

Measures of current velocity are an important metric for site characterization. These include:

- Mean speed (m/s). For ebb tides this is defined as the mean of speeds greater than 0.5 m/s in the ebb direction, and comparable for flood. For this metric, the value reported for the composite tide is the average over the entire tidal cycle, including points around slack water.
- Maximum sustained speed: maximum current observed. This establishes design loads on device support structures and foundations.
- Ebb/flood speed asymmetry: ratio of mean ebb to flood speed.

The vertical variation of the current strength with depth at a site Tacoma Narrows is shown in Figure 2.5. Currents are strongest near the surface and weakest near the seabed, with flood currents somewhat stronger than ebb.

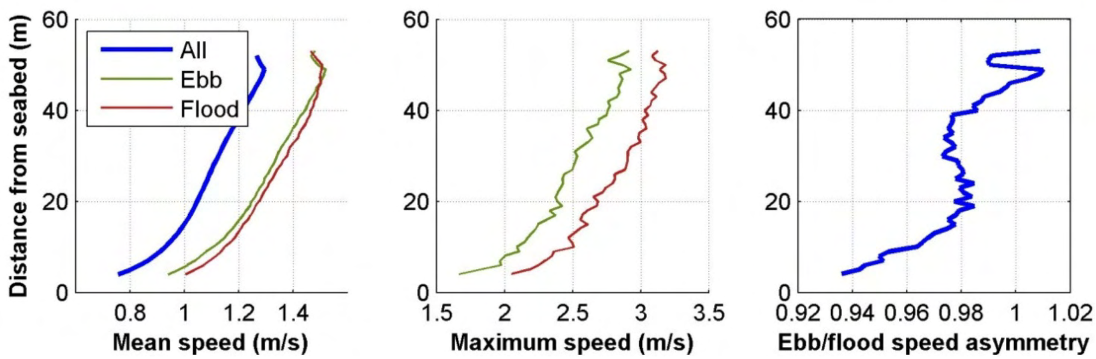


Figure 2.5 – Vertical variation in current strength (Tacoma Narrows, site 2)

(2) Current Direction

For a hydrokinetic turbine, the direction of the currents help to determine an optimal device orientation or type of device suitable for a site (e.g. devices that yaw can adjust to variations in current direction over the tidal cycle). Metrics characterizing the current direction include:

- Principal axis: principal direction of current flow (0^{o} corresponds to north, clockwise positive)
- Standard deviation: variation in current direction relative to the principal axes
- Ebb/flood directional asymmetry: degrees departure from a bidirectional current (0o corresponds to ebb and flood in 180o opposition)

The directionality of the currents is often visualized by a scatter plot of the horizontal velocity measurements over the ADCP deployment period (Figure 2.6). The principal axes of the currents show a minor asymmetry between flood and ebb and decreasing directional variation higher in the water column. In general, current direction shows the highest scatter near the seabed, where bathymetric features influence direction, and close to the surface, where waves, wind, and marine traffic play important roles.

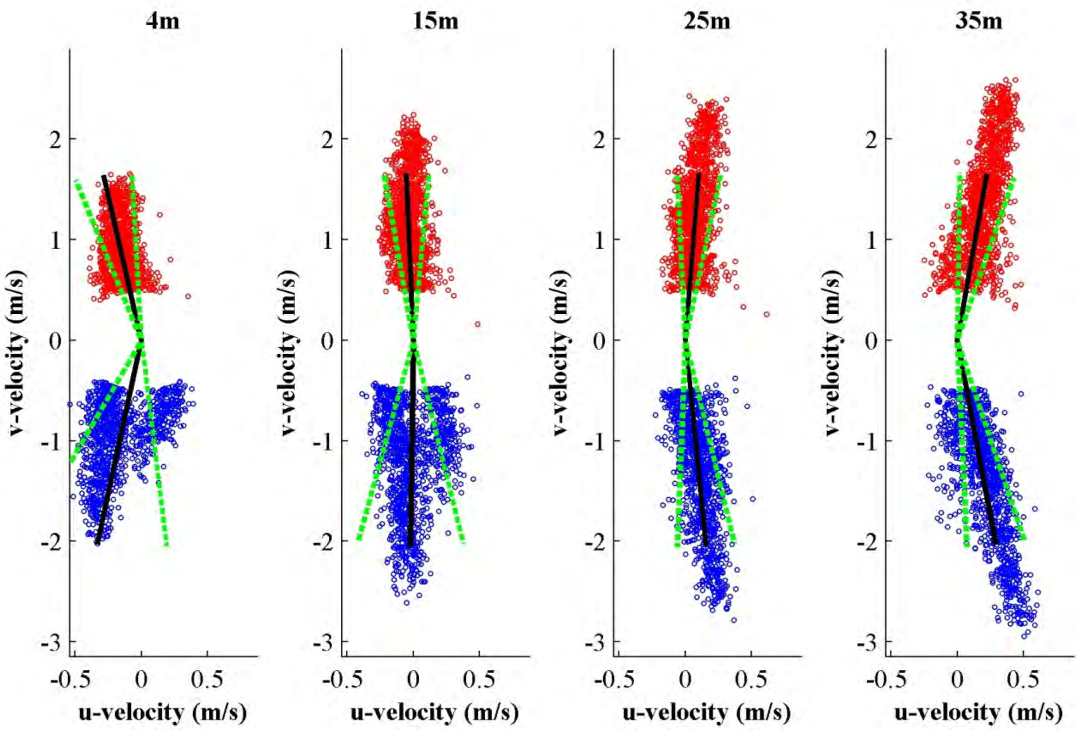


Figure 2.6 – Scatter plot of horizontal velocity measurements in Tacoma Narrows (July 2 – August 2, 2007, site 2) at various distances above the seabed. Red points are the ebb tide, blue points are the flood tide. Points around slack water (*u* < 0.5 m/s) are not shown. Solid black lines denote the principal axes on ebb and food and the dashed green lines denote the standard deviation.

The vertical variation in the metrics described above is shown in Figure 2.7. Both the principal axis direction and directional variance have weak depth dependencies. More interesting is the relative difference between ebb and flood. At the surface and seabed there is a pronounced directional asymmetry, but ~20m off the seabed, currents are effectively bi-directional.

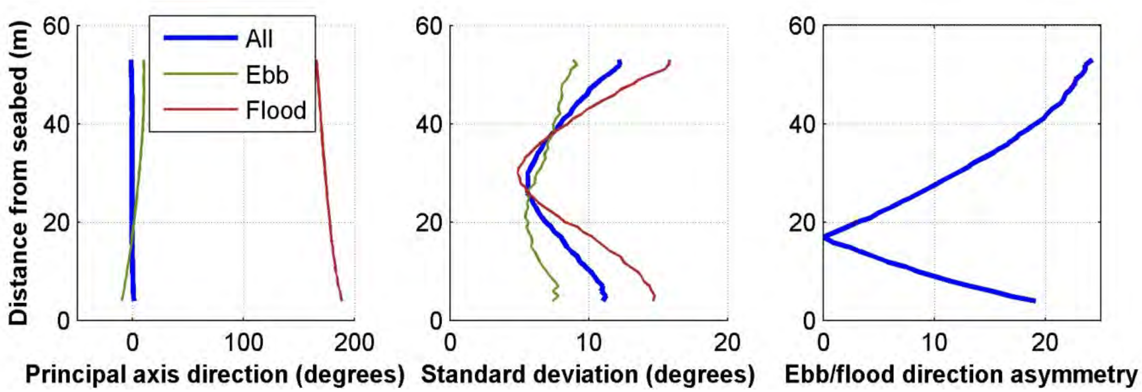


Figure 2.7 – Vertical variation in current direction (Tacoma Narrows, site 2)

(3) Vertical Structure

For sites at which measurements are only available at a particular depth (e.g., the surface), a power law is often used to describe the variation in current speed with depth. This law is generally of the form

$$u = u_0 \left(\frac{z}{z_0} \right)^{1/\alpha} , \qquad (2.2)$$

where u is the velocity at an arbitrary depth (z), u_0 is the velocity measured at a reference depth (z_0) and α is the power law exponent. By finding a best fit for actual measurements, it is possible to determine:

- Power law exponent: the average exponent over ebb and flood currents
- Power law exponent standard deviation: the variation in the exponent
- % of vertical profiles fit: the % of measurements which can be described to a reasonable approximation by a power law (R^2 for fit > 0.5).

For site 2 in Tacoma Narrows, the best fit for a power law profile has an exponent of 4.3±1.6, with 84% of the vertical profiles well-described by a power law. This result indicates that the vertical profile is relatively shallow; that is to say, the velocity increases substantially with increasing distance from the seabed. A blunter profile (e.g., α=10) corresponds to a site where currents do not increase dramatically once beyond the boundary layer directly adjacent to the seabed. Profiles for several power laws in a 60m deep flow with a surface current of 3 m/s are shown for comparison in Figure 2.8.

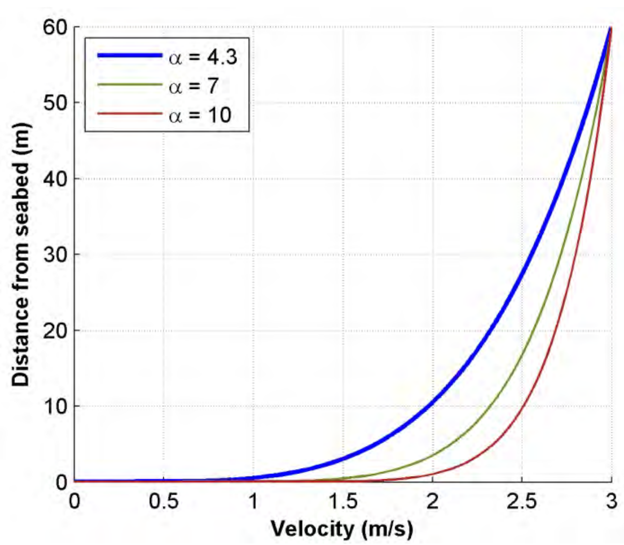


Figure 2.8 – Power law profiles of velocity in water 60m deep with a surface current of 3 m/s

(4) Kinetic Resource

The kinetic power density is the primary metric used to characterize the potential of in-stream energy sites. It may be described in terms of:

- Mean power density (kW/m^2) using the same designations for ebb, flood, and the full tidal cycle as current strength. Note, however, that sites with exceptionally high mean power density may have undesirable characteristics (e.g., large, turbulent eddies, large directional standard deviation, etc).
- Ebb/flood power asymmetry: ratio of mean ebb to flood kinetic power density. Sites with a large power asymmetry will generate substantially more power on one stage of the tide.

The vertical variation in these metrics is shown in Figure 2.7 and indicate that power density increases substantially with distance from the seabed (as expected by the shallow result for the power law exponent) and that there is a significant power asymmetry between ebb and flood tides, particularly near the seabed.

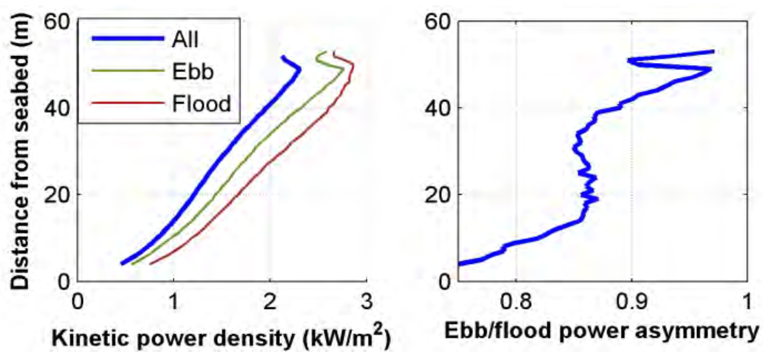


Figure 2.9 – Vertical variation in kinetic resource (Tacoma Narrows, site 2)

In addition to these metrics, measurements with higher temporal resolution may be used to characterize the turbulence of the currents in terms of eddy intensity, acceleration, and angular velocity. In general, temporal resolution on the order of one minute or less is required to accurately calculate turbulence metrics.

2.1.2 Bathymetry and Seabed

Publicly available bathymetric data for Tacoma Narrows dates from a 1935 National Ocean Service survey using lead weighted lines to measure depth. The spatial resolution in this data set is approximately 100 m, but these data may be interpolated to a uniform, higher resolution grid (Figure 2.10 - 3D Site Bathymetry), for the purposes of scenario analysis. This does not, of course, actually improve the resolution of the data. Higher resolution bathymetry exists for the region surrounding the new Tacoma Narrows Bridge, but these data are not in the public domain. As described previously, the bathymetry in the northern and central regions of the Narrows is characterized by deep, asymmetric depressions, while the southern region is relatively uniform.

Figure 2.10 - 3D Site Bathymetry

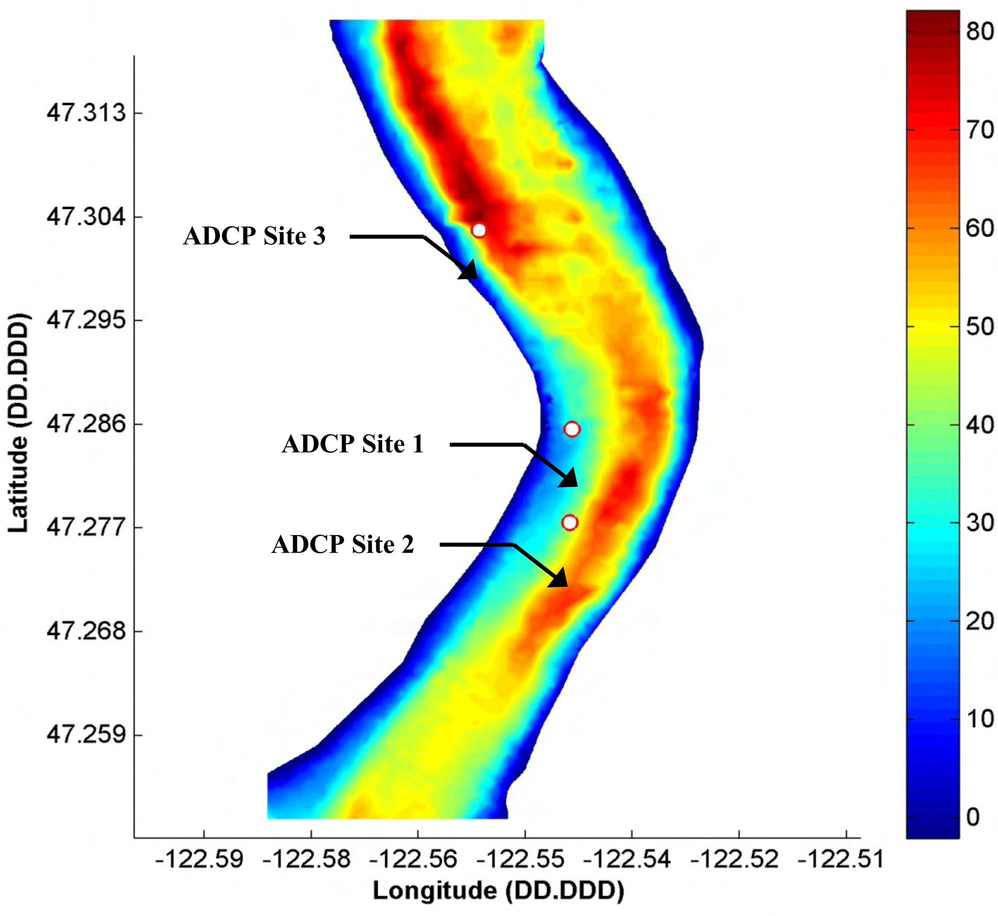
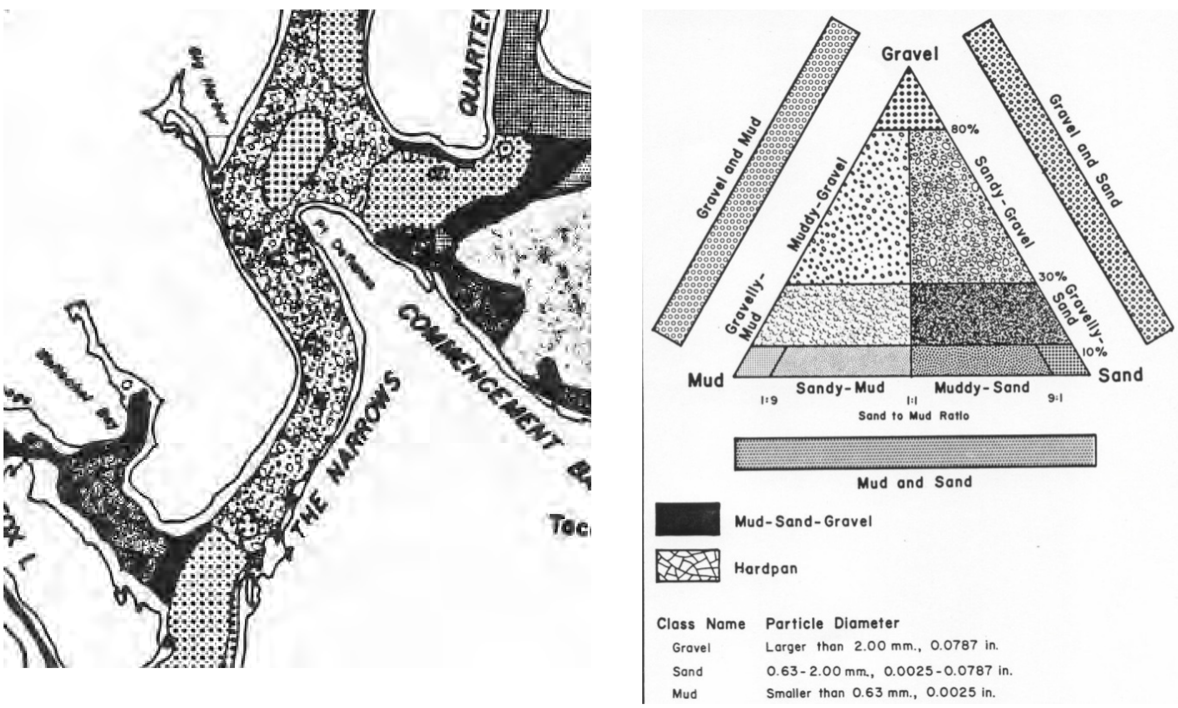


Figure 2.11 – Interpolated Tacoma Narrows bathymetry (depth relative to mean lower low water). Interpolation is on to a 5m grid. Underlying data is from the 1935 NOS survey and is at ~100m resolution. 2007 ADCP deployment locations as marked.

The seabed throughout Tacoma Narrows is classified as sandy gravel (Figure 2.12). The triangular legend indicates the relative composition of the seabed between sand, mud, and gravel. Based on the texture in the sediment map for Tacoma Narrows, the seabed type is classified as a mix of sand, gravel, and rock. Like other energetic channels in Puget Sound, Tacoma Narrows is excluded from the Washington Department of Ecology's sediment sampling program because of the cobbled nature of the seabed. Personal communications with those familiar with conditions in Tacoma Narrows suggest that the seabed is scoured, with the top layer consisting primarily of gravel and cobbles.

Geologic surveys for the new span of the Tacoma Narrows Bridge describe the underlying layer as outwash deposits from glacial retreat consisting for clean to silty sand, gravelly sand, and sandy gravel with cobbles and boulders common (Shannon & Wilson 2001). These sediments range from loose to very dense. While the thickness and density of this layer varies throughout Tacoma Narrows, these surveys provide a qualitatively useful description of the underlying geology.



(a) Seabed composition **(b) Legend**

Figure 2.12 – Tacoma Narrows seabed composition (Richards 1979)

The percent grade of the seabed throughout Tacoma Narrows is shown in Figure 2.13. While the data are relatively coarse, owing to the underlying resolution of the bathymetric data, they indicate a grade of less than 10% along the central axis of Tacoma Narrows. The grade is defined as

$$\text{Grade}(\%) = \frac{\Delta z}{\Delta x} x100,$$

where Δz is th e chan g ein seabed elevatio n per Δx of horizontal distance. High grade angles can significantly complicate the deployment of some types of foundations. Consequently, device deployment may be technically challenging along the eastern side of the Narrows or the western side north of Point Evans. However, the kinetic resource is also indicated to be relatively weak in those regions, so device deployment in areas with high grades is unlikely.

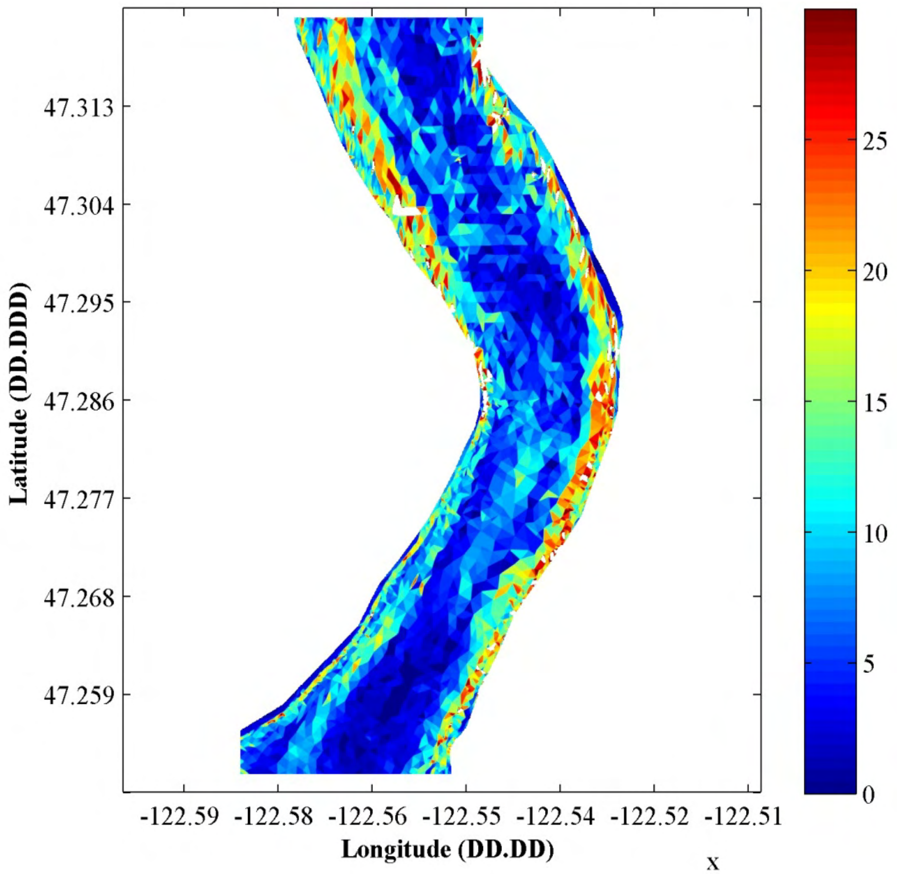


Figure 2.13 – Grade (%) of Tacoma Narrows seabed

2.1.3 Infrastructure

The Tacoma Narrows Bridge is 1.8km in length and crosses the Narrows at the midpoint of the southern end of the channel. The bridge is a twin-span structure, each supported by two caissons on the eastern and western edges of the channel. The wake generated by the caissons may persist up to 15 times their characteristic width of 24 m, 360 m. Because of the turbulent mixing in the wake, turbines should not be deployed in this region upstream or downstream of the bridge.

The only other surface piercing structure in the Narrows is a marker light on a steel frame, located in very shallow water just offshore of Point Evans.

There is a small, public airport at the southern end of Tacoma Narrows (Figure 2.2). The Tacoma Narrows Airport has a single runway 1.5km in length and primarily serves local and transient general aviation.

A rail line serving freight and passenger traffic parallels the eastern shoreline of Tacoma Narrows from about 2km south of Point Defiance to the southern end of the channel.

A network of secondary roads approaches the eastern and western side of Tacoma Narrows. WA Route 16, a substantial highway linking the Kitsap Peninsula to the mainland, crosses the Narrows on the bridge. The nearest interstate highway is several miles to the east, where Interstate 5 crosses through the city of Tacoma.

2.1.4 Interconnection

Electrical infrastructure owned either by Tacoma Power or Peninsula Light Company (Penlight) is in close proximity to Tacoma Narrows. Penlight maintains a 12.5kV distribution network on the western side of Tacoma Narrows. Tacoma Power operates a 115kV transmission line crossing at Point Evans, with a substation located approximately one-half mile away on the western shore. Transmission infrastructure in the vicinity of Point Evans is shown in Figure 2.14. The proximity of the Penlight distribution network to shore is representative of locations elsewhere along Tacoma Narrows. There is also a distribution network on the eastern shore, but the level of existing development on that side of the Narrows may complicate the task of landing the subsea electrical cable from the array.

The interconnection voltage provides a directional indicator of the amount of power which can be integrated in to the grid. Distribution lines rated at 12.5kV are unlikely to support more than 5 MW of power – less if near the end of a weak grid. Transmission lines rated at 115kV may be able to accept up to 100 MW of power, sufficient from moderate scale commercial generation.

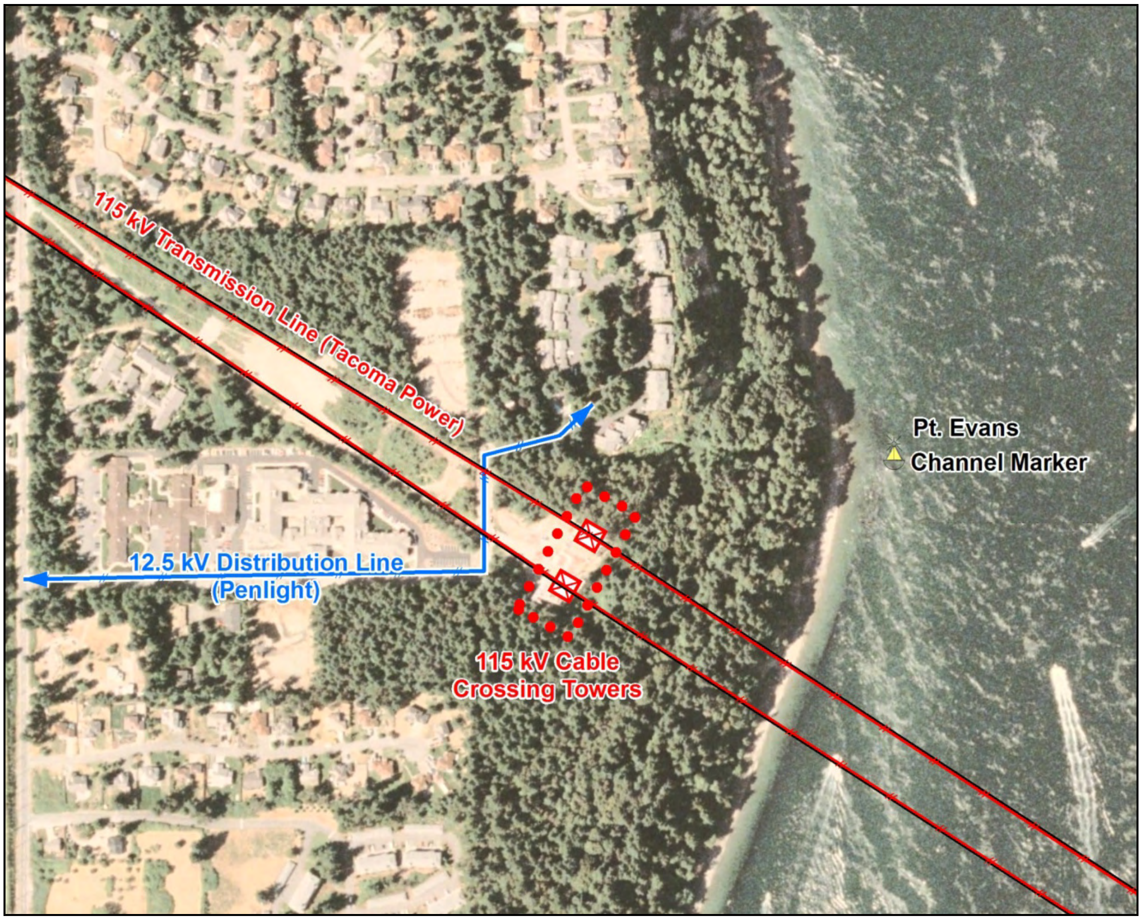


Figure 2.14 – Interconnection infrastructure near Point Evans, Tacoma Narrows

2.1.5 Navigation

Both commercial and recreational vessels pass through Tacoma Narrows. However, commercial traffic is of greatest interest with respect to siting as the vessel draft of the largest commercial traffic establishes the minimum overhead clearance for a tidal energy device deployed in the channel. While vessel traffic through Tacoma Narrows is not recorded, the only major port to the south is Olympia. Therefore, information about commercial vessel traffic to Olympia can be used to infer major vessel traffic through the Narrows. Statistics on trips and drafts are maintained by the Waterborne Commerce Statistics Center (Army Corp of Engineers, New Orleans, LA) and electronic records are available from 1990 through 2006. Statistics about trips and drafts for Olympia, Washington are summarized in Figure 2.15 and Figure 2.16. These indicate that more than 95% of all trips are by vessels with drafts less than 6m. However, vessels with drafts as great as 12m have transited the channel on a few occasions. The federal channel to the Port of Olympia is only maintained to 9m (Coast Pilot, Volume 7), so the largest vessels are required to time their arrival to be coincident with large high tide. Additionally, as shown in Figure 2.17, the number of vessel trips through the Narrows has declined by nearly 50% since 1990.

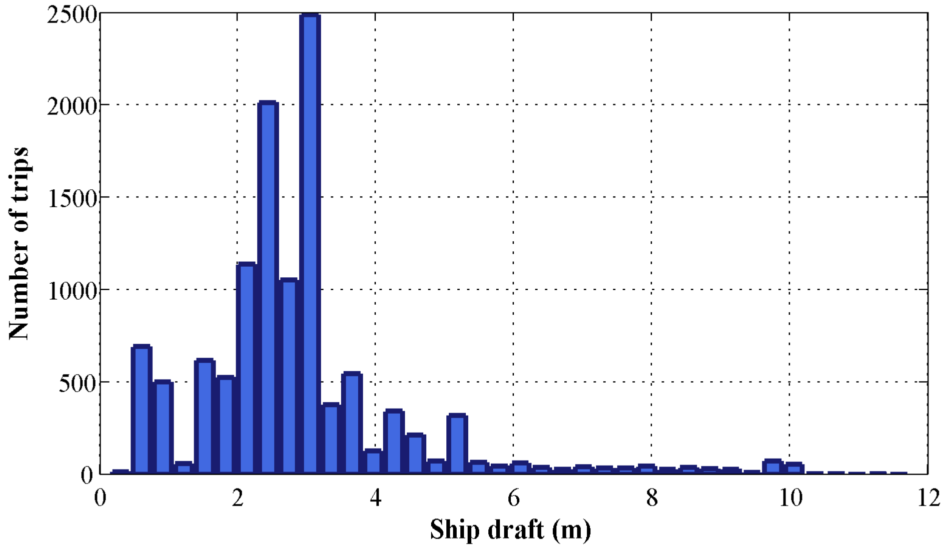


Figure 2.15 – Ship draft histogram, Port of Olympia 1990-2006 (source: Waterborne Commerce Statistics Center)

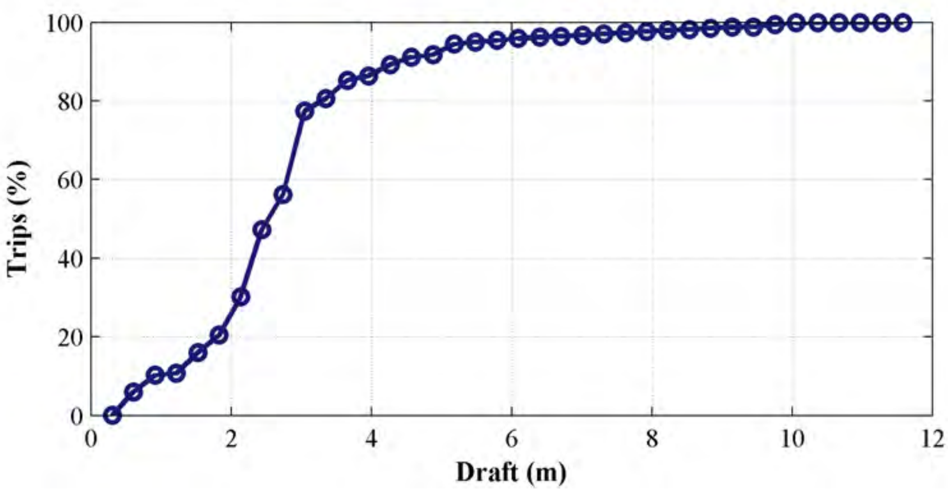


Figure 2.16 – Cumulative ship drafts, Port of Olympia 1990-2006 (source: Waterborne Commerce Statistics Center)

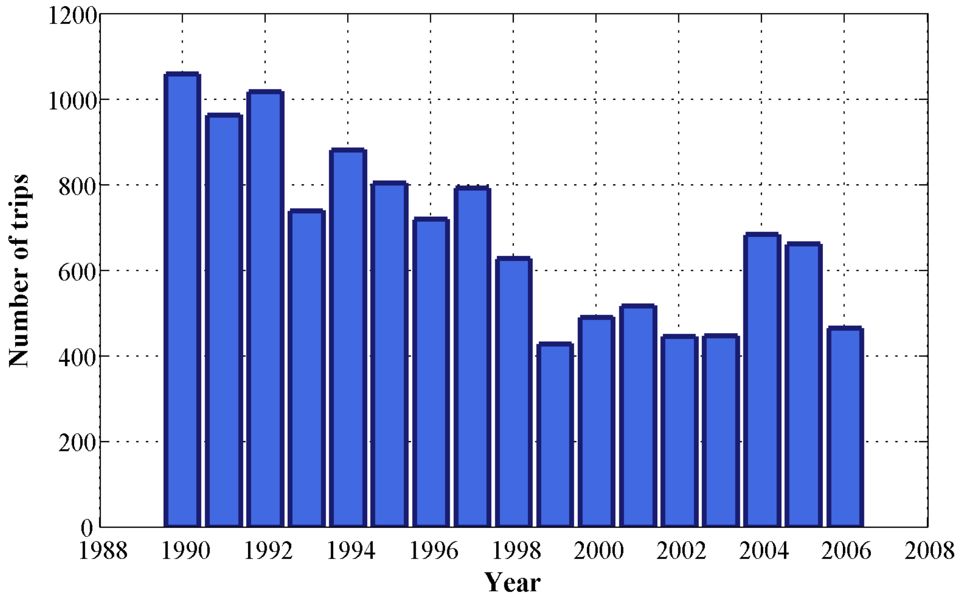


Figure 2.17 – Number of trips, Port of Olympia 1990-2006 (source: Waterborne Commerce Statistics Center)

While there is no formal navigation lane in Tacoma Narrows, vessels transiting the channel are said to hold close to the 37m (20 fathom) contour off Point Evans. Because greater overhead clearance is required for hydrokinetic turbines in navigation lanes, this provides useful guidance for device siting.

One possibility for obtaining better resolved statistics for marine traffic would be to install an AIS (Automatic Information System) receiver in the vicinity of Tacoma Narrows. AIS transmitters are required by the Coast Guard on all vessels over 300 gross tons. When vessels are underway they transmit location data every ten seconds and their identification (including vessel dimensions) every six minutes. While the AIS network is intended primarily for real-time information, received information may be logged and post-processed to determine ship tracks to a high degree of precision.

2.1.6 Port Facilities

Tacoma Narrows is located in close proximity to a number of major port facilities. The Port of Tacoma is approximately 20km (12.5 miles) from Point Evans (the midpoint of the Narrows). Tacoma is the second largest port in Washington, behind Seattle. The Port of Seattle could also serve as staging areas for installation and maintenance, but is more distant – approximately 45 km (28.1 miles) – which would increase equipment mobilization time. Depending on the resources required, Gig Harbor, which is located closer to the Narrows, could serve as a staging area for maintenance operations. However, there are insufficient facilities for Gig Harbor to serve as a staging area for device installation.

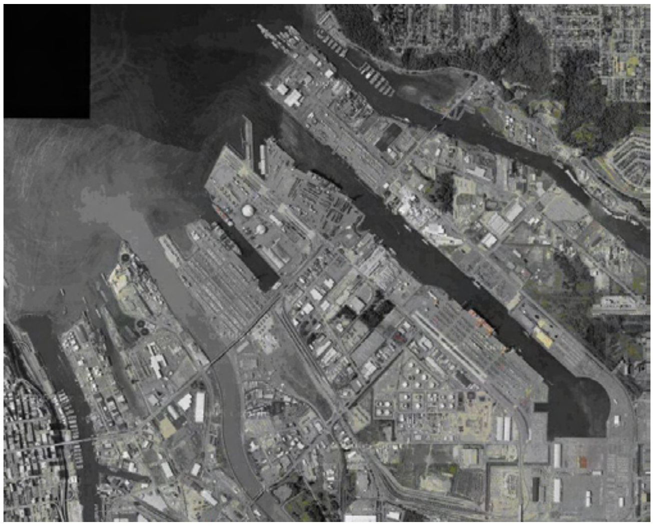


Figure 2.18 – Port of Tacoma (source: Google Maps)

2.1.7 Existing Users

In addition to shipping, which is discussed previously, there are a number of existing users present in Tacoma Narrows. Titlow Beach, at the southern end of the Narrows, is a popular location to launch kayaks and canoes or to enter the water for SCUBA diving. Mixed-gas diving on the artificial reef formed by the wreckage of the original Tacoma Narrows Bridge (directly beneath the present alignment) is also popular. While the Narrows does not support any commercial fisheries, sport fishing is popular along the western edge of the channel, particularly in eddies formed by flow separation around Pt. Evans. Finally, the Nisqually, Puyallup, Squaxin Island, Muckleshoot tribes maintain treaty rights to fish within Tacoma Narrows. Any site development within Tacoma Narrows will require consultations with tribal governments whose rights or activities could be disrupted. The near shore area directly adjacent to Titlow Beach is a marine protected area, though the protected area lies outside the region suitable for power generation.

2.1.8 Water Quality

Water quality data for Tacoma Narrows are routinely sampled by PRISM, a University of Washington led initiative to better understand Puget Sound. Research cruises occur several times each year and sample water quality characteristics at various stages of the tide. Information from these surveys in summarized in Figure 2.19. Survey data indicates that the water column is generally well-mixed (limited variation from seabed to surface), consistent with high-speed, turbulent flow through the Narrows.

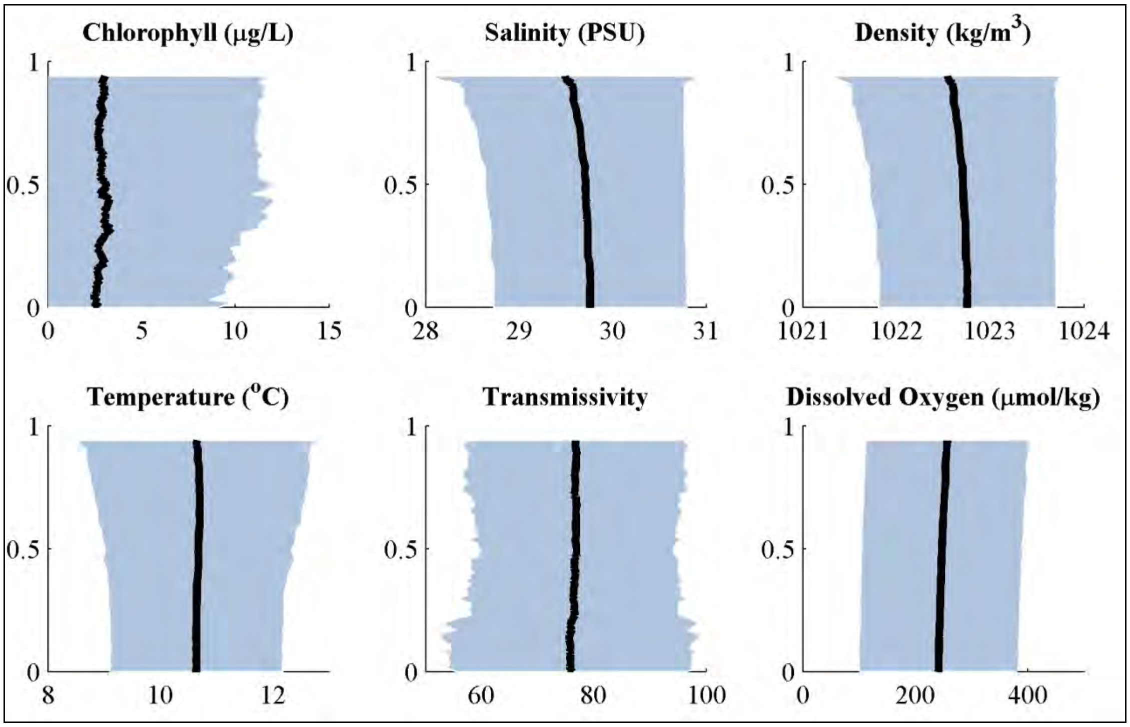


Figure 2.19 – Water quality measurements in Tacoma Narrows (PRISM). Vertical profiles are shown with respect to normalized depth (0 = seabed). Black lines denote mean values for all surveys, blue outlines denote two standard deviations from the mean value.

2.2 Biological Environment

As part of a previous feasibility study, Devine Tarbell & Associates (now HDR) compiled a summary of the biological environment in Tacoma Narrows (Devine Tarbell & Associates 2006). The following section describes key outcomes from that work. Additional, detailed information from the area in the immediate vicinity of the Tacoma Narrows Bridge is available in the Environmental Impact Statement (EIS) for that project (WSDOT 2000).

Marine vegetation of concern to resource management agencies in Puget Sound includes eelgrass and kelp. Data compiled by the Washington Department of Natural Resource's ShoreZone Inventory indicate that no eelgrass is present in the Narrows and that patchy kelp is present along the eastern and western shores. Macro-algae are present only in the upper 12m of the water column (MLLW).

Puget Sound, including Tacoma Narrows, is designated as Habitat of Particular Concern (HPC), a subset of Essential Fish Habitat (EFH) for a number of species of salmon (coho, chinook, pink) and groundfish. In general, a number of invertebrates, fish, and shellfish are present in Tacoma Narrows (WSDOT 2000). Invertebrates include shrimp, sea urchins, sea cucumbers, mussels, geoducks, Pacific giant octopus, and crabs. Marine fish include baitfish (Pacific herring, Pacific sandlance), groundfish (lingcod, rockfish, flatfish, wolf eel, spiny dogfish), surf perches, salmon (chinook, coho, sockeye, chum, pink), trout (cutthroat, bull, steelhead), and sixgill sharks.

In addition, a number of marine mammals may be present in Tacoma Narrows. The most common are California sea lions and harbor seals. However, Steller sea lions, humpback whales, grey whales, killer whales (orcas), Minke whales (Evans-Hamilton Inc. 1987), harbor porpoises, and Dall's porpoise have been reported as well. There are no pinniped haul outs in Tacoma Narrows.

Waterfowl and seabirds are observed (WSDOT 2000), but there are no seabird nesting sites within the Narrows (Evans-Hamilton Inc. 1987).

A number of the species which have been observed in the project area are either threatened or endangered. Threatened species include bald eagles, chinook salmon, chum salmon, and bull trout. Endangered species include marbled murrelets, humpback whales, southern resident killer whales, and Steller sea lions. Steelhead trout, coho salmon, and several species of rockfish are not presently listed species, but have been flagged for concern due to declining population.

In addition to these considerations, the tidal exchange for South Sound passes exclusively through Tacoma Narrows. The South Sound contains a number of inlets (e.g., Case, Carr, Budd, and Eld) which have experienced hypoxic conditions in recent years (Edwards et al. 2007). An important consideration for any project in Tacoma Narrows will be to demonstrate that the additional flow resistance due to turbines will not materially contribute to this problem.

2.3 Tidal Resource Assessment

Assessing the tidal resource and power production potential for a site requires information about how the currents vary in both space and time. Further complicating matters, large-scale conversion will measurably alter the tidal resource, as discussed in Section 2.4. The baseline resource may be established by:

1. A well-calibrated numerical model of the site
2. A year-long measurement of velocity at the site
3. A shorter duration measurement used as a basis for an annual prediction by harmonic decomposition

A year-long measurement has the highest accuracy, but such measurements are rare, particularly during the early stages of a project. Therefore, predictions or calibrated model output are the more standard approaches. Because there are not numerical models of sufficiently high resolution in the public domain for Tacoma Narrows, this assessment proceeds from the basis of recent and historical measurements. 2007 is chosen as a representative model year. While there is some year-to-year variability in the tidal currents, this is a lower-order effect and often neglected during initial site assessments.

2.3.1 Harmonic Analysis

Because tidal currents are driven primarily by the gravitational pull of the sun and the moon on the earth's oceans, they are deterministic and it is possible to make predictions of the resource intensity at some time in the future based on a relatively short-term measurement. In order to make a prediction, a time series for the tides (water surface elevation) or currents (water velocity), is broken down into a number of underlying harmonic constituents of known phase and amplitude, such that the original time series is described as

$$h(t) = \sum_i A_i \sin(\omega_i t + \phi_i) \quad (2.3)$$

where $h(t)$ is the time series for tidal elevation and A_i, ω_i, and φ_i are the amplitude, frequency, and phase of the i^{th} tidal constituent in the prediction. Each constituent in a prediction relates to a particular solar or lunar cycle (e.g., declination of moon's axis relative to the earth's axis). A tidal prediction of this type for Tacoma Narrows is shown in Figure 2.20 with reasonably good agreement between measurement and prediction. While predictions (such as the one below) can be made from a series as short as 30 days, more than 180 days of data are required to further reduce the residual between measurement and prediction.

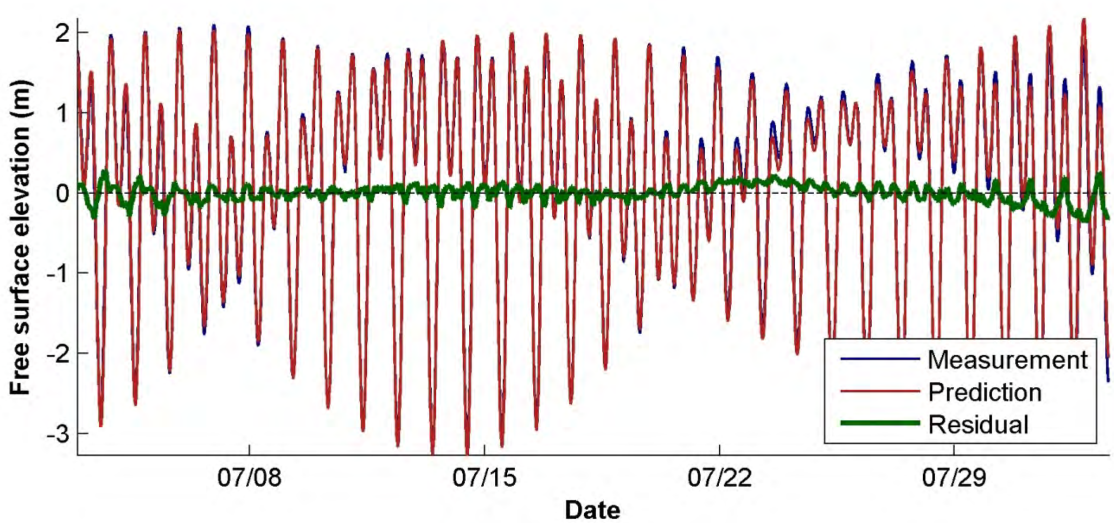


Figure 2.20 – Tidal elevation measurement and prediction (12 constituents) for Tacoma Narrows (July 2 – August 2, 2007, Site 2). The residual (variation between prediction and measurement) is relatively small, on the order of 10cm. The larger residuals at the ends of the time series are a common feature of harmonic analysis.

Tidal currents may be predicted in a similar manner, though the approach is somewhat more complicated by the two-dimensional nature of the currents. There are several approaches to this issue, including making a two-dimensional prediction, making a prediction only along the major axis, or making a prediction in the basis of a signed speed (velocity magnitude, positive for flood, negative for ebb). The results for the latter approach are shown in Figure 2.21. The residuals are still small, but there is considerably more sub-tidal noise in the measurement which cannot be reproduced by harmonic analysis.

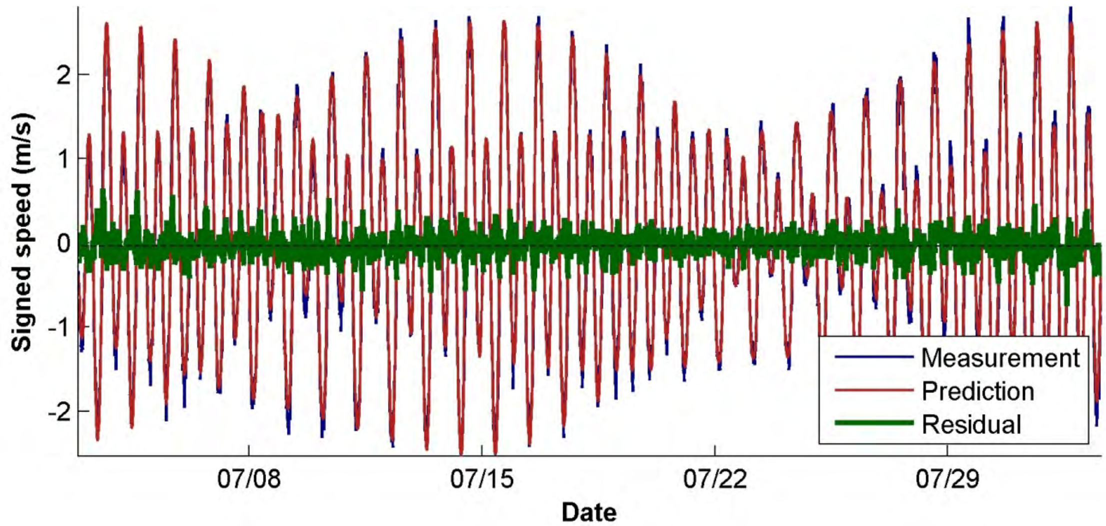


Figure 2.21 – Tidal current measurement and prediction (12 constituents) for Tacoma Narrows (July 2 – August 2, 2007, Site 2). The residual for the prediction exceeds 0.5 m/s in some cases, but is generally on the order of 0.2 m/s.

Because the power density varies with the cube of velocity, the prediction for power density has a higher residual, as shown in Figure 2.22. However, the average power density for the measurement and prediction are nearly identical, so the variation is primarily with the phase, rather than amplitude of the tidal currents.

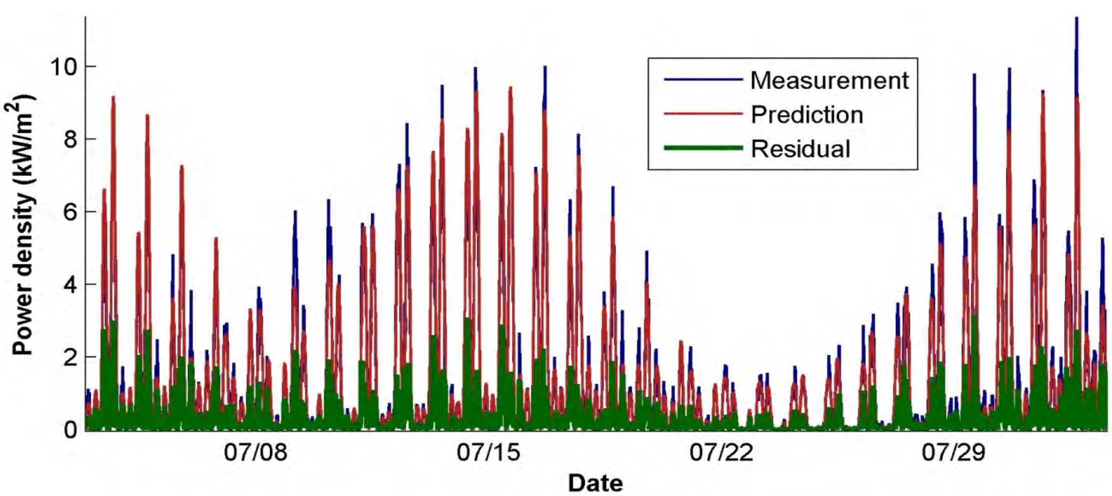


Figure 2.22 – Tidal power measurement and prediction (12 constituents) for Tacoma Narrows (July 2 – August 2, 2007, Site 2). The residual power density exceeds 3 kW/m^2 during some stages of the tide.

The process of harmonic decomposition and subsequent prediction are largely automated by publicly available software (Pawlowicz et al. 2002).

2.3.2 Sources of Data

There are two primary sources of measurement data for Tacoma Narrows: direct ADCP measurements and current predictions based on historical measurements.

ADCP measurements were obtained during surveys in 2007 at three locations (Figure 2.11). The data from site 2 are of high quality and incorporated into this analysis. The data from site 3 are from a region with a very large ebb/flood asymmetry. The data for site 1 appear to be of high quality, but are not amenable to automated harmonic analysis, possibly because of the proximity to the headland. As a result, an annual current prediction is not possible. Statistics for all three measurement locations are summarized in Table 2.1.

Table 2.1 – Summary statistics for ADCP measurements in Tacoma Narrows (mid-water column)

Category/Metric	Units	Site 1	Site 2	Site 3
Velocity				
Mean	m/s	1.2	1.1	0.8
Max	m/s	3.3	2.9	2.7
Ebb/flood asymmetry		0.8	1.0	0.6
Vertical shear	m/s per m	0.03	0.02	0.01
Kinetic Power				
Mean	kW/m^2	1.7	1.4	0.9
Ebb/flood asymmetry		0.5	0.9	0.1
Direction				
Principal axis	degrees (N=0)	12	-1	-28
Standard deviation	Degrees	7	6	8
Ebb/flood asymmetry	Degrees	14	10	4
Vertical Profile				
Exponent		4.4	4.3	10.0
Standard deviation		1.2	1.6	4.5
% of profiles fit		95%	84%	60%
Site				
Measurement duration	Days	32	31	31
Vertical resolution	M	1	1	1
Temporal resolution	Min	15	15	15

NOAA makes current predictions based on historical current measurements at three locations within Tacoma Narrows, shown in Figure 2.23. The prediction off Pt. Evans (Site 1) is in close agreement with ADCP measurements at the same location, as indicated by the time series plots in Figure 2.24. Most of the residual between the two signals is a result of a slight phase shift, not amplitude difference, and does not affect the frequency distribution of velocities. It is assumed, for the purposes of this analysis, that the other two prediction stations achieve a similar degree of accuracy and are suitable for resource assessment. Because NOAA current predictions are for surface velocities, the profile over the entire water depth is described by a power law using a 1/5th power law exponent, which is consistent with ADCP measurements.

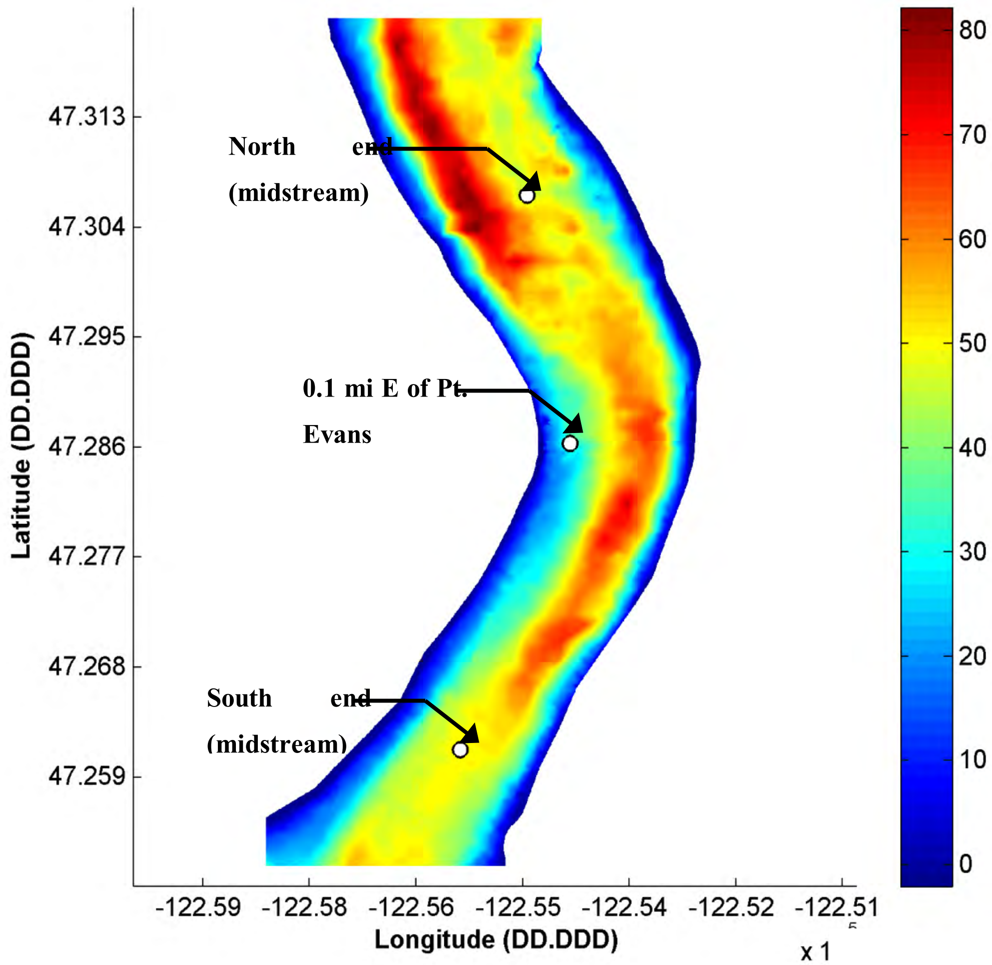


Figure 2.23 – NOAA current prediction stations superimposed on Tacoma Narrows bathymetry

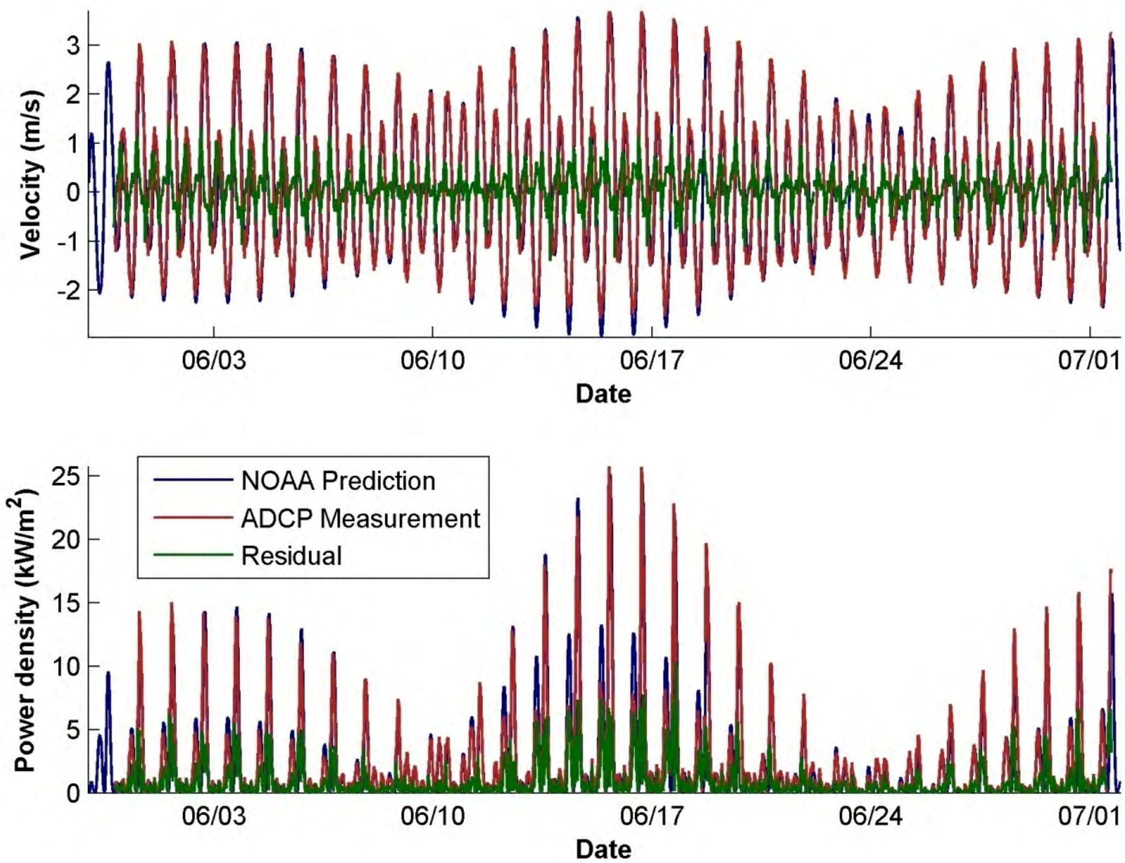


Figure 2.24 – Comparison between ADCP measurements off Pt. Evans and NOAA current predictions for the same location. Signed speed shown on top panel, kinetic power density on bottom panel.

2.3.3 Resource Blocks

For the purposes of this analysis, currents in Tacoma Narrows are described by four resource blocks. Within each block, the velocity frequency distribution is assumed to be a function of normalized depth. For example, at mid-depth in the water column, the velocity frequency distribution will be identical, even though the absolute depth varies. Resource blocks are shown superimposed on channel bathymetry in Figure 2.25. These blocks form a continuous corridor for potential turbine deployments along the central axis of Tacoma Narrows and account for roughly 1/3 of the total surface area. Regions on the eastern and western edges of the Narrows are excluded based on anecdotal evidence of weak currents and eddy fields. Statistics for the four resource blocks are summarized in Table 2.2. Note that the northern portion of Tacoma Narrows has substantially weaker currents and devices deployed there will have a correspondingly lower power output.

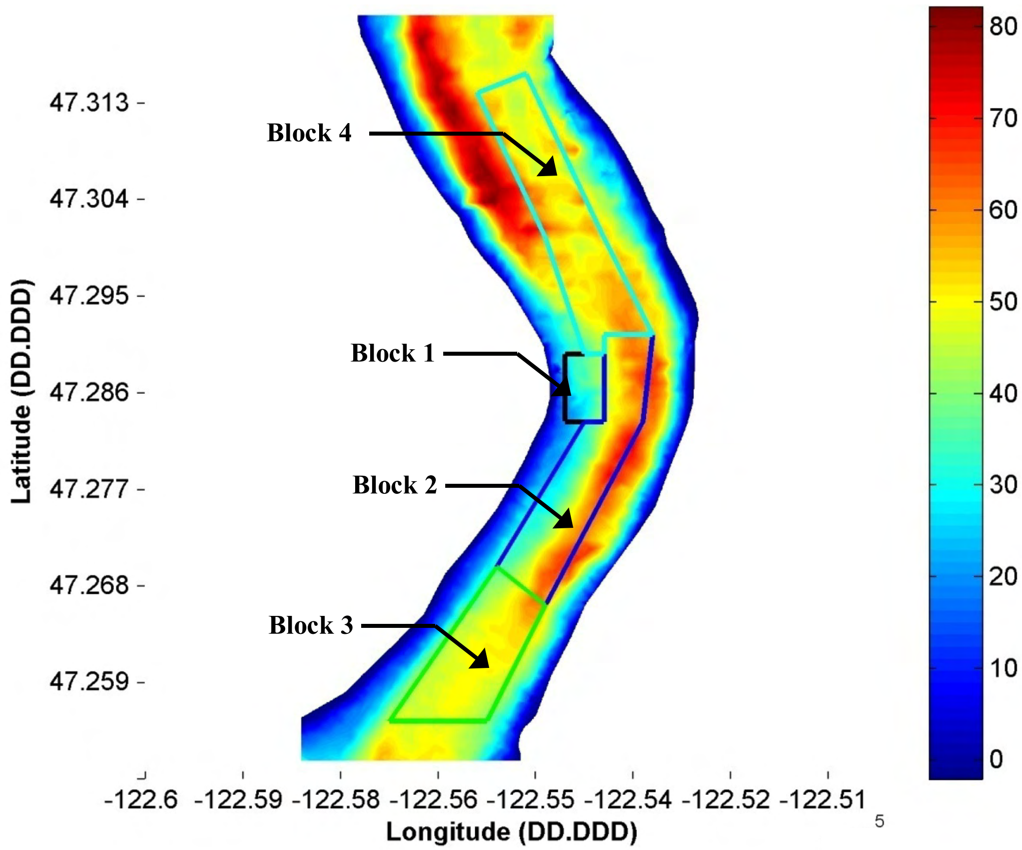


Figure 2.25 – Resource blocks superimposed on Tacoma Narrows bathymetry

Table 2.2 – Resource block statistics

	Block 1	Block 2	Block 3	Block 4
Surface area (km^2)	0.3	1.5	1.2	1.7
Tacoma Narrows coverage (%)	2%	11%	9%	12%
Mean water depth (m)	33	49	48	51
Water depth standard deviation (m)	7	12	4	4
Annual depth-average kinetic power density (kW/m^2)	1.4	1.4	1.1	0.7
Data source	NOAA: 0.1 mi E of Pt. Evans	ADCP: Site 2	NOAA: South end (midstream)	NOAA: North end (midstream)

Velocity frequency distributions for the resource block are shown in Figure 2.26. The distributions are relatively consistent between blocks, though the distribution for Block 2 has less of a tail, possibly because the short-term harmonic analysis is unable to accurately reproduce current extremes on ebb and flood.

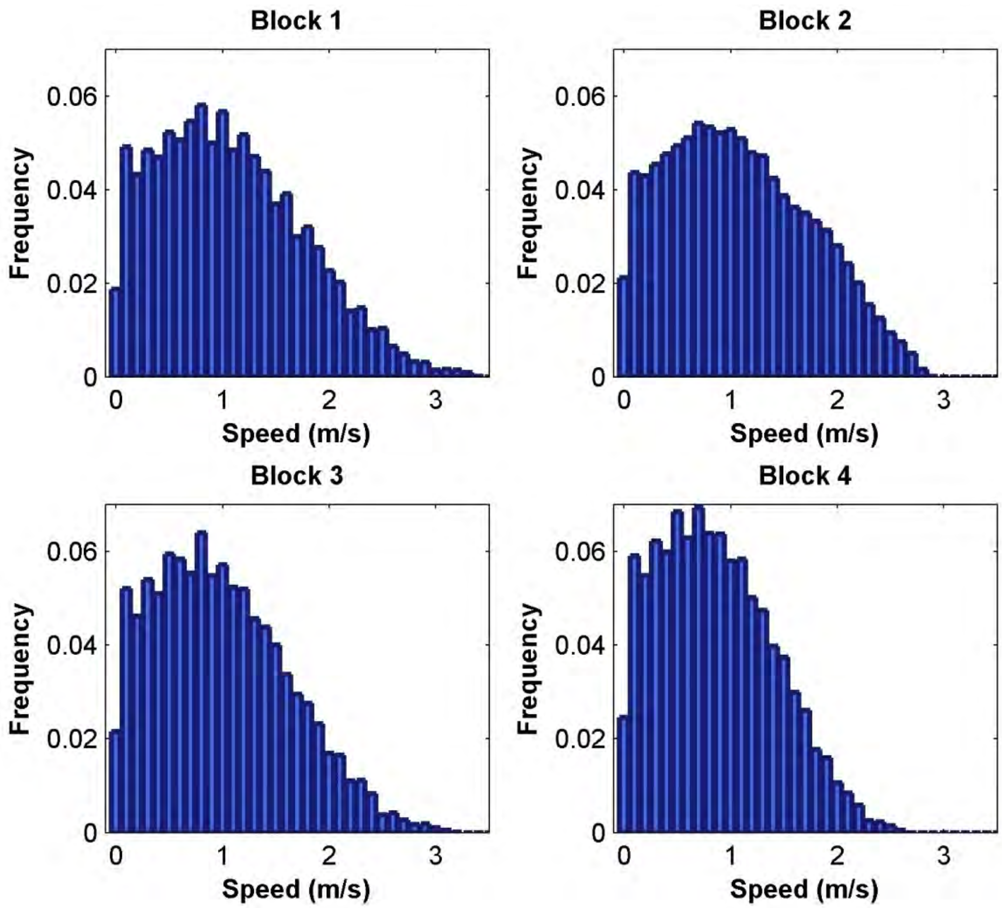


Figure 2.26 – Velocity frequency distributions for resource blocks (mid-water column)

Within each block, the kinetic resource varies with the stage of the tide. Representative hourly, daily, and monthly average kinetic power densities are shown in Figure 2.27. While there is considerable variability on the hourly and daily time-scale, month-to-month variability is lower and annual variations are on the order of only a few percent. For the hourly average, the diurnal inequality is apparent to either side of the strong tides during daylight hours and, for a daily average over a month, two neap-spring cycles are apparent.

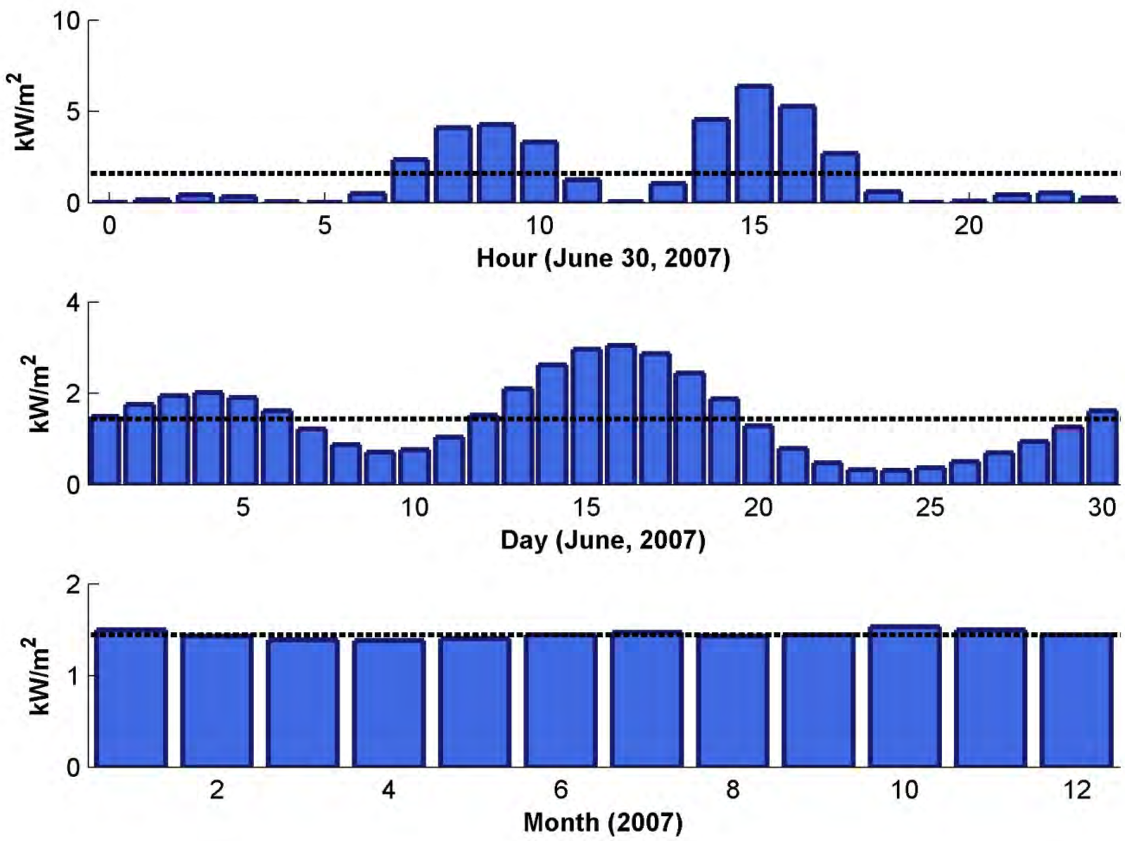


Figure 2.27 – Variations in average kinetic power density on an hourly (top), daily (middle), and monthly (bottom) basis for Resource Block 2 (mid-water column)

2.4 Far-field Conversion Effects

2.4.1 Background

The environmental effects of tidal energy development may be classified as either near-field or far-field effects. Near-field effects occur within close proximity to the tidal energy device (i.e., within several device diameters) and include changes to the flow field due to the wake, device noise, toxicity from fouling coatings, electromagnetic fields, and the physical presence of the device (strike potential and aggregation due to artificial reefing). Owing to the small number of device demonstrations conducted to date, detailed information on near-field environmental effects is limited. Far-field effects result from the increased flow resistance associated with each device. Because estuarine flows are general subcritical, these effects are experienced throughout the estuary and are not confined to the immediate vicinity of the project. Far-field effects include changes to tidal range, current velocities, volume transport, and mixing (Polagye 2009) and are in proportion to the amount of power removed from the flow. For limited development (e.g., pilot scale and some small commercial installations), numerical modeling suggests that these effects will be negligible. However, at larger scales, far-field effects may result in significant environmental changes throughout an estuary (e.g., exacerbation of hypoxia). In addition to environmental considerations, because kinetic power density depends on the cube of velocity, the far-field effect on kinetic power density (and, therefore, device performance) is particularly pronounced, as shown in Figure 2.28.

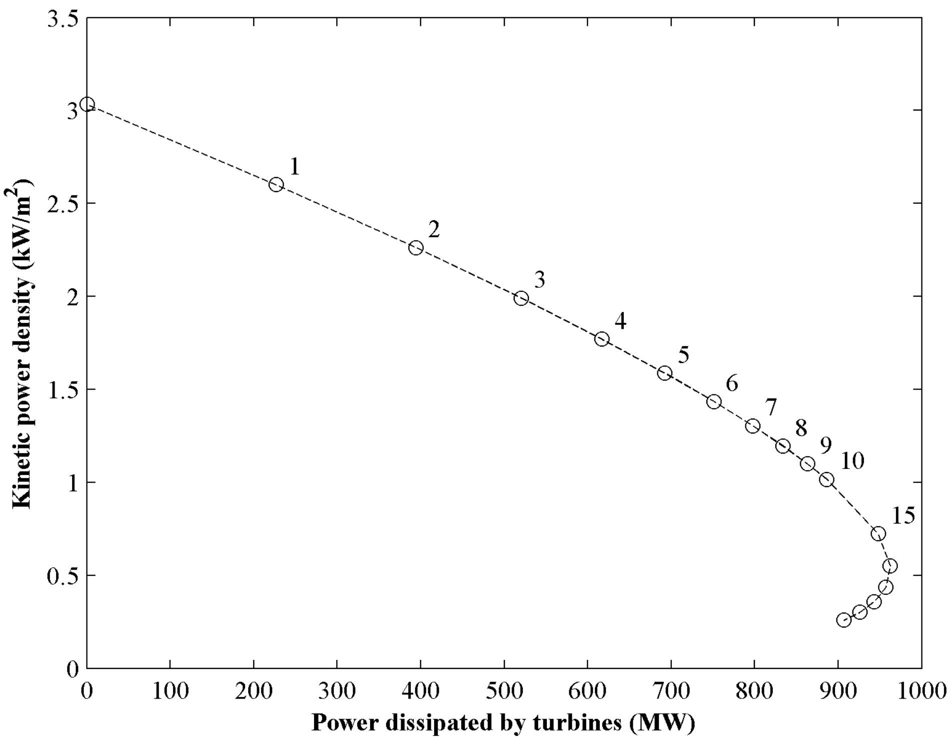


Figure 2.28 – Kinetic power density as a function of in-stream turbine power dissipation for an idealized tidal energy site (after Polagye 2009). Numbers denote turbine transects (rows) deployed across the constricted channel.

Because no large arrays have been constructed, all research on this topic is theoretical (Garrett and Cummins 2005, Sutherland et al. 2007 Blanchfield et al. 2008, Karsten et al. 2008, Polagye et al. 2008, Polagye et al. 2009). A significant complication is that the effects of energy conversion are strongly site specific and not related to the measurable kinetic resource on a channel cross-section (Garrett and Cummins 2008). Consequently, site-specific numerical modeling is necessarily to quantify this effect. Results from the model described by Polagye et al. (2009) are used for the present assessment of Tacoma Narrows, Washington, but other assessments may require new modeling.

Far-field changes, including kinetic power reduction, are controlled by the sum all fluidic losses associated with hydrokinetic power conversion. This is referred to as dissipated power and includes the power extracted from tidal currents for power generation, losses associated with the mixing of turbine wakes with the free stream, and losses associated with drag on turbine foundations. While foundation losses may be minimized by engineering design (Polagye 2009), wake losses are fundamental to the energy conversion process and depend on the turbine efficiency, the fraction of the channel cross-section occupied by turbines, and the ratio of inertial to gravitation forces in the flow (Froude number). For this assessment, analytical theories (Garrett and Cummins 2007, Polagye 2009) indicate that ~16% of the dissipated power should be attributable to wake losses. Foundation losses are estimated as 5% of total dissipation. Therefore, 79% of the power dissipated by hydrokinetic turbines is converted by the device, with the balance dissipated as turbulent kinetic energy. Diversion of flow around the ends of or over rows of turbines may lead to additional performance losses (Garrett and Cummins 2005), but these effects are neglected in the present study.

2.4.2 Puget Sound Model

In the numerical model described in Polagye et al. (2009), Puget Sound is parameterized as a series of interconnected, one-dimensional channels, as shown in Figure 2.29. Each channel segment has a constant, rectangular cross-section and roughness. Geometric properties (length, width, depth) are selected such that each channel is approximately as long as the equivalent section of the Sound and has the same average depth and surface area. The seabed drag coefficient parameterizes a number of dissipation processes (e.g., turbulence) and is adjusted to provide good agreement between modeled and observed tidal amplitude and phase. Flows are described by the 1D shallow-water equations and solved using the explicit McCormack predictor-corrector scheme. Power conversion by turbines is modeled as a flow discontinuity spanning the channel in discrete transects. The open boundary is prescribed at the interface between the Strait of Juan de Fuca and Admiralty Inlet using a modified form of a Flather boundary condition. Full details of the model calibration and numerical methods may be found in Polagye et al. (2009).

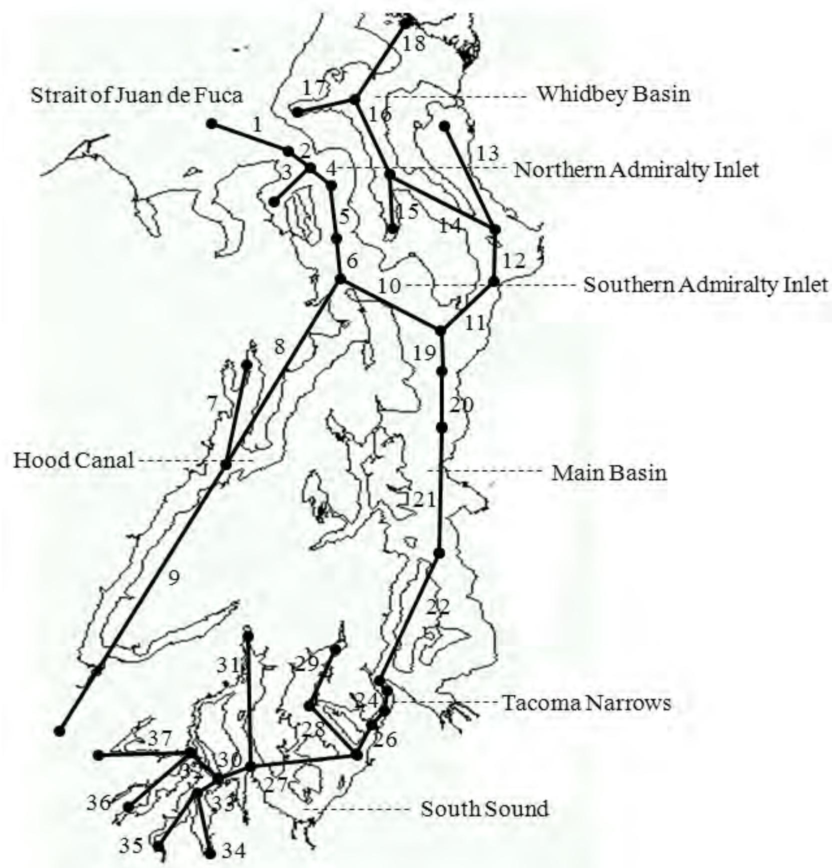


Figure 2.29 - Puget Sound channel network superimposed on Puget Sound coastline. Solid black lines denote channel segments (numbered) and black dots denote channel junctions or boundaries.

2.4.3 Results for Energy Conversion from Tacoma Narrows

The far-field effects of kinetic power conversion from Tacoma Narrows are quantified at four key locations in Puget Sound. Changes to the tidal range (M2 amplitude), transport, and mixing (using frictional dissipation as a proxy) are shown in Figure 2.30. In general, power conversion from Tacoma Narrows only affects the tidal regime along the main axis of Puget Sound and not terminal basins branching seaward of the Narrows (Hood Canal and Whidbey Basin). Along the main axis, the tidal range increases seawards of Tacoma Narrows and decreases in the landward direction. Transport and frictional dissipation are reduced along the main axis, with frictional dissipation showing the greatest dependence on power conversion.

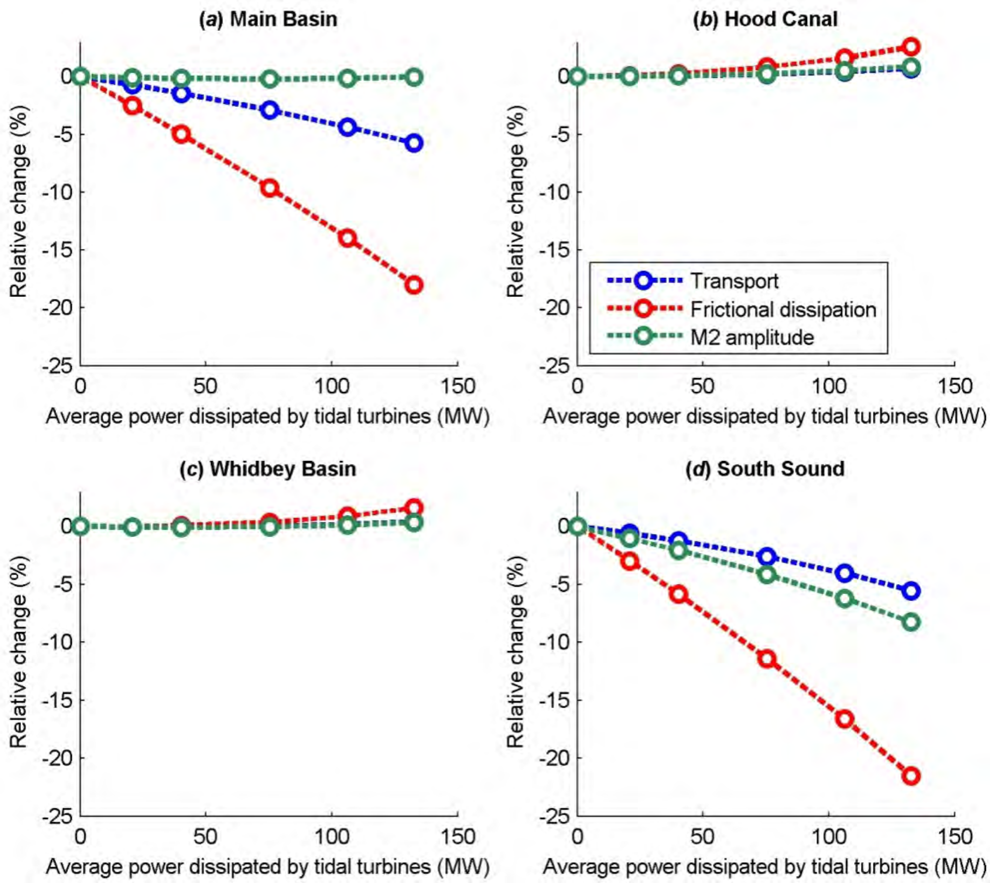


Figure 2.30 – Far-field energy conversion effects in Puget Sound as a consequence of kinetic power conversion in Tacoma Narrows. Markers represent discrete numbers of turbine transects.

The effect on kinetic power density in Tacoma Narrows is shown in Figure 2.31. Because the reductions in kinetic power density are relatively modest for the size of arrays being considered (Section 4), the performance implications of this change are approximated by reducing the average power output of each device by the same percentage as kinetic power decreases.

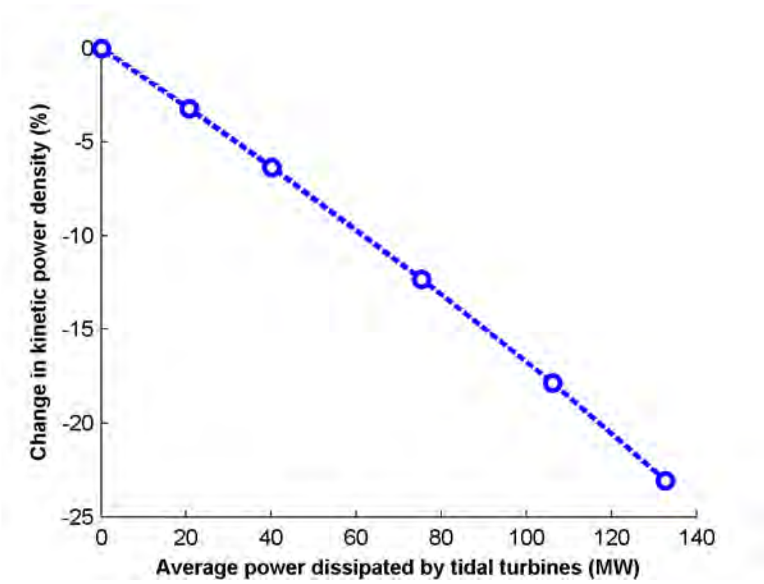


Figure 2.31 – Change in kinetic power density in Tacoma Narrows as a consequence of kinetic power conversion. Markers represent discrete numbers of turbine transects.

The following equations provide approximate relationships between power dissipation by hydrokinetic turbines and far-field effects for up to ~20 MW of average power dissipation in Tacoma Narrows (where *D* is the power dissipation in MW):

- M2 range change in South Sound -0.050 * *D in* % (2.4)
- Transport change into South Sound -0.029*D* % (2.5)
- Frictional dissipation (mixing) change in South Sound -0.14*D* % (2.6)
- Kinetic power density in Tacoma Narrows -0.16*D* % (2.7)

At a pilot scale, with average energy conversion of less than 1 MW, these results imply that far-field effects would be immeasurably small. For commercial scale projects, effects are likely to be measurable (on the order of 1% reductions to transport), but further work is required to understand the significance of such changes.

3. Tidal In-stream Devices

3.1 System Components

While there are a multitude of tidal energy devices under development, it is possible to generalize some of the components: rotors, power train, mooring, and foundation. Additionally, all devices or arrays require electrical transmission to shore and protection against bio-fouling.

3.1.1 Rotor

As with wind energy, the rotor is the means by which the energy in tidal currents is converted to rotational kinetic energy. Most devices presently at an advanced demonstration stage employ a horizontal axis where the axis of rotation is parallel to the direction of the flow. This is the same type of rotor used by modern wind turbines. Rotors may also have a vertical axis, where the axis of rotation is perpendicular to the direction of the flow. In both cases, the rotors typically have aerofoil cross-sections and operate on the principle of hydrodynamic lift. All three devices chosen for this scenario analysis are horizontal axis turbines. Within this category of turbines, there are a number of variations which typically trade-off rotor efficiency against device reliability.

The most efficient rotors are variable pitch in which the angle of attack of the aerofoil is adjusted according to the speed of the currents to maintain an optimal tip speed ratio (speed at rotor tip/current speed). Reversing currents may be accommodated by either a yaw control system which aligns the rotor with the direction of flow or, in nearly bidirectional currents, the blades may be rotated approximately 180 degrees[1]. Variable pitch rotors require motors at the blade root to adjust the pitch and a control system – both of which introduce potential failure mechanisms. However, in addition to optimizing power conversion efficiency over a range of current speeds, the variable pitch mechanism also provides for better control of device loads than for a fixed pitch system. Because the angle of the attack of the aerofoil is adjustable throughout the tidal cycle, device loads peak at rated speed and decline thereafter. Also, in the event that the rotor must be parked, the pitch angle can be adjusted to a neutral orientation and the blades held in place with a minimum of braking force.

Less efficient are fixed pitch, asymmetric rotors in which the pitch angle of the blade is fixed, but the aerofoil cross-section is asymmetric. Fixed pitch blades operate at an optimal angle of attack during only a portion of the tidal cycle and, therefore, have a lower average efficiency than variable pitch rotors. In order to operate in reversing tidal currents, fixed pitch designs must rotate the entire turbine at slack water

[1] This approach has been patented by Marine Current Turbines, Ltd

to set up for the next stage of the tide. This is generally accomplished by a yaw control, which keeps the turbine aligned into the direction of the flow. However, this rotational mechanism introduces a possible failure point.

The most robust design is a fixed pitch, symmetric rotor in which the pitch angle of the blade is fixed and the aerofoil shape is symmetric. As a result, the turbine may operate without yaw control in a bi-directional flow. However, symmetric aerofoils are considerably less efficient at converting power.

For all three of these variants, it is theoretically possible to increase device efficiency by incorporating a diffusing duct downstream of the rotor. However, there are two potential complications. First, in practice, it is very difficult to design a diffusing duct, as evidenced by the fact that no commercial wind turbines incorporate diffusers. Second, because it is generally impractical to rotate the diffuser during slack water, diffusers are required both upstream and downstream of the water. This gives bi-directional diffusers the appearance of a flow-accelerating venturi, but they operate on entirely different principles.

3.1.2 Power train

Once the rotor has converted flow translation to mechanical rotation, a power train is required to further convert rotation to electrical energy. Power trains may be generally separated into those incorporating a gearbox speed increaser between the rotor shaft and electrical generator, those in which the rotor shaft is directly coupled to the generator, and those in which the connection is hydraulic. Gearboxes have been problematic in the power trains of wind turbines, particularly due to the difficulty of replacing or repairing a failed unit, and may also be problematic for tidal turbines. However, direct drive turbines operate at much higher torque and require permanent magnetic generators which, until recently, were considerably more expensive than the induction or asynchronous generators which can be used in a power train with a gearbox. Hydraulic power trains require fewer rotating seals and are, therefore, considered more robust, but are significantly less efficient than either direct drive or conventional gearboxes.

In nearly all cases, power electronics are required to condition the output before transmission to shore and interconnection with the grid. For example, the voltage may be stepped up to 12-35kV to decrease transmission losses between the array and shore.

3.1.3 Mooring

The rotor and power train must be moored to a foundation which resists the forces generated by the rotor. In general, this mooring will be either a rigid or flexible, compliant connection. Examples of rigid connections include piles similar to those used in the offshore wind industry or tubular trusses. Because the amount of material required for a rigid mooring increases as the turbine moves up in the water column, the maximum hub height for a rigid mooring is limited by economic considerations. Compliant moorings, in which the mooring consists of flexible steel cable or chain, have much lower material costs and do not limit hub height. However, a device with a compliant mooring must incorporate a control system which utilizes buoyancy or lifting surfaces to offset the downward force generated by the device mass and tension on the mooring line. That is to say, while compliant moorings have advantages, they also introduce dynamic stability considerations absent from rigid mooring systems.

3.1.4 Foundation

Whether compliant or rigid, the mooring must be anchored to the seabed in a way that secures both the turbine and mooring against movement. One option is a penetrating anchor, such as a driven or drilled pile, which is secured in the seabed. In most consolidated or rocky seabeds, a penetrating anchor provides the most holding power for the smallest footprint. However, because the anchor is generally driven or drilled from the surface, installation in water deeper than 50-60m becomes uneconomical for a large diameter pile. In contrast, a gravity foundation does not significantly penetrate the seabed, but is held in place by its friction alone. Gravity foundations are lowered into position by a surface vessel and do not have a maximum deployment depth. However, for an equivalent resistive load, the footprint of a gravity foundation is greater than a penetrating foundation. Additionally, scour around a gravity foundation may be a consideration and require seabed preparation, such as laying scour mats, in advance of installation.

3.1.5 Electrical Transmission

Electrical transmission from devices to shore is an integral aspect of any tidal energy project. The electrical connection consists of two distinct segments: (1) the primary connection from land-based electrical networks to the offshore site and (2) collector circuits between one or more devices making up an array.

The nearshore area around tidal energy projects may contain particularly sensitive ecology which could be disturbed by trenching a cable into the seabed. Therefore, the preferred option is to utilize horizontal directional drilling (HDD) from the on-shore cable termination point (e.g., substation) to out beyond the nearshore region (i.e., cable exits from drilling onto seabed in water deeper than 20m). The feasibility of directional drilling is site-dependent, not appropriate in all soil types, and requires a careful geotechnical evaluation. HDD drill rigs are operated on shore and drill out to sea, as shown in Figure 3.1. A drilling fluid containing water and bentonite or a polymer is pumped to the cutting head and facilitates the removal of cuttings, cools the cutting head, lubricates the passage of the product pipe, and stabilizes the bore hole. An environmental concern is that some of this drilling fluid will enter into the marine environment, though such spillage can be minimized.

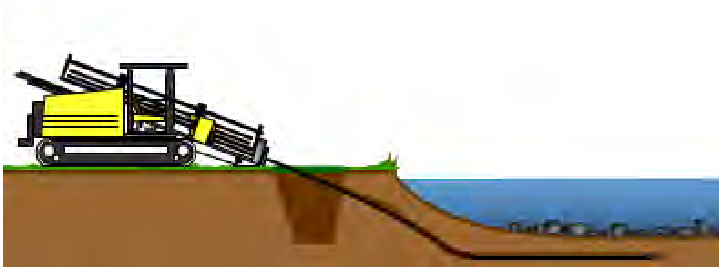


Figure 3.1- Horizontal directional drilling (HDD) rig

For a subsea cable landing, the installation starts by positioning a barge with the cable spool above the HDD conduit outfall. Then the cable is pulled through the conduit from the shoreline. Pulling forces need to be carefully monitored during this process to avoid damage to the cable. From the point where the cable emerges on the seabed, it is trenched, weighted, or bolted down (depending on the type of substrate) to prevent motion on its path to the turbine. A similar approach is used to secure the cable between devices.

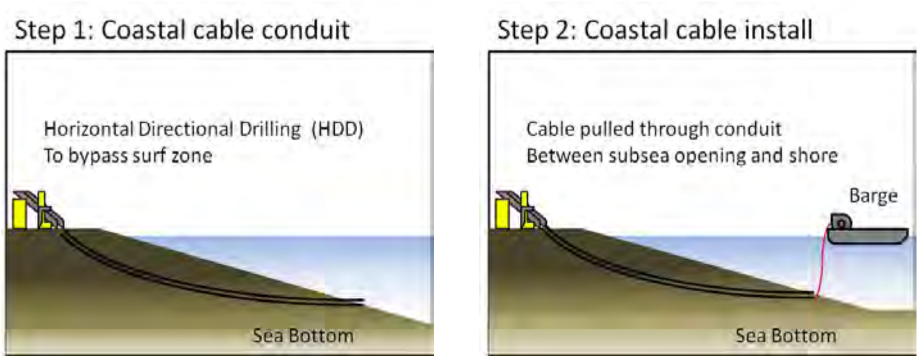


Figure 3.2 – Subsea cable installation

The umbilical cables required to connect turbines to shore are comparable to those used in the offshore oil and gas industry and for the inter-connection of different locations or entire islands. Cables are equipped with water-tight insulation and external armor, which protects the cables from the harsh ocean environment and the high stress levels experienced during the cable laying operation. While traditionally, sub-sea power cables have been oil-insulated, recent offshore wind projects in Europe have shown that environmental risks preclude the use of such cables in sensitive coastal environments. XLPE insulation has proven to be an excellent alternative. The electrical transmission cable typically also contains communication fibers to transfer data about device performance and/or environmental monitoring to shore and to allow an on-shore operator to shut down a device for maintenance activities.

For arrays of devices, an electrical network collects the outputs of the individual units for transmission back to shore (rather than laying a dedicated cable to shore for each device). Depending on the deployment scale and distance to shore, different topologies may be deployed. For larger systems, the collector system will put a number of units onto a single collector circuit and include provisions to isolate that circuit in case of an electrical fault. Further, some larger scale deployments may require the electrical voltage to be stepped up before transmission back to shore to minimize line losses. Electrical voltage levels on the collector system are usually limited by the rating of electrical connectors and switch-gear, which will be below 40kV. The transmission link back to shore may require higher voltage levels, depending on distance and required capacity.

3.1.6 Fouling Protection

Fouling from biological growth on devices represents a significant performance risk (Orme et al. 2001). While turbines operating beneath the photic zone are at lesser risk, fouling by barnacles and algae remains an issue for devices with long maintenance intervals. As a result, working surfaces are generally treated with an anti-fouling or foul release coating. Possibilities include conventional biocide paints and inert, low friction coatings. For economic or environmental reasons, other components of the foundation and support may remain uncoated, with sacrificial anodes for cathodic protection.

3.2 Performance Model

3.2.1 Individual Device

A simplified model is used to evaluate performance (i.e., electrical power produced) for an individual device. At any stage of the tide, the turbine is operating in one of three states, as shown in Figure 3.3

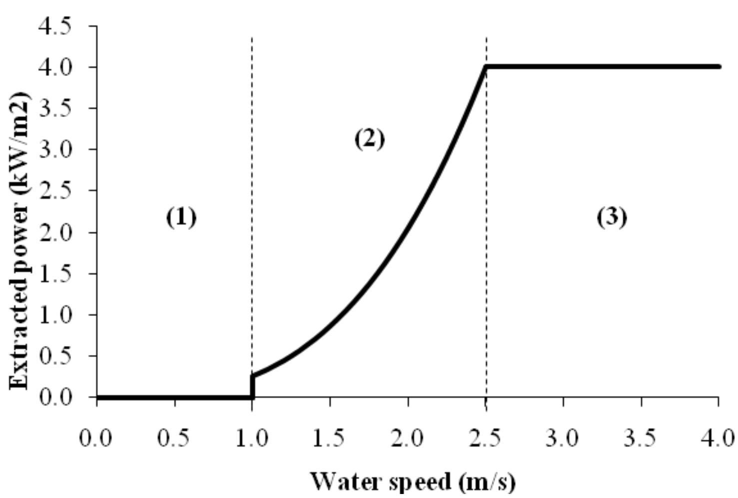


Figure 3.3 – Representative turbine power curve for a variable pitch rotor. Region (1) is below the cut-in speed and the turbine converts no power. In Region (2), power is converted in proportion to the kinetic power incident on the rotor swept area. Region (3) is above the rated speed and power conversion is constant.

1. Below cut-in speed: The water speed is insufficient to rotate the blades and the turbine generates no power. Typical cut-in speeds are between 1 and 2 knots (0.5-1 m/s).

$$P_{extracted} = 0 \tag{3.1}$$

2. Between cut-in and rated speed: The turbine converts power in proportion to the kinetic power incident over the rotor swept area (A). The constant of proportionality is the rotor conversion efficiency (η_e);

$$P_{extracted} = \frac{1}{2}\eta_e \rho A u^3 . \tag{3.2}$$

   For all devices evaluated, the rotor efficiency is assumed to be constant. This is nearly true for variable pitch rotors. For fixed pitch rotors, the efficiency varies with the current speed. However, because most developers consider their power output curves to be proprietary, a constant, but lower, efficiency is also assumed for fixed pitch rotors.

3. Above rated speed: Constant power is converted from the flow;

$$P_{extracted} = P_{rated} . \tag{3.3}$$

   This is either achieved by varying the blade pitch or designing a fixed pitch blade such that the hydrodynamic performance (η_e) declines faster than the kinetic power incident on the rotor. The rated speed and, therefore, rated power are determined by economic considerations. Previous parametric cost, performance and economic studies (Bedard et al. 2006) broadly suggest that the rated speed should be chosen to achieve a 30% capacity factor for US west coast sites with a mixed, mainly semidiurnal tidal regime and 40% capacity factor for east coast sites with a mainly semidiurnal tidal regime. The capacity factor is defined as the ratio of the average power output to the rated power converted.

Once the converted power is known, the electrical power generated by a device is given by the efficiency of the power train;

$$P_{generated} = P_{extracted}\eta_{power\ train} \tag{3.4}$$

The average power output on an annual basis is the average of all power generated.

For the purposes of a first-order performance assessment, the velocity distribution at the device is described by a histogram, as described in Section 2.3. While the velocity distribution varies with depth and, therefore, is not constant over the rotor swept area, the hub height velocity distribution has been shown to approximate the integrated distribution over the entire rotor (Hagerman and Polagye 2006).

Performance degradation due to bio-fouling, turbulent intensity, and off-axis flows are neglected for the purposes of this analysis due to a lack of quantifiable data. However, these effects may be appreciable.

3.2.2 Device Arrays

Estimating the power output of an array of devices follows that of an individual device, with the power output of an array being the sum of the power from all turbines. Two additional considerations at an array scale are far-field effects (wide-area changes associated with increased resistance to flow) and near-field effects (changes to fluid flow within a few rotor diameters of the device).

As described in Section 2.4, the installation and operation of hydrokinetic turbines increases resistance to flow. While the velocity frequency distribution may not be uniformly reduced, at the relatively low levels of conversion assessed here, it is assumed that the power output reduction will be in proportion to the kinetic power reduction described by equation (2.7).

Each turbine also generates a low speed wake downstream of the device. Turbulent action mixes the wake with the free stream, eventually restoring the flow to a more homogenous profile. If a turbine operates in the wake up an upstream device, its power output will be substantially reduced. Therefore, it is important that devices be spaced sufficiently far apart. For the purposes of this assessment, the minimum longitudinal spacing between each device is assumed to be 15 turbine diameters. This is a conservative estimate based on flume experiments with scale models (Myers and Bahaj 2007) and numerical simulations of in-stream turbines (Sun et al. 2008). Because of the predictable, reversing nature of tidal streams, a lateral spacing of ½ a turbine diameter is assumed for rigid moorings and 1 turbine diameter for compliant moorings. Wind turbine arrays require greater lateral spacing because the direction of the wind has considerably more variability. For arrays in which rows of turbines span the entire channel cross-section, the assumption used here for lateral spacing could result in an unacceptably high blockage for aquatic species. However, the scenarios described in Section 4 all have low blockage ratios - less than 5% of the channel cross-section. With these lateral and longitudinal spacing assumptions, it is expected that there will be no turbine-turbine interactions that reduce performance.

Array performance is estimated as follows. Based on device placement rules (e.g., minimum overhead clearance) and longitudinal and lateral spacing assumptions, all possible turbine deployment locations within Tacoma Narrows are identified. The average power output for each possible device is determined for a range of rated speeds and a coarse adjustment is made for the reduction in power density at a particular array scale due to far-field effects. Each development scenario has a targeted rated electrical capacity (1 MW for pilot, 10 MW for small commercial, 50 MW for large commercial). The final array configuration consists of the fewest number of contiguous devices capable of meeting the desired rated power and capacity factor. That is to say, for the purposes of this assessment, an optimal array is clustered in the region of highest power output and rated at an assumed level of economic competitiveness. Based on previous parametric studies for this site (Polagye et al. 2006), a capacity factor of 30% is assumed. An alternative optimization would be to select the devices with high power outputs regardless of location, but this results in unfeasibly sparse arrays (e.g., long subsea cable runs).

While many of the environmental effects of array-scale operation cannot be assessed due to a lack of at-sea test data, some of the near-field and far-field environmental stressors can be quantified:

1. Volume of lubricants/hydraulic fluid
2. Seabed footprint: surface area of seabed disturbed by the device foundation (does not include seabed disturbed by cable laying activities)
3. Permanent hard substrate: surface area of hard substrate estimated to remain in the water over the service life of the project. These are surfaces that will eventually be colonized by marine life.
4. Blockage ratio: ratio of rotor swept area to channel cross-section (average value for all transects in the array)
5. Operational time: fraction of time device operates (currents above cut-in speed) on an annual basis. Below cut-in speed, rotors are stationary and the device will not greatly increase near-field noise.
6. South Sound transport: percentage reduction in volume transport in South Sound, with implications for flushing of pollutants and general water quality.

These metrics can assist in scenario comparisons and structuring monitoring plans for different scales of development.

3.2.3 Devices Selected for Evaluation

Three devices have been selected for evaluation: the Marine Current Turbines SeaGen, the Lunar Energy RTT, and the SMD TidEl. The components for each design are summarized in Table 3.1. These devices have been selected to be representative of the variety of device concepts under development. Each is described in considerable detail in the following sections.

Table 3.1 – Device summary

	Marine Current Turbines SeaGen	Lunar Energy RTT	SMD TidEl
Rotor	Dual rotor, horizontal axis: variable pitch aerofoil	Horizontal axis: fixed pitch, symmetric aerofoil Ducted	Dual rotor, horizontal axis: fixed pitch, asymmetric aerofoil
Power train	Gearbox speed increaser	Hydraulic	Gearbox speed increaser
Mooring	Rigid: pile	Rigid: tubular truss	Compliant: cable
Foundation	Penetrating pile	Gravity base	Gravity base

These devices are at relatively different stages of development. A commercial prototype of the SeaGen has been operating since the end of 2008 in Strangford Lough, Northern Ireland. The RTT has been tested at small scale in a laboratory tank and a full-scale test is planned within the next year. A 1/10th prototype of the TidEl has been tested in a converted drydock at NaREC in the UK. As such, these devices are also representative of the general stage of development for the tidal energy industry. To date, only five developers have conducted at-sea trials:

- Marine Current Turbines: 11m diameter SeaFlow pilot test off Devon, UK (3 years duration) and the 16m diameter dual rotor SeaGen commercial prototype in Strangford Lough, Northern Ireland (< 1 year duration)
- Verdant Power: 6 *x* 5m diameter demonstration array in the East River, New York (several months duration)
- Clean Current: 6m diameter pilot test off Race Rocks, British Columbia (several months duration)
- OpenHydro: 6m diameter pilot test at the European Marine Energy Center (EMEC) in the Orkney Islands, UK (several months duration)
- Hammerfest Strøm: 14m diameter pilot test off Hammerfest, Norway (3 years duration)

While these tests have provided valuable insight on the technical aspects of installation and commissioning, there have not yet been any long-term installations of commercial prototypes to develop a full understanding of device survivability and reliability.

3.3 Operational Procedures

Common to all devices, are several operational procedures: pre-installation, installation, operation, and decommissioning. While there are some activities requiring a fixed level of effort per site, the duration of most procedures scales with the size of the turbine array. For the purposes of this report, three deployment scales are considered, defined by their rated electrical power:

1. Pilot: ~ 1 MW
2. Small Commercial: ~ 10 MW (representative of an early commercial array)
3. Large Commercial: ~50 MW (representative of a mature commercial array)

Because of the specifics of the site and devices, these three scales involve a different number of devices for each technology type, as described in detail in Section 4. The resources and duration for each category of procedure are discussed in more detail for each of the three devices being evaluated in the following sections. The durations listed are estimates for time on station only and do not include the time required to mobilize and demobilize operational resources (e.g., vessels). These are meant as representative examples of an in-stream deployment and only one of several options. For example, a large-scale development might mobilize additional equipment to conduct several installations in parallel or mobilize specialty equipment with a long lead time capable of performing the same tasks more quickly (i.e., mobilize equipment from Europe to the US west coast).

3.3.1 Pre-installation

Pre-installation activities depend more on site characteristics and the scale of development than the particular device being deployed. In fact, the results of pre-installation activities (e.g., type of substrate, resource characteristics) may determine which device is best suited for a site. From an engineering perspective, pre-installation activities include:

- High resolution bathymetric survey at deployment site and along cable route to identify problematic subsea features (rocky outcroppings, locally high slopes, old cables, wreckage, etc). Multi-beam and side-scanning sonar is deployed from a small survey vessel to accomplish this.
- Sub-bottom profiling to identify the structure of the underlying seabed. A "chirp" profiler operating at around 3.5 kHz is deployed from a small survey vessel to accomplish this. Cobbled seabeds tend to scatter the acoustic pulse, making it difficult to identify the underlying substrate using this method. While the sea floor of tidal energy sites are often consists of scoured bedrock or cobble, the route for the electrical cable may cross areas of looser sediments.
- Visual inspection of seabed in deployment area and along cable route. For shallow sites, it may be possible to conduct diver surveys, but in most cases it will be necessary to deploy an ROV (remotely operated vehicle). ROV surveys should be carried out during periods of neap tides as slack water windows during spring tides may be very short (e.g., 5-15 minutes).
- To characterize the in-stream resource, accurate velocity measurements are required. The instrument of choice for such measurements is an ADCP (acoustic Doppler current profiler) which determines velocity based on the Doppler shift of an acoustic return from sound scatterers in the water column (e.g., suspended particulate). ADCPs should be deployed on the seabed to generate a long-term measurement of the currents (necessary for resource prediction) and aboard a survey vessel to collect information about spatial variation. The European Marine Energy Center (EMEC) has published guidelines for both shipboard and bottom mounted ADCP surveys (Legrand 2009). Shipboard surveys require several days of effort. Bottom-mounted ADCPs should be deployed for at least a month and require a day of effort on either end to deploy and recover. In addition to the strength and direction of the resource, ADCP measurements provide higher level statistics (e.g., eddy intensity) as discussed in Section 2.1.1. Note that high-quality resource predictions may require up to half a year of current measurements to resolve a full set of tidal constituents.

- Environmental baseline studies are required by regulatory agencies to assess the potential impacts of a tidal energy project. These studies may require several years of data collection to build up an accurate picture of seasonal and annual variation and include: background noise, aquatic species identification and behavior in project area, and water quality.

For bathymetric and sub-bottom surveys, most of these effort is weighted towards mobilization and demobilization of equipment and is relatively insensitive to the size of the site being developed. ROV surveys are operationally more time-intensive, with the duration of the survey increasing with the scale of development. The same is true of ADCP surveys, particularly bottom-mounted instrumentation, which may have to be deployed at several locations within a project area to accurately characterize spatial and temporal variations in the in-stream resource. As project scale increases, the duration of environmental baseline studies is likely to increase somewhat. However, more importantly, the type of studies may change as, in general, baseline studies should be commensurate with the scale of development. Projects which are within the envelope of existing environmental variability (e.g., pilot scale development at a large site) should require fewer baseline studies. However, large-scale development which has the potential to substantially alter the ecology of site may require more detailed studies to understand the effects of a project. Rigorous baseline studies may also be required in waters which are habitat for endangered species protected by federal statute.

3.3.2 Installation

The impacts of installation activities are perhaps the easiest to quantify as they are significantly derived from existing maritime operations and compressed in a relatively short (1-4 year) time frame. Offshore construction activities are dependent on the weather window for a site and the strength of the tidal currents. For tidal energy sites close to the open ocean, calm seas are required for many operations, which will likely constrain the construction season to the May through early September time period. Tacoma Narrows, which is far inland, has relatively minor wave action throughout the year and the construction window will be considerably wider.

Some installation operations may be possible around slack water, but at energetic sites, the period of actual slack water may be very short, on the order of only a few minutes, and accompanied by strongly sheared flow throughout the water column (Figure 3.4). Rather than attempting to operate in this window, it may be preferable to wait until the current has set weakly in one direction. Multi-hour operational windows may be possible during neap tides or periods of diurnal inequality within spring tides (depending on the tidal regime at the site).

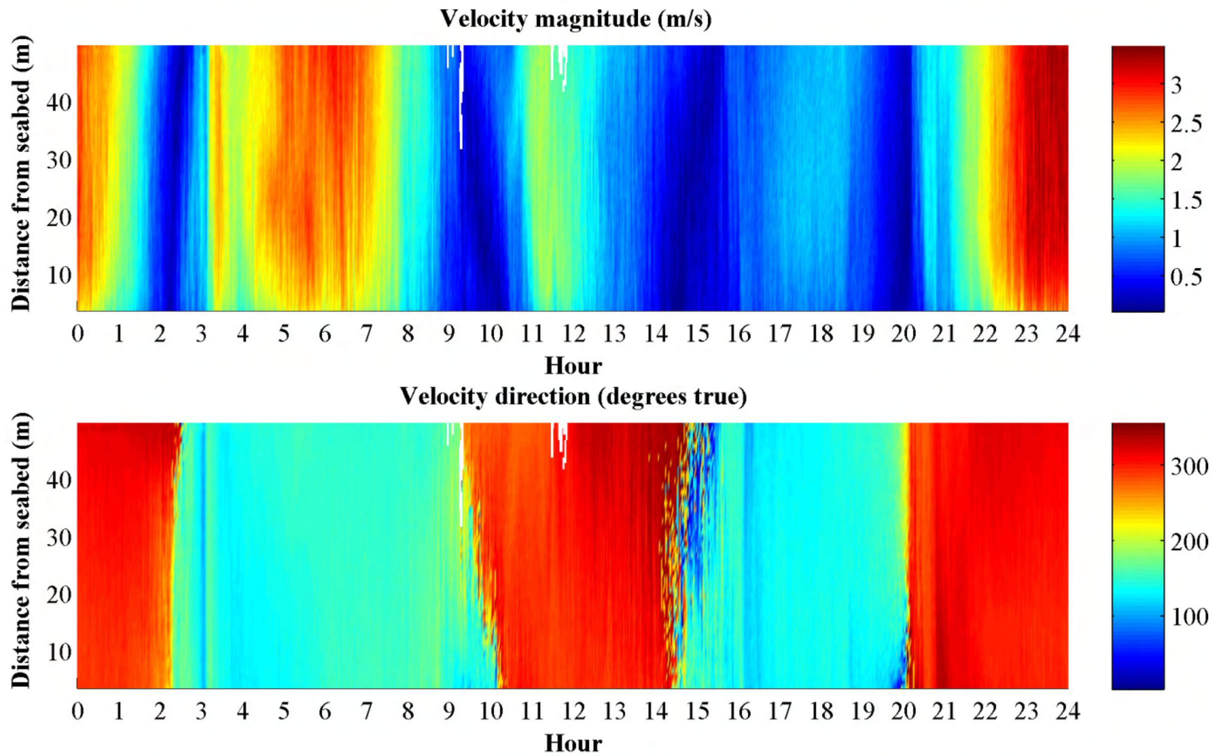


Figure 3.4 – Velocity magnitude and direction over a 24 hour period in Admiralty Inlet, Washington (source: high-resolution ADCP measurement by Northwest National Marine Renewable Energy Center). Note the directional shear around slack water (hours 9-10, 14-15) and the diurnal inequality (12 hours of relatively weak currents bracketed by strong currents). For this site, currents around 150 degrees are set to flood and those around 330 degrees set to ebb.

Device installation consists of three steps:

1. Installation of foundation and mooring on seabed
2. Installation and commissioning of device (i.e., rotor, power train, duct)
3. Installation and connection of subsea cable

The particulars of these tasks depend on the site and the device, but the type of resources required for installation is similar for the all devices under evaluation:

- Derrick barge: the workhorse for device deployment is a large barge equipped with cranes and/or hydraulic strand jacks. A moored barge provides a stable platform to carry out installation. Note that while jack-up barges can also provide a stable working platform, few are available for use in North America.
- Tugs: As a derrick barge is unpowered, tugs are required to bring it on site and maneuver it into position during anchoring operations.

- Supply boat: While the device and foundation will be loaded on the derrick barge, smaller piece of equipment and consumables may be brought to site over the course of the installation by a smaller boat.
- ROV (remotely operated vehicle): ranging in size from a shoe box to large car, these unmanned vehicles are controlled by an operator on the surface. They are equipped with cameras, lights, and tools for visual inspection and simple mechanical tasks.
- Divers: Because of the strong currents and deep water of potential tidal energy sites, divers should be used sparingly for reasons of safety and cost. As depth increases, dives become increasingly technical and require the use of mixed gasses (mixtures other than compressed air) and staged decompression on the way back to the surface. This may be logistically infeasible for sites with semidiurnal tides, but possible for mixed, mainly semidiurnal sites where the diurnal inequality provides a longer operating window. Technical diving will also require an additional surface support vessel equipped with a decompression chamber, which adds significantly to cost.
- Hydraulic strand jacks: hydraulic systems for raising and lowering heavy loads, such as gravity foundations. These work by sequential hydraulic expansion and contraction of a steel cable core.

Installation of the subsea power and data cable requires an onshore directional drilling rig and an offshore vessel for laying cable, securing it to the seabed, and connecting it to each device. Depending on the type of substrate, cable laying operations may also require an ROV. Directional drilling and cable laying operations are described in more detailed in Section 3.1.5.

Installation activities may have significant economies of scale. For example, the time to mobilize or demobilize heavy construction equipment to the project site is somewhat independent of the number of devices being deployed. There will also be some learning scale as installation crews adjust procedures to account for site-specific conditions. Conversely, seasonal weather windows may extend the time required to complete operations (e.g., six months of continuous effort may be spread over two seasons). Neither of these considerations are taken into account in the following operational procedures.

3.3.3 Operation and Maintenance

There are a number of approaches to turbine design and maintenance. On one end is a highly efficient device with more complex control mechanisms and a greater risk for device failure. Such a device may require a relatively frequent maintenance cycle to ensure no subsystem suffers a catastrophic failure and should be designed accordingly. On the other end of the spectrum is a highly robust device with an absolute minimum of moving parts. For such a device, the maintenance cycle may be longer, but this is balanced against a less efficient rotor and power train.

There are two broad categories of maintenance operations for the rotor and power train:

- Maintenance and inspection at sea: For most devices this will involve visual inspection of submerged components with an ROV deployed from a support vessel. However, maintenance of the power train will be generally impractical while at sea. The exceptions are devices designed to provide a stable platform for at-sea rotor and power train maintenance, such as the Marine Current Turbines SeaGen where it is possible to raise the power trains out of the water using an onboard hydraulic lifting system. For such devices, many routine maintenance activities can be carried out at sea and only require a vessel to transport personnel and equipment to the device (e.g., rigid inflatable boat). Further, such a system allows for smaller sub-systems to be extracted for more extensive overhaul on shore.
- Recovery of power train to shore: For devices without stable at-sea platform, the rotor and power train are recovered to the surface in a manner comparable to their deployment. A replacement rotor and power train are then deployed and the unit requiring maintenance returned to shore. This is economically preferable to attempting repairs at-sea, given the challenging physical environment or leaving the foundation and mooring unoccupied for an extended period during repairs.

Generally, non-mechanical components of a device (foundation, mooring, etc.) are not scheduled for recovery or maintenance during their service life (20-30 years). In the case of a premature failure to the mooring or foundation, it may be possible to recover these components to shore and re-install a new unit at the site.

One aspect of device and array maintenance which is not well understood is the necessary servicing interval for instrumentation installed to monitor the possible environmental effects of the installation. This instrumentation may be sensitive to biofouling and/or sensor drift and require servicing at a more frequent interval than the tidal energy device. For example, the intake lines for dissolved oxygen sensors, which could be required by water quality agencies, foul over time, leading to sensor drift and eventually cut-off flow over the sensors. The permits to operate a turbine array will, generally, be linked to specific monitoring requirements and instrumentation failure, while not directly integral to device operation, may require a turbine or array to be deactivated until repairs can be carried out. Because of these considerations, instrumentation packages should be designed so that they may be serviced independently of the device.

3.3.4 Decommissioning

Decommissioning of a device or an array at the end of its service life mirrors installation procedures in most cases. In all cases, all moving parts (rotor and power train) would be recovered and returned to shore. In most cases, the foundation would also be recovered. The exception to this would be gravity foundations exceeding the lift capacity of maritime vessels (e.g., installed in pieces, but can only be recovered as a single unit) or seabed penetrating piles (which would be cut at the mudline so that only the penetrating portion of the pile remains on site). Electrical infrastructure between turbines and to the shore would also be recovered and any on-shore civil works decommissioned.

The above approach would return the site to nearly its original state after a period of disruption associated with decommissioning. However, this may not necessarily be desirable. For example, full removal of a gravity foundation which has been heavily colonized by marine life over a 20-30 year period could be more disruptive than leaving it in place. Likewise, power and data cables could serve as a means for important cabled observations along the seafloor. These considerations will need to be addressed on a site-by-site basis with project stakeholders at the end of a devices service life or permit period.

3.4 Navigation

As with all project elements, navigation safety will need to be addressed through a consultation process with the relevant stakeholders. In broad terms, navigation safety should address the interaction of the device array and its operation with other users of the sea-space and should minimize risk for all users. For details on navigational considerations related to wave and tidal power projects, the reader is encouraged to review a document recently released by PCCI (Marine and Hydrokinetic Renewable Energy Technologies: Potential Navigational Impacts and Mitigation Measures, December 2009). PCCI also released a checklist that can be used by project developers to insure that they address potential aspects affecting navigation during the siting process.

The U.S. Coast Guard (USCG) and other agencies will participate in the National Environmental Policy Act (NEPA) review process conducted by the primary licensing agency. That participation will include advice on potential navigational hazard issues that may result from a proposed Renewable Energy Installation (REI) and possible mitigation for those issues.

3.4.1 USCG Concerns over Hazards

The USCG's concerns[2] over possible hazards that result from an REI may vary, depending on the project phase. These phases include: design, construction, transportation to and from the site, installation, operations and finally decommissioning. For each of these phases the USCG requests developers to consider potential navigational impacts of the installation, including;

Platform, Stationkeeping, Device, Mooring, Transmission Cable and other design considerations

- Visual Navigation and Collision Avoidance
- Effects on Communications, Radar and Positioning Systems

Site and Waterway considerations

- Effects upon Tides, Tidal Streams, and Currents
- Effects upon seafloor soil movement
- Effects of varying weather and sea state
- Effects of ice where applicable

Maritime Traffic and Vessel Considerations

- Traffic Survey Recommendations
- Risk of Collision, Allision, or Grounding
- REI Structure Clearances and Responseto allision
- Access to and Navigation Within, or close to, the REI

USCG Mission Considerations

- Recommended design requirements, operational requirements, and operational procedures for installation shutdown in the event of a Search and Rescue (SAR), Pollution, or Homeland Security Operation
- Recommendation to work with the USCG to assess likely impacts on USCG SAR, Marine Environmental Protection (MEP) and Homeland Security missions

3.4.2 Key Mitigation Measures

Consultation with Stakeholders

Developers should schedule meetings/events with stakeholders and relevant permitting agency personnel to understand siting conflicts. These meetings/events should begin early and continue through the licensing or permitting process.

[2] These concerns are included in USCG policy guidance:Navigation and Vessel Inspection Circular 02-07, which is available online at http://www.uscg.mil/hq/cg5/NVIC/pdf/2007/NVIC02-07.pdf

Navigation Studies and Risk Assessment

A key mitigation measure involves undertaking the requisite navigational studies and evaluating the navigational risk of proposed projects. These studies will be required to provide the information necessary for environmental assessments, environmental impact statements and permit applications. Based on the results of navigation studies and risk assessment, a developer may want to consider mitigation measures, including alternative siting and incorporating stakeholder concerns. It is the responsibility of the developer to fund or provide the studies and analysis to support recommendations for their installation.

IALA Recommendation O-139

Another key mitigation measure involves incorporating the marking schemes in International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) Recommendation O-139 (2008)[3] in developers' proposals, with the realization that the USCG may modify an initial marking scheme proposal, based on its review of traffic, risk and other factors.

Private Aids to Navigation (PATON)

The U.S. Aids to Navigation System is administered by the USCG. It consists of federal aids operated by the USCG, by the other armed services, and private aids to navigation operated by other persons. The U.S. System is consistent with the IALA Maritime Buoyage System, but as of 2009, its regulations do not incorporate specific IALA recommendations for PATON covering offshore wave and tidal energy devices. USCG policy guidance recommends incorporating the marking schemes in IALA recommendation O-139 as providing an equivalent level of safety and environmental protection to marking schemes specified in USCG regulations.

3.4.3 Likely Demarcation Measures

From a navigation point of view the deployment of many individual wave or tidal power conversion units arranged in arrays raises the question of how these devices are best marked to avoid potential vessel allisions[4]. Navigation demarcation may include — (1) paint color, (2) lighting, (3) active and passive radar aids, (3) warning sounds and (4) an automatic identification system. How exactly they need to be applied begins with the developer's evaluation of potential impacts on navigation and proposal of navigational demarcation for the proposed site. The final demarcation scheme will be determined through

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3 http://site.ialathree.org/pages/publications/documentspdf/-doc_225_eng.pdf

4 An allision is a term of reference that is used when a moving object strikes a stationary object. This is in contrast to a collision, where both objects are in motion when a strike occurs.

open consultation with stakeholders such as Coast Guard and affected waterways users. This section provides general demarcation schemes for illustrative purposes only.

Paint Scheme	Paint Color and scheme is standardized for different navigation obstacle types. In addition, visual aids such as reflective materials and numerical characters may be required for proper identification of a structure at sea.
Lighting	Lighting color, flashing synchronization, and visibility range will depend on the specific application.
Sound Signals	Fog-horns are typically used and should be considered for marking marine energy structures and arrays. Minimal audible range is 2Nm.
Radar Reflector	For structures that do not provide a good radar signature consideration for a radar reflector mounted on top of the structure should be given. Radar reflectors are designed to best reflect radar signals.
AIS	Automatic Identification System (AIS) is a short range coastal tracking system used on ships and by Vessel Traffic Services (VTS) for identifying and locating vessels by electronically exchanging data with other nearby ships and VTS stations. AIS was developed with the ability to broadcast positions and names of objects other than vessels, like navigational aid and marker positions.
RACON	RAdar BeaCON, also called radar responders, or radar transponder beacons, are receiver/transmitter transponder devices used as a navigation aid, identifying landmarks or buoys on a shipboard marine radar display. A racon responds to a received radar pulse by transmitting an identifiable mark back to the radar set. The displayed response has a length on the radar display corresponding to a few nautical miles, encoded as a Morse character beginning with a dash for identification. The inherent delay in the racon causes the displayed response to appear behind the echo from the structure on which the racon is mounted.
SPS	Significant Peripheral Structure (SPS) - Significant Peripheral Structure (SPS) is a corner or other significant point on the periphery of the array. Every SPS should be fitted with light, visible in all directions in the horizontal plane. These lights should be synchronized to display a 'Special Mark' characteristic, flashing yellow, with a range of not less than 5 nautical miles. The distance between SPSs should not normally exceed 3 nautical miles. Some typical demarcation schemes are included below.

Scheme 1: Bottom standing and surface piercing devices – *Single Device*

Device Example	MCT SeaGen
Paint Scheme	Marked for isolated danger. These marks are colored black with one or more broad horizontal red bands and are equipped with a topmark of two black spheres, one above the other. Consideration should be given to the use of additional retro-reflective material (i.e. visually reflective material in addition to lighting).
Lighting	White light – a group flash light Fl(2), with two flashes in a group. Required range is not less than 5 nautical miles.
Sound Signal	Consideration may be given to sound signals, where appropriate. Typical sound signal is not less than 2 nautical miles.
AIS	Consideration should be given to the provision of AIS on selected wave and/or tidal energy devices. For a single surface-piercing SeaGen in the Tacoma Narrows, a RACON should be considered.
SPS	No SPS needed for single device

Scheme 2: Bottom standing and surface piercing devices – Array

Device Example	MCT SeaGen
Paint Scheme	Yellow paint
Lighting	SPS – synchronized flashing yellow lights with 5Nm visibilityIndividual devices – white flash lights synchronized with 2Nm visibility. Not every device may need to have a light.
Sound Signal	Considerations should be given to sound signals on selected devices.
AIS	Consideration should be given to the provision of AIS on selected wave and/or tidal energy devices.
SPS	Outer array boundaries should be marked with SPS.

Scheme 3: Completely Submersed Structures (no interference with surface navigation)

It may be reasonable to mark subsurface arrays, even though the clearance and safety factor would indicate there to be no interference. Marking upper and lower extremes of the channel sides with yellow Special Mark buoys/pilings/small structures with yellow lights – a total of four would be reasonable. Additional features of retro-reflecting material and RACONs on each buoy/piling/small structure would also be reasonable. For completely submersed structures in the open ocean, only an entry in navigation charts may be required.

Construction and Operation – The Developer would likely propose a Safety Zone in the application for private Aid to Navigation and include the information in submittal of environmental information in the EIS process. Coast Guard would also distribute Notices to Mariners and publish the Safety Zone in the Federal Register. Lighting during construction/deconstruction is by keeping lighted vessel/work barge on site.

3.5 Marine Current Turbines

	
(a) Strangford Lough commercial prototype with rotors raised for inspection	(b) Artist's rendering of device in operation

Figure 3.5 – Marine Current Turbines (MCT) SeaGen

Device Specifications

Number of Rotors	2
Rotor Diameter	20m
Rotor Swept Area	630m^2 (both rotors)
Power Train	Variable speed, gearbox coupled to induction generator
Rotor Efficiency	45%
Power Train Efficiency	94%
Cut-in Speed	0.7 m/s
Rated Capacity @ 2.0 m/s	1.1MW
Maximum Operating RPM	11.5 RPM (tip speed limited to 12 m/s)
Foundation Type	Seabed penetrating monopile
Hub Height	Variable – Minimum 18 m
Hydraulic Fluid or Lubricant	110 L of gearbox lubricant (BP Energol GR-XP100)
Power Train Weight	49 tonnes (rotor and power train)
Total Device Weight	394 tonnes
Generator Voltage	480V or 690V
Footprint on seabed	7 m^2
Service Life	20+ years

Company Information

Company Name	Marine Current Turbines Ltd.
Website	www.marineturbines.com

The above specifications describe an MCT device which could be deployed in Tacoma Narrows. In practice, SeaGen can accommodate a range of rotor diameters (15-20m). Additionally, the device described here is somewhat different than the commercial prototype presently deployed in Strangford Lough, Ireland. The prototype has 16m diameter rotors (for a combined swept area of 400 m^2), is rated at 1.2 MW (for a 2.4 m/s current), rotates at 15 RPM, and is secured to the seabed by a pin piled jacket rather than a penetrating monopole. Because of the smaller rotor size, the power train weight is also lower, at 28 tonnes.

3.5.1 Principle of Operation

The Marine Current Turbine (MCT) SeaGen free flow water power conversion device has twin open axial flow rotors mounted on "wings" to either side of a monopile support structure. Each rotor consists of two blades. Rotors have full span pitch control and drive induction generators at variable speed through three stage gearboxes. Gearboxes and generators are submersible, with casings directly exposed to the passing sea water for efficient cooling.

Sample dimensions of the SeaGen device with 20m diameter rotors are shown in Figure 3.6. The monopile is 3m is diameter, penetrates the seabed by about 15-20m depending on substrate type, and is grouted in place.

Power management equipment (transformer, power conditioning, communications, etc.) are housed in the pile and superstructure. The electrical cable runs through a J-tube near the seabed and up the side of the support pile.

A patented and important feature of the technology is that the entire wing together with the rotors can be raised up the pile above the water surface for maintenance. Blade pitch is rotated 180º at slack water to accommodate bi-directional tides without a separate yaw control mechanism. However, substantially off-axis flows will reduce power output. The support wings are engineered for low drag to reduce shadowing penalties.

In an array, the lateral spacing between devices is ½ the rotor diameter (10m) and the longitudinal spacing is 15 times the rotor diameter (300m).

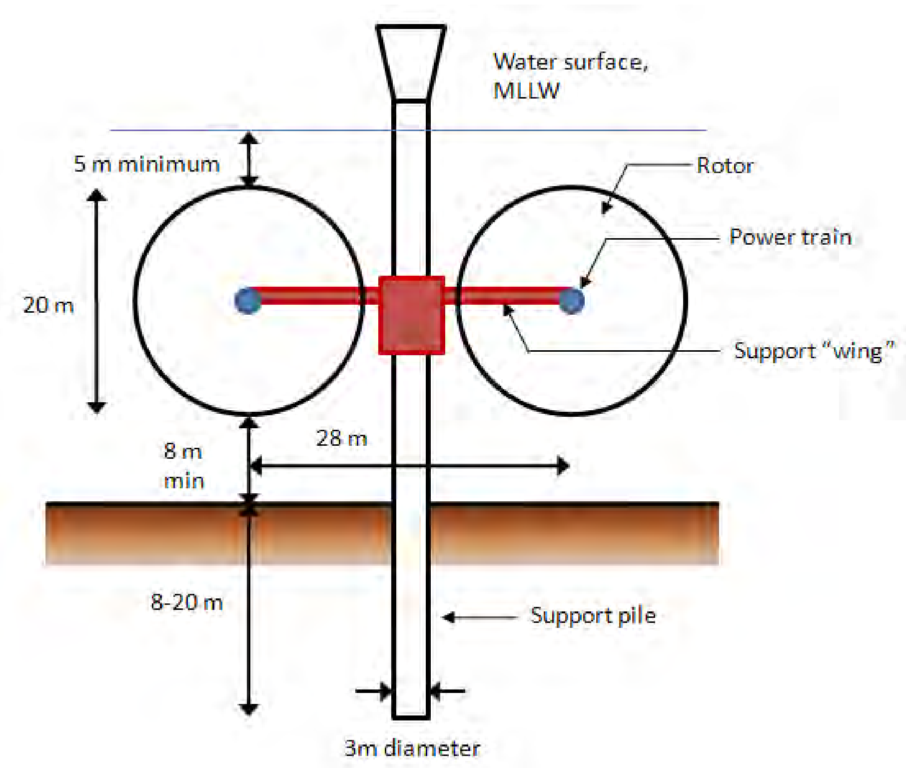


Figure 3.6 – MCT SeaGen device dimensions

3.5.2 Navigation

The MCT SeaGen is a surface piercing device. As such, it will require a full set of lights and markings as described in Section 3.4. Because the surface piercing pile will present a hazard to navigation, the minimum overhead clearance for each rotor is assumed to be 5m, which is sufficient for pleasure craft and maintenance vessels to pass within close proximity to the device.

3.5.3 Operational Procedures

As described in Section 4, a pilot scale MCT SeaGen installation in Tacoma Narrows would consist of a single device, a small commercial array would consist of 10 devices, and a large commercial array would consist of 30 devices. Note that due to navigational considerations associated with a large array of surface piercing structures in a confined channel, the large commercial array scenario for the MCT device is smaller than for other, fully submerged, devices. The resources and duration required for pre-installation, installation, maintenance, and decommissioning are described in detail in this section. The durations listed are for time on station only and do not include the time required to mobilize and demobilize equipment or allowances for bad weather. It is assumed that offshore operations occur seven days per week under favorable conditions. Resources and durations for pre-installation activities are summarized in Table 3.2.

Table 3.2 – MCT SeaGen pre-installation resources and duration

Activity	Resources	Duration		
		Pilot (1 device)	Small Commercial (10 devices)	Large Commercial (30 devices)
Survey to map high-resolution bathymetry at deployment site and cable route	Survey vessel	< 1 week	< 1 week	1 week
Sub-bottom profiling to identify underlying structure of seafloor	Survey vessel	< 1 week	< 1 week	1 week
Visual inspection of seabed in deployment area and along cable route	Survey vessel ROV	< 1 week	1 week	1 month
ADCP survey	Survey vessel	> 1 month	> 3 months	> 6 months
Environmental baseline studies	Survey vessel Stand-alone instrumentation	1-2 years	2-3 years	3-4 years

Installation activities, summarized in Table 3.3 consist of bringing a power cable to the array site and installing the devices and foundations. This is a several stage process:

1. A derrick barge holding installation equipment is towed to position and moored in place. The derrick barge is dynamically positioned using its mooring spread which is controlled by hydraulic winches. Depending on platform availability, a jack-up barge or subsea drilling rig could also be used to accomplish this task.
2. The pile hole is drilled. A conductor tube is used to allow for accurate placement of the drill-bit. A casing shoe is installed over the top of the hole to maintain its stability for pile installation. It is likely that the pile hole would need a casing to prevent rock material from falling back into the hole during drilling.
3. The pile is fabricated on shore and the cross-arm “wing” with rotor and power train are installed on the pile, dockside. The J-tube for connection with the subsea power cable is also attached to the pile at this time.
4. The assembled turbine is transported to the site and lowered into the conductor tube via the derrick crane. The pile is then grouted into place.
5. The top of the device, which includes power management electronics, a loading platform for operation and maintenance, and controls for the lift mechanism is transported to the site and installed.
6. The subsea power cable is connected to the device.
7. Turbine rotors are lowered via built in lifting mechanism to their operational depth and the entire device is commissioned.

MCT intends that, in the future, the all components of the turbine, including the superstructure with power electronics will be attached to the pile at dockside. This will eliminate the need for any at-sea assembly operations.

Table 3.3 – MCT SeaGen installation resources and duration

Activity	Resources	Duration		
		Pilot (1 device)	Small Commercial (10 devices)	Large Commercial (30 devices)
Directional drilling to land power take-off cable on shore (directionally drilled to deployment site)	Drill rig	< 2 months	< 2 months	< 2 months
Subsea cable installation (directionally drilled to site)	Derrick barge, 2 Tugs, Supply boat	< 1 week	< 2 weeks	< 5 weeks
Pile drilling	Drill rig, Derrick barge, Tugs, Supply boat	1 month	< 5 months	> 1 year
Pile and device installation	Derrick barge, 2 Tugs, Supply boat	< 1 week	1 month	3 months
Installation of power management and maintenance platform	Derrick barge, 2 Tugs Supply boat	<1 week	1 month	3 months
Connection to subsea cable	Derrick barge, 2 Tugs, Supply boat, Technical divers/ROV	< 1 week	< 1 month	2 months
Commissioning	Derrick barge, Tugs Supply boat, Technical divers/ROV	< 1 week	1 month	3 months

The guiding philosophy behind the MCT design is to provide low cost access to critical turbine systems. Since the integrated lifting mechanism on the pile is able to lift the rotor and all subsystems out of the water, general maintenance activities do not require specialized ships or personnel. ROVs or divers would only be used to make repairs to the submerged portion of the lifting mechanism or inspect the pile foundation.

Annual inspection and maintenance activities are carried out using a small crew of 2-3 technicians on the device itself. Tasks involved in this annual maintenance cycle include activities such as replacement of gearbox oil, applying bearing grease and changing oil filters. In addition, all electrical equipment can be checked during this inspection cycle and repairs carried out if required. Access to the surface-piercing platform can be carried out safely using a small craft such as a rigid inflatable boat (RIB) in seas with a mean wave height less than 1m.

For repairs on larger subsystems such as the gearbox, the individual components can be hoisted out with a crane or winch and placed onto a barge, which is a relatively low cost vessel. The barge can then convey the systems ashore for overhaul, repair or replacement. Based on experience with wind turbines, the most critical component is the gearbox (Bywaters et al. 2005) which will be replaced with a refurbished unit every 5-10 years. The resources and duration for each maintenance activity are summarized in Table 3.4.

Table 3.4 – MCT SeaGen operational activity resources and duration

Activity	Resources	Duration	Frequency
Onboard maintenance	Rigid inflatable boat (RIB)	1 day/device	Annual
Recover power train to pier side	Tug, Barge	1 day/device	Every 5 years
Redeploy power train to device	Tug, Barge	1 day/device	Every 5 years
Visual inspection of underwater elements	Survey vessel, ROV	1 day/device	Every 5 years

Decommissioning of a SeaGen device at the end of its service life proceeds in three stages:

1. All electrical and mechanical equipment associated with the device (e.g., power train, transformer) is removed from the support pile and returned to pier side.
2. Cut the pile foundation near the seabed. This could either be carried out by technical divers or a water jet cutting system operating inside the pile. The protruding section of the pile is recovered and returned to pier side.
3. The subsea cable is pulled back through the directionally drilled hole. Segments of cable running along the seabed between multiple units are recovered by a barge equipped with a winch on the surface.

The resources and duration for each activity are summarized in Table 3.5.

Table 3.5 – MCT SeaGen decommissioning resources and duration

Activity	Resources	Duration		
		Pilot (1 device)	Small Commercial (10 devices)	Large Commercial (30 devices)
Recover all electrical and mechanical components to pier side	Derrick barge, 2 Tugs, Supply boat	1 week	< 2 months	4 months
Cut off pile near seabed and recover to pier side	Derrick barge, 2 Tugs, Supply boat Technical divers	< 1 month	< 3 months	< 8 months
Subsea cable removal	Derrick barge, 2 Tugs, Supply boat	< 1 week	< 2 weeks	< 2 months
Cap shore landing from directional drilling	None	1 day	1 day	1 day

3.6 Lunar Energy

The Lunar RTT is a ducted, horizontal axis turbine secured to the seabed by a gravity foundation. The device is fully submerged and a modular cassette allows the entire power train to be recovered for maintenance and inspection activities.

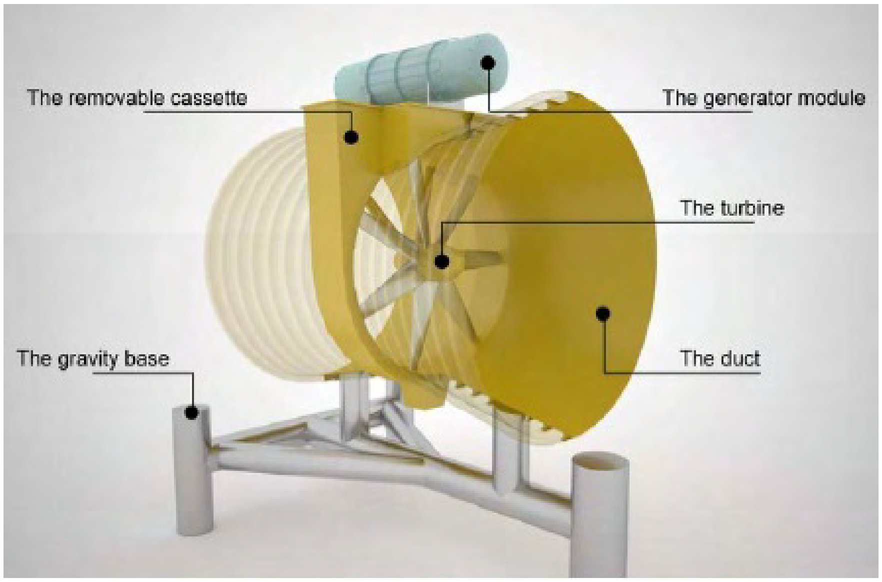


Figure 3.7 – Lunar RTT turbine concept (source: Lunar Energy)

3.6.1 Device Specifications

Inlet Diameter	21 m
Inlet Area	346 m^2
Device Length	27 m
Rotor Diameter	16 m
Power Train	Hydraulically driven induction generator
Rotor Efficiency	45%
Power Train Efficiency	80%
Cut-in Speed	0.77 m/s
Rated Power @ 2.0 m/s	0.5 MW
Maximum Operating RPM	14.3 (tip speed limited to 12 m/s)
Foundation Type	Tubular truss on a gravity base
Height Hub	Fixed – 20.5 m
Hydraulic Fluid of Lubricants	2500 L of hydraulic oil (Panolin HLP Synth)
Power Train Weight	265 tonnes (cassette)
Duct and Foundation Weight	465 tonnes (excluding cassette)
Ballast	1270 tonnes
Total Device Weight	2000 tonnes (support structure and foundation)

Generator Voltage	11 kV
Footprint on seabed	29 m^2
Service Life	30 years

Company Information

Company Name	Lunar Energy
Website	www.lunarenergy.co.uk

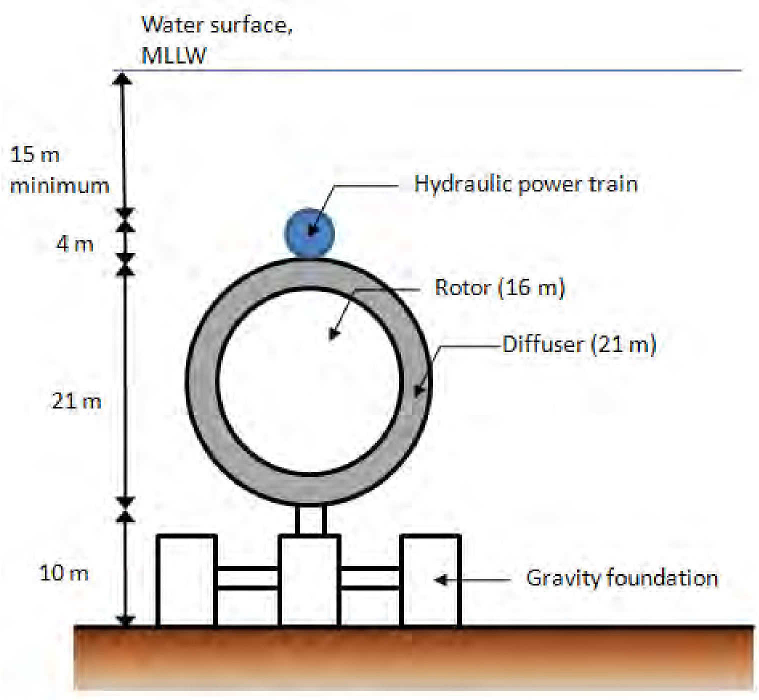


Figure 3.8 – RTT device dimensions

3.6.2 Principle of Operation

The Lunar Energy technology, known as the Rotech Tidal Turbine (RTT) and illustrated above, is a horizontal axis turbine centered in a symmetrical duct. Unique features of the RTT are the use of a fixed duct and a hydraulic power train. The duct and blades are symmetrical, which allows energy capture in a reversing current. Tank testing and numerical modeling suggests that the Lunar RTT performs well in off-axis flows.

Figure 3.9 – Lunar RTT cassette deployment/recovery (Source: Lunar Energy) Note: the foundation and support structure shown have been superseded by the design in Figure 3.7.

A cassette containing the complete power take off, including rotor, hydraulic power train, electrical generation and grid synchronization equipment is inserted as a module into the duct (Figure 3.9). This enables relatively simple removal and replacement of the electromechanical system and simplifies operations and maintenance procedures.

The power train and duct are supported by a steel truss structure, as shown in Figure 3.7. The device is held in place on the seabed by a gravity foundation consisting of three steel can feet filled with concrete and aggregate. The size of the cans and weight of the foundation depends on the type of seabed and rated power of the device. A nominal dimension for the cans is 5m diameter.

In an array, the lateral spacing between devices is ½ the inlet diameter (10.5m) and the longitudinal spacing is 15 times the inlet diameter (315m).

3.6.3 Navigation

The Lunar RTT is a fully submerged device which does not present a hazard to navigation. Minimum overhead clearance is 15m, which is sufficient to allow passage by any vessel bound for Olympia. The periphery of the array must be marked with buoys as described in Section 3.4.

3.6.4 Operational Procedures

As described in Section 4, a pilot scale Lunar RTT installation in Tacoma Narrows would consist of 3 devices, a small commercial array would consist of 27 devices, and a large commercial array 183 devices.

The resources and duration required for pre-installation, installation, maintenance, and decommissioning are described in detail in this section. The durations listed are for time on station only and do not include the time required to mobilize and demobilize equipment or allowances for bad weather. It is assumed that offshore operations will occur seven days per week under favorable conditions. Resources and durations for pre-installation activities are summarized in Table 3.6.

Table 3.6 – Lunar RTT pre-installation resources and duration

Activity	Resources	Duration		
		Pilot (3 devices)	Small Commercial (27 devices)	Large Commercial (183 devices)
Survey to map high-resolution bathymetry at deployment site and cable route	Survey vessel	< 1 week	< 1 week	1 week
Sub-bottom profiling to identify underlying structure of seafloor	Survey vessel	< 1 week	< 1 week	1 week
Visual inspection of seabed in deployment area and along cable route	Survey vessel ROV	< 1 week	1 week	1 month
ADCP survey	Survey vessel	> 1 month	> 3 months	> 6 months
Environmental baseline studies	Survey vessel Stand-alone instrumentation	1-2 years	2-3 years	3-4 years

Installation activities, summarized in Table 3.7, consist of bringing a power cable to the array site and installing the devices and foundations. The power cable is brought to the installation site by a combination of directional drilling and subsea cable installation. The foundation and duct are moved into place by a derrick barge and lowered to the seabed by hydraulic strand jacks. These are detached by an ROV. The power train cassette is then lowered from the barge into the duct. Once the subsea power cable is connected, the device will go through commissioning.

Table 3.7 – Lunar RTT installation resources and duration

Activity	Resources	Duration		
		Pilot (3 devices)	Small Commercial (27 devices)	Large Commercial (183 devices)
Directional drilling to land power take-off cable on shore (directionally drilled to deployment site)	Drill Rig	< 2 months	< 2 months	< 2 months
Subsea cable installation (directionally drilled to site)	Derrick barge, 2 Tugs, Supply boat, ROV	1 week	1 month	<7 months

Foundation and duct installation	Derrick barge, 2 Tugs, Supply boat, ROV, Hydraulic strand jacks	< 2 weeks	< 3 months	18 months
Cassette (rotor and power train) installation	Derrick barge, 2 Tugs, Supply boat, ROV	< 1 week	< 1 month	6 months
Commissioning	Derrick barge, 2 Tugs, Supply boat, ROV	< 2 weeks	< 3 months	18 months

The operations and maintenance philosophy of the Lunar RTT is to provide a robust design that would require a minimal amount of intervention over its lifetime. In order to accomplish this Lunar Energy decided early on to use highly reliable and proven components even at the cost of reduced power conversion efficiency and performance as a result. All of the power conversion equipment on the RTT is mounted on a cassette, which can be removed from the duct and brought into a port to carry out operation and maintenance activities. The expected interval for extraction and maintenance of the cassette is every 4 years, at which time it undergoes a comprehensive overhaul. The resources and duration for each operational activity are summarized in Table 3.4.

Table 3.8 – Lunar RTT operational activity resources and duration

Activity	Resources	Duration	Frequency
Recover/replace power train cassette	Derrick barge, 2 Tugs ROV	1 day/device	Every 4 years
Visual Inspection of underwater elements	Survey vessel, ROV	1 day/device	Every 4 years

Decommissioning at the end of the service life proceeds in three stages:

1. The power train cassette is removed from the duct and returned to pier side, as would be the case during routine maintenance activities.
2. Barge recovery of foundation and duct. An ROV is required to attach strand jacks from the barge to the foundation as this is not a standard maintenance procedure.
3. The subsea cable is pulled back through the directionally drilled hole. Segments of cable running along the seabed between multiple units are recovered by a barge equipped with a winch on the surface.

The resources and duration for each activity are summarized in Table 3.5.

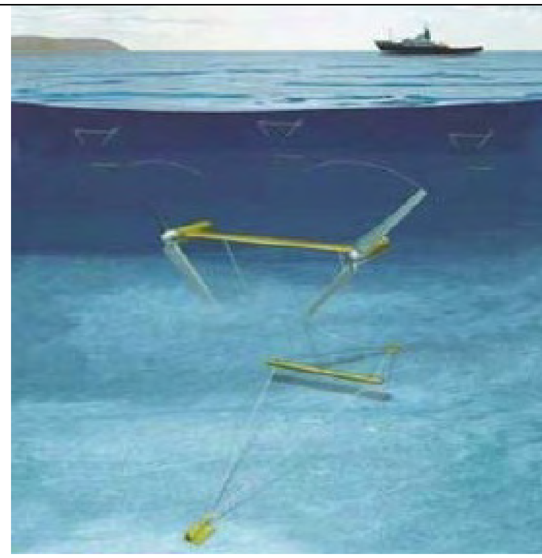
Table 3.9 – Lunar RTT decommissioning resources and duration

Activity	Resources	Duration		
		Pilot (3 devices)	Small Commercial (27 devices)	Large Commercial (183 devices)
Recover power train cassette to pier side	Derrick barge, 2 Tugs, Supply boat, ROV	< 1 week	< 1 month	6 months
Recover foundation and duct to pier side	Derrick barge, 2 Tugs, Supply boat, Hydraulic strand jacks, ROV	< 2 weeks	< 3 months	18 months
Subsea cable removal	Derrick barge, 2 Tugs, Supply boat	1 week	1 month	6 months
Cap shore landing from directional drilling	None	1 day	1 day	1 day

3.7 SMD

The SMD TidEl is a dual rotor turbine connected to the seabed by a compliant mooring.

(a) SMD TidEl prototype testing at NaREC



(b) SMD TidEl full-scale concept

Figure 3.10 – SMD TidEl

Device Specifications

Number of Rotors	2
Rotor Diameter	18.5 m
Rotor Swept Area	540m^2 (both rotors)
Power Train	Variable speed gearbox coupled to synchronous generator
Rotor Efficiency	35%
Power Train Efficiency	94%
Cut-in Speed	0.77 m/s
Rated Capacity @ 2.0 m/s	0.9 MW
Maximum Operating RPM	20 RPM
Foundation Type	Compliant mooring secured by gravity base[5]
Hub Height	Variable – 18 m minimum
Hydraulic Fluid	Gearbox lubricant
Device Weight	64 tonnes (rotor and power train)

[5] SMD plans to utilize a number of foundation and mooring approaches depending on the seabed conditions. These include gravity bases, jacket structures, and twin-piled anchors for foundations and rigid moorings.

Total Device Weight	700-1100 tonnes
Generator Voltage	11 kV
Footprint on seabed	192 m^2 (gravity base – 16m *x* 12m)
Service Life	20 years

Company Information

Company Name	SMD Hydrovision
Website	www.smd.co.uk

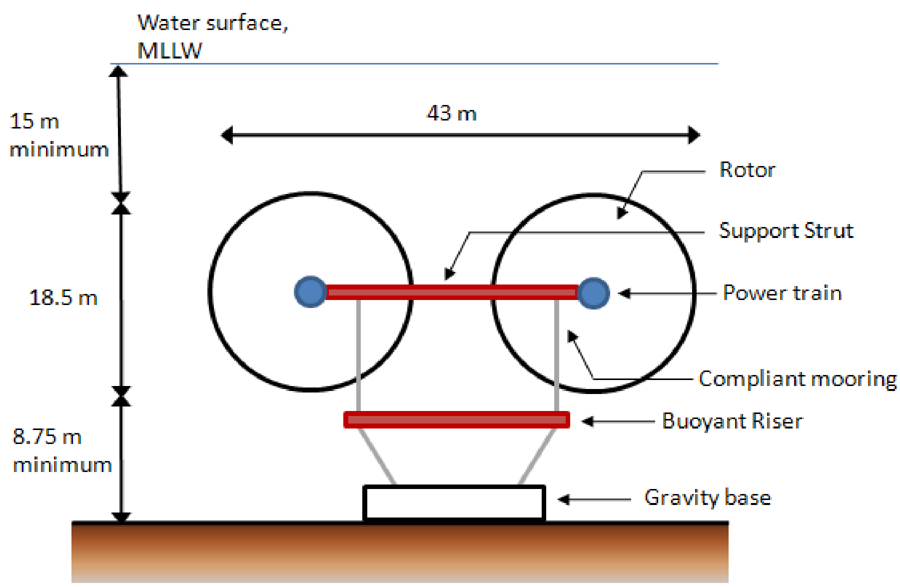


Figure 3.11 – SMD TidEl device dimensions

3.7.1 Principle of Operation

SMD's TidEl system consists of two horizontal axis counter-rotating rotors linked by a crossbeam which is restrained by mooring lines that orient the rotors downstream of the prevailing current. The device operates at mid-water to minimize both weather and boundary layer effects from the seafloor. The mooring arrangement also allows for an easy device recovery to the surface, minimizing operational costs. This device is well suited for deep water sites or sites that require the device to be located a significant distance from the seabed. The mooring lines are connected (via a buoyant riser) to a gravity anchor on the seabed which must be sized sufficiently to resist the maximum load on the rotor. In an array, the lateral spacing between devices is equal to the rotor diameter (18.5m) and the longitudinal spacing is 15 times the rotor diameter (278m).

3.7.2 Navigation

The SMD TidEl is a fully submerged device which does not present a hazard to navigation. As such, the periphery of the array must be marked with buoys as described in Section 3.4. The device hub height is selected such that the overhead clearance is 15m.

3.7.3 Operational Procedures

Detailed design of the installation, recovery and decommissioning system is under development by SMD. The following tables and procedures represent an estimate of operational requirements. SMD is also assessing the feasibility of using an ROV to carry out a wider range of operational procedures (e.g., inspection during strong tidal currents).

As described in Section 4, a pilot scale SMD TidEl installation in Tacoma Narrows would consist of 2 devices, a small commercial array would consist of 15 devices, and a large commercial array 81 devices. The resources and duration required for pre-installation, installation, maintenance, and decommissioning are described in detail in this section. The durations listed are for time on station only and do not include the time required to mobilize and demobilize equipment or allowances for bad weather. It is assumed that offshore operations will occur seven days per week under favorable conditions. Resources and durations for pre-installation activities are summarized in Table 3.10.

Table 3.10 – SMD TidEl pre-installation resources and duration

Activity	Resources	Duration		
		Pilot (2 devices)	Small Commercial (15 devices)	Large Commercial (81 devices)
Survey to map high-resolution bathymetry at deployment site and cable route	Survey vessel	< 1 week	< 1 week	1 week
Sub-bottom profiling to identify underlying structure of seafloor	Survey vessel	< 1 week	< 1 week	1 week
Visual inspection of seabed in deployment area and along cable route	Survey vessel, ROV	< 1 week	1 week	1 month
ADCP survey	Survey vessel	> 1 month	> 3 months	> 6 months
Environmental baseline studies	Survey vessel Stand-alone instrumentation	1-2 years	2-3 years	3-4 years

Installation activities, summarized in Table 3.11, consist of bringing a power cable to the array site, installing the gravity anchor, attaching the compliant mooring, and installing the power train and rotor.

The electrical cable is brought to the installation site by a combination of directional drilling and subsea cable installation. The foundation anchors are positioned on the seabed (using hydraulic strand jacks), the riser cables for the compliant mooring are installed, and then the support strut and turbines are attached.

Table 3.11 – SMD TidEl installation resources and duration

Activity	Resources	Duration		
		Pilot (2 devices)	Small Commercial (15 devices)	Large Commercial (81 devices)
Directional drilling to land power take-off cable on shore (directionally drilled to deployment site)	Drill Rig	< 2 months	< 2 months	< 2 months
Subsea cable installation (directionally drilled to site)	Derrick barge, 2 Tugs Supply boat, ROV	< 1 week	< 1 months	< 3 months
Gravity anchor installation	Derrick barge, 2 Tugs Supply boat	1 week	< 2 months	8 months
Compliant mooring installation	Derrick barge, 2 Tugs Supply boat, ROV	< 1 week	< 3 weeks	< 3 months
Support strut installation	Derrick barge, 2 Tugs Supply boat, ROV	< 1 week	< 3 weeks	< 3 months
Rotor and power train installation	Derrick barge, 2 Tugs Supply boat	< 1 week	1 month	< 6 months
Commissioning	Derrick barge, 2 Tugs Supply boat, ROV	1 week	< 2 months	8 months

Every two years, the wing (turbines and support strut) is recovered and towed back to port for inspection and maintenance. Device recovery occurs during slack waters by remotely triggering the release of a buoyed mooring line that can be used by a tug to bring the device to the surface. Resubmergence can be attained using the same mechanism. Every four years, the underwater elements (mooring lines and anchors) are visually inspected by a ROV. The resources and duration for each operational activity are summarized in Table 3.12.

Table 3.12 – SMD TidEl operational activity resources and duration

Activity	Resources	Duration	Frequency
Recovery/redeployment of wing. Recovered wing and rotors towed back to port	Tugs (2)	1 day/device	Every 2 years
Visual inspection of underwater elements	Survey vessel ROV	1 day/device	Every 4 years

Decommissioning at the end of service life proceeds in three stages:

1. The power train cassette is removed from the duct and returned to pier side, as would be the case during routine maintenance activities.
2. Barge recovery of compliant mooring using ROV to detach mooring from gravity anchors
3. Gravity anchor recovery using hydraulic strand jacks, attached by ROV.
4. The subsea cable is pulled back through the directionally drilled hole. Segments of cable running along the seabed between multiple units are recovered by a barge equipped with a winch on the surface.

The resources and duration for each activity are summarized in Table 3.13.

Table 3.13 – SMD TidEl decommissioning resources and duration

Activity	Resources	Duration		
		Pilot (2 devices)	Small Commercial (15 devices)	Large Commercial (81 devices)
Recover wing and tow back to port	Tugs (2)	< 1 week	< 1 month	< 3 months
Recover compliant mooring	Derrick barge, 2 Tugs, Supply boat, ROV	< 1 week	< 1 month	< 3 months
Recover gravity anchor	Derrick barge, 2 Tugs, Supply boat, ROV. Hydraulic strand jacks	< 1 week	1 month	< 6 months
Subsea cable removal	Derrick barge, 2 Tugs, Supply boat	< 1 week	< 1 month	< 3 months
Cap shore landing from directional drilling	None	1 day	1 day	1 day

4. Scenario Results

This section describes the scenarios that were developed for the tidal power site of interest. A total of nine tidal power scenarios are presented (3 technologies *x* 3 scales). The following table presents summary statistics for all scenarios.

Table 4.1 – Scenario summary

Device	MCT SeaGen			Lunar RTT			SMD TidEl		
Scale	Pilot	Sm. Comm.	Lg. Comm.	Pilot	Sm. Comm.	Lg. Comm.	Pilot	Sm. Comm.	Lg. Comm.
Scenario Index	1	2	3	4	5	6	7	8	9
Number of devices	1	10	30	3	27	183	2	15	81
Array rated power (MW)	1.2	10.9	30.3	1.2	10.1	50.1	1.5	10.5	50.4
Array average power (MW)	0.4	3.3	9.1	0.4	3.0	15.0	0.5	3.1	15.2
Capacity factor	30%	30%	30%	30%	30%	30%	30%	30%	30%
Device rated power (kW)	1173	1090	1010	404	372	274	753	698	622
Device rated speed (m/s)	2.05	2.00	1.95	1.85	1.80	1.63	2.03	1.98	1.90
Average deployment depth (m)	44	39	39	52	57	56	68	56	53
Average hub height (m)	29	24	24	21	21	21	44	33	29
Volume of lubricant (L)	110	1100	3300	7500	67,500	457,500	*	*	*
Seabed footprint (m^2)	7	70	210	87	780	5300	380	2900	16,000
Hard substrate (m^2)	280	2300	6900	11,000	96,000	650,000	720	5400	29,000
Average row blockage	1%	3%	3%	2%	5%	5%	2%	5%	6%
Operating time	70%	70%	70%	62%	61%	57%	65%	64%	63%
% reduction in South Sound transport	0.0%	0.1%	0.3%	0.0%	0.1%	0.6%	0.0%	0.1%	0.6%

***information not provided by device developer**

Background information for the site and technology are discussed in Sections 2 and 3, respectively. A regional map is presented in Figure 4.1. This section only outlines the likely configuration and provides overview maps and technical summary tables to illustrate major differences. It is important to understand that these scenarios are developed based on high-level site and device data and can by no means be compared to a complete licenses application document or a project plan informed by baseline studies. The scenarios are developed for illustrative purposes only to inform stakeholders of what such deployments could look like and to initiate discussions on potential conflicts and generic market adoption considerations of this emerging technology. Array layouts developed in consultations with stakeholder groups may vary considerably from those presented here. Scenario descriptions are broken down by device. Each section includes an overview of the scenario attributes, maps of device deployments, and a brief qualitative discussion.

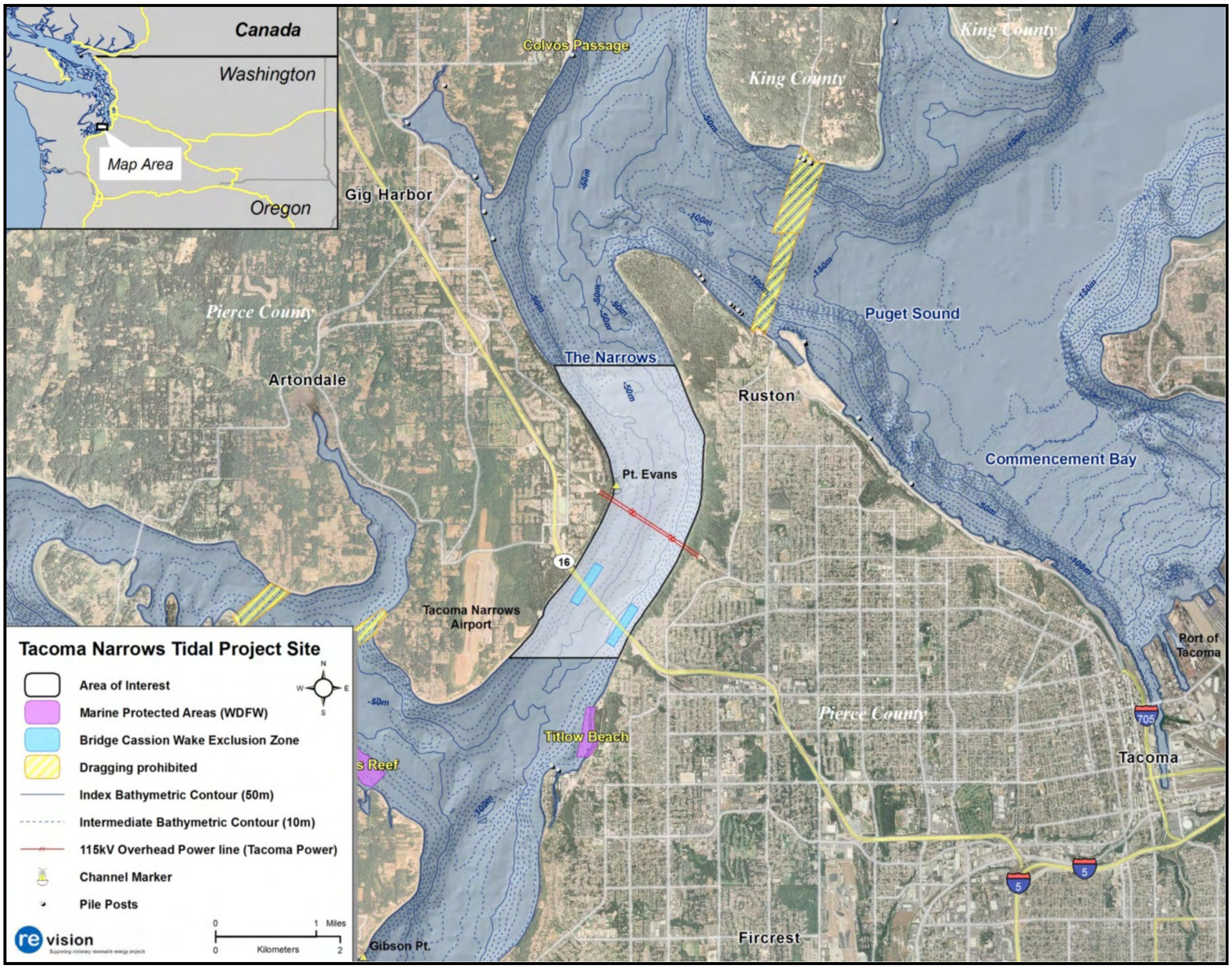


Figure 4.1 - Tacoma Narrows site overview

4.1 Marine Current Turbines (SeaGen)

Table 4.2 – MCT scenario attributes

Scale	Pilot	Sm. Comm.	Lg. Comm.
Scenario Index	**1**	**2**	**3**
Device			
Rated electrical power (kW)	1173	1090	1010
Average electrical power (kW)	354	330	304
Rotor	Dual 20 m diameter, horizontal axis		
Foundation type	Penetrating pile		
Total device weight	394 tonnes		
Operational Considerations			
Installation time	1 month	< 1 year	< 3 years
Decommissioning time	< 1 month	< 5 months	1 year
Planned operational interventions per year	< 2	< 20	< 50
Project life	> 20 years	> 20 years	> 20 years
Site			
Seabed composition	Cobbles and consolidated sediments		
Kinetic power density (kW/m^2)[1]	1.6	1.6	1.5
Array Performance			
Number of devices	1	10	30
Average electrical power (MW)	0.4	3.3	9.1
Rated electrical power (MW)	1.2	10.9	30.3
Capacity factor	30%	30%	30%
Average deployment depth (m)	44.4	39.1	39.4
Average hub height (m)	29.4	24.1	24.4
Array Environmental Footprint			
Volume of lubricant (L)	110	1100	3300
Physical footprint on seabed (m^2)	7	70	210
Permanent hard substrate (m^2)	280	2300	6900
Average blockage ratio	1%	3%	3%
% of time operating	70%	70%	70%
% transport reduction in South Sound	0.0%	0.1%	0.3%
Navigation Considerations	Surface piercing: Lighted, painted pile w/ surrounding safety zone		

[1]**Kinetic power density is baseline average for locations occupied by turbines**

The array layouts and performance for each of the three scenarios are presented in the following figures. Because of the deployment depth limitations posed by the penetrating pile foundation (50 m), device installations are restricted to the western edge of Tacoma Narrows for all three scenarios. The large commercial scenario is restricted to 30 MW rated electrical capacity because a full-sized array (50 MW rated capacity) cannot be sited in Tacoma Narrows under this constraint.

Figure 4.2 – MCT pilot array layout

Figure 4.3 – MCT small commercial array layout

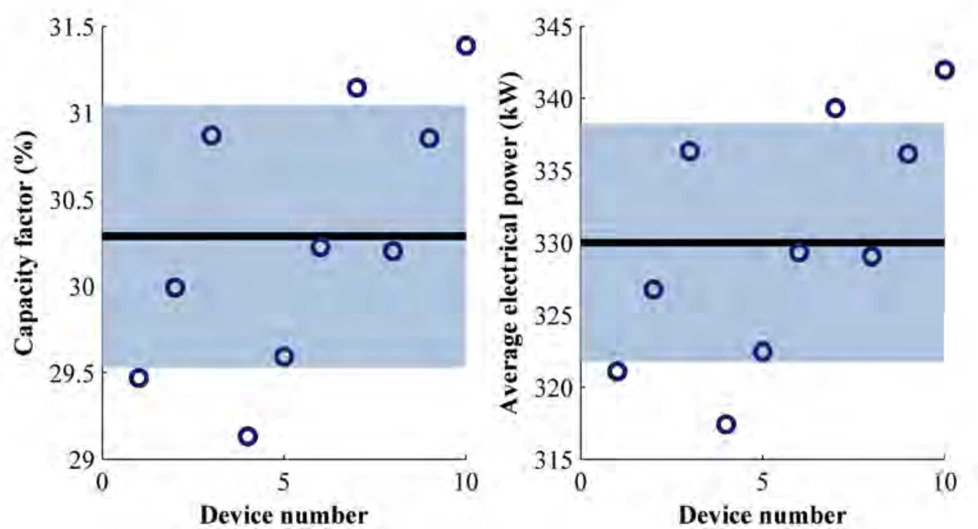


Figure 4.4 – MCT small commercial array performance. Circles denote capacity factor or performance of individual device in array. Solid line is average for array. Shaded rectangle is one standard deviation.

Figure 4.5 – MCT large commercial array layout

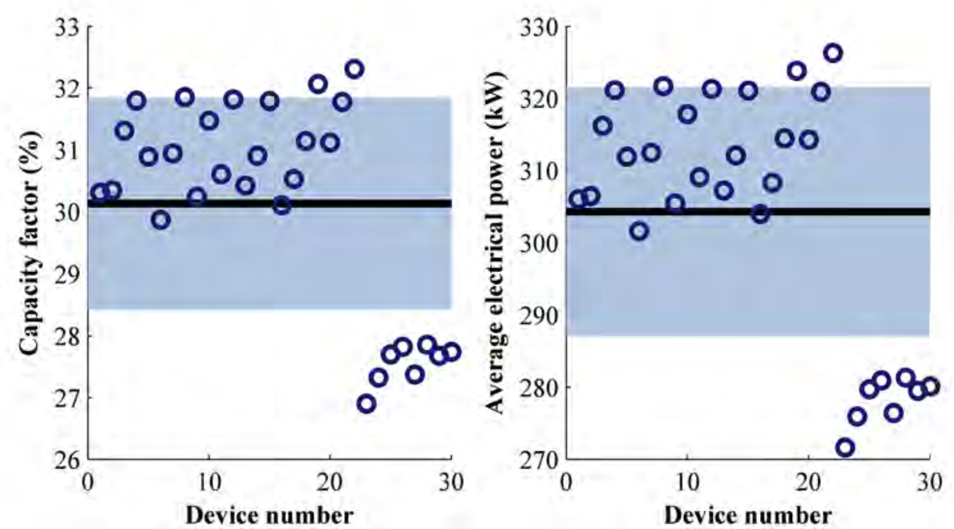


Figure 4.6 – MCT large commercial array performance. Circles denote capacity factor or performance of individual device in array. Solid line is average for array. Shaded rectangle is one standard deviation.

4.2 Lunar Energy (RTT)

Table 4.3 – Lunar scenario attributes

Scale **Scenario Index**	**Pilot** **4**	**Sm. Comm.** **5**	**Lg. Comm.** **6**
Device			
Rated electrical power (kW)	404	372	274
Average electrical power (kW)	120	113	82
Rotor	21 m inlet diameter, ducted horizontal axis		
Foundation type	Tubular truss on a gravity base		
Total device weight	2000 tonnes		
Operational Considerations			
Installation time	1 month	< 8 months	< 5 years
Decommissioning time	< 1 month	< 5 months	< 3 years
Planned operational interventions per year	< 2	< 20	< 100
Project life	30 years	30 years	30 years
Site			
Seabed composition	Cobbles and consolidated sediments		
Kinetic power density (kW/m^2)[1]	1.2	1.1	0.9
Array Performance			
Number of devices	3	27	183
Average electrical power (MW)	0.4	3.0	15.0
Rated electrical power (MW)	1.2	10.1	50.1
Capacity factor	30%	30%	30%
Average deployment depth (m)	51.7	56.6	55.8
Average hub height (m)	20.5	20.5	20.5
Array Environmental Footprint			
Volume of lubricant (L)	7500	67,500	457,500
Physical footprint on seabed (m^2)	87	780	5300
Permanent hard substrate (m^2)	11,000	96,000	650,000
Average blockage ratio	2%	5%	5%
% of time operating	62%	61%	57%
% transport reduction in South Sound	0.0%	0.1%	0.6%
Navigation Considerations	Submerged: lighted navigation buoys at corners of array		

[1]**Kinetic power density is baseline average for locations occupied by turbines**

The array layouts and performance for each of the three scenarios are presented in the following figures. Because the Lunar RTT protrudes relatively high into the water column, deployments are limited to the deep water along the central axis of Tacoma Narrows. Further, because the vertical profile of currents and power density are relatively shallow and the Lunar RTT is restricted to the lower portion of the water column, device power output is relatively lower than for the MCT and SMD cases (as evidenced by the kinetic power density shown in the above table). Consequently, in order to develop a large commercial array, some of the devices must be sited in the less energetic waters in the northern portion of the Narrows and the overall area required for the arrays is the largest of all devices assessed.

Figure 4.7 – Lunar pilot array layout

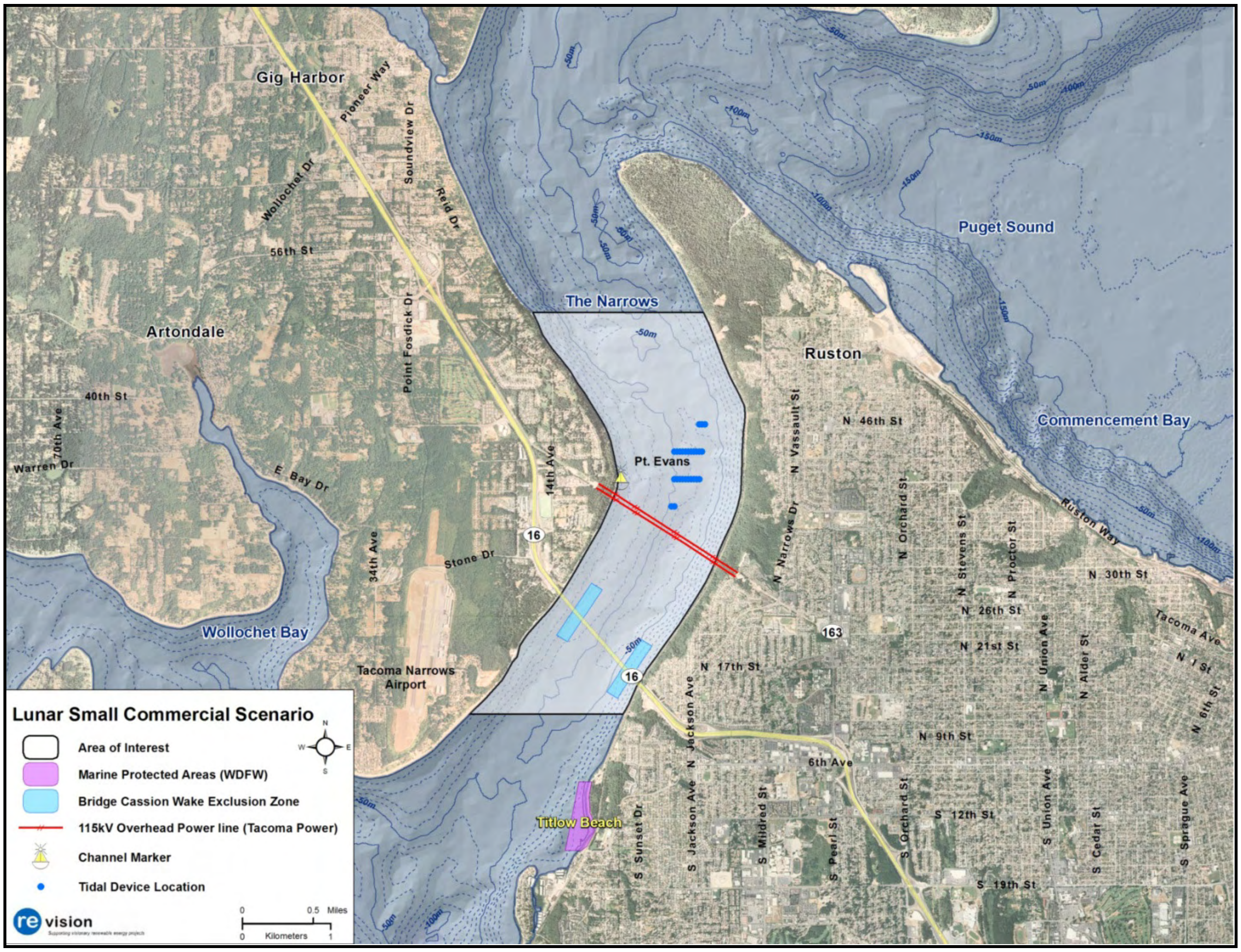


Figure 4.8 – Lunar small commercial array layout

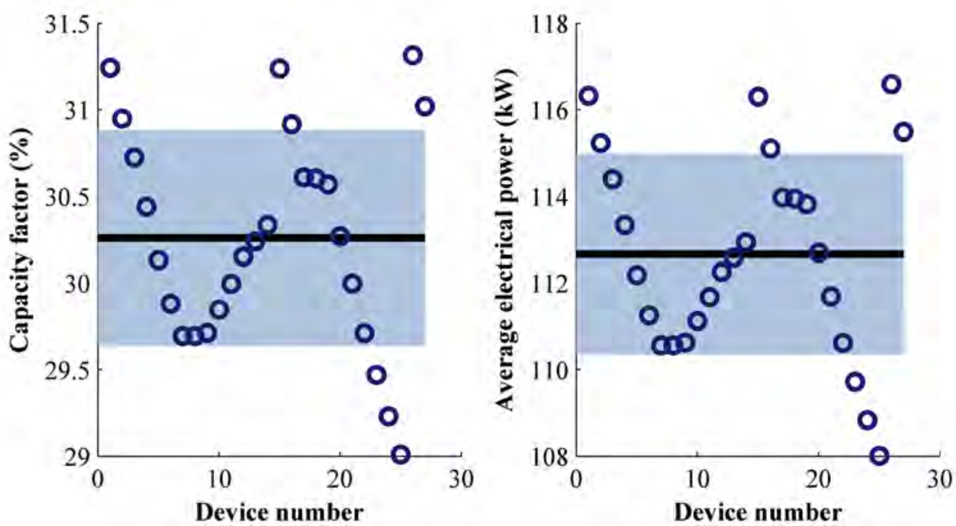


Figure 4.9 – Lunar small commercial array performance. Circles denote capacity factor or performance of individual device in array. Solid line is average for array. Shaded rectangle is one standard deviation.

Figure 4.10 – Lunar large commercial array layout

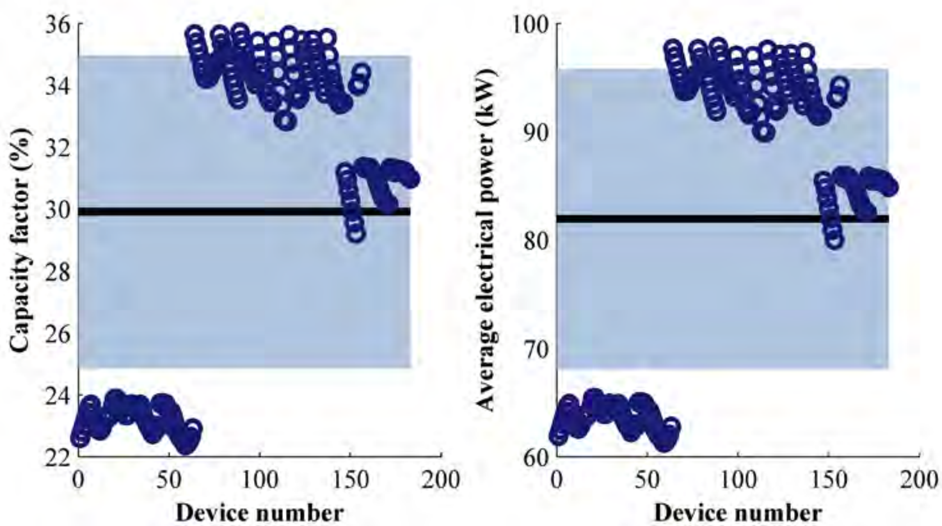


Figure 4.11 – Lunar large commercial array performance. Circles denote capacity factor or performance of individual device in array. Solid line is average for array. Shaded rectangle is one standard deviation.

4.3 SMD (TidEl)

Table 4.4 – SMD scenario attributes

Scale Scenario Index	Pilot 7	Sm. Comm. 8	Lg. Comm. 9
Device			
Rated electrical power (kW)	753	698	622
Average electrical power (kW)	227	209	188
Rotor	Dual 18 m diameter, horizontal axis		
Foundation type	Compliant mooring secured by gravity base		
Total device weight	700-1100 tonnes		
Operational Considerations			
Installation time	< 1 month	< 6 months	< 3 years
Decommissioning time	< 1 month	< 3 months	< 2 years
Planned operational interventions per year	< 2	< 20	< 70
Project life	20 years	20 years	20 years
Site			
Seabed composition	Cobbles and consolidated sediments		
Kinetic power density (kW/m^2)[1]	1.6	1.5	1.4
Array Performance			
Number of devices	2	15	81
Average electrical power (MW)	0.5	3.1	15.2
Rated electrical power (MW)	1.5	10.5	50.4
Capacity factor	30%	30%	30%
Average deployment depth (m)	68.3	55.5	52.5
Average hub height (m)	44.0	32.5	29.4
Array Environmental Footprint			
Volume of lubricant (L)	-[2]	-	-
Physical footprint on seabed (m^2)	380	2900	16,000
Permanent hard substrate (m^2)	720	5400	29,000
Average blockage ratio	2%	5%	6%
% of time operating	65%	64%	63%
% transport reduction in South Sound	0.0%	0.1%	0.6%
Navigation Considerations	Submerged: lighted navigation buoys at corners of array		

[1]**Kinetic power density is baseline average for locations occupied by turbines**

[2]**No information provided by SMD**

The array layouts and performance for each of the three scenarios are presented in the following figures. Of the three technologies considered, the SMD TidEl has the greatest flexibility in deployment (no limit on depth, variable hub height) and devices in the small and large commercial arrays are clustered along the central axis of Tacoma Narrows.

Figure 4.12 – SMD pilot array layout

Figure 4.13 – SMD small commercial array layout

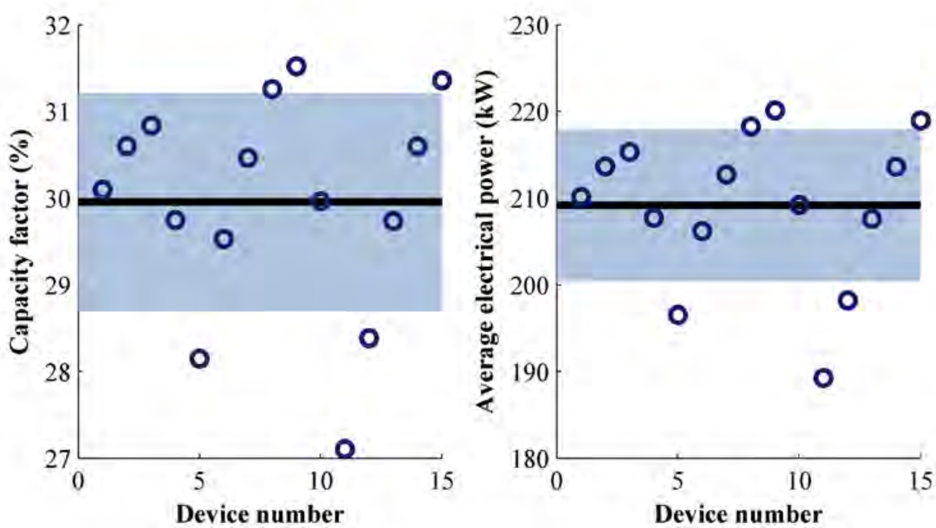


Figure 4.14 – SMD small commercial array performance. Circles denote capacity factor or performance of individual device in array. Solid line is average for array. Shaded rectangle is one standard deviation.

Figure 4.15 – SMD large commercial array layout

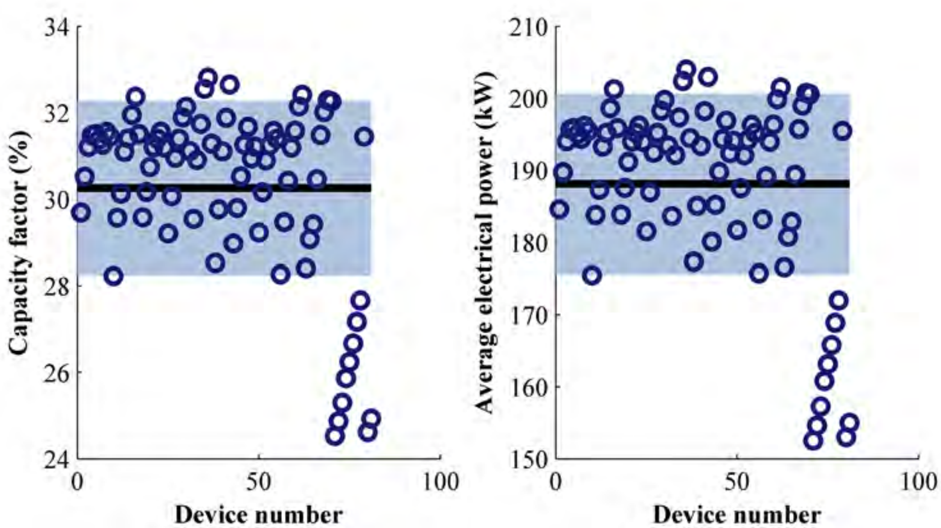


Figure 4.16 – SMD large commercial array performance. Circles denote capacity factor or performance of individual device in array. Solid line is average for array. Shaded rectangle is one standard deviation.

5. Conclusions

This project has established baseline scenarios for tidal power conversion in Tacoma Narrows, WA. The scenarios capture variations in technical approaches and deployment scales and characterize some environmental impacts and navigational effects. This should provide all stakeholders with an improved understanding of the potential effects of these emerging technologies and focus all stakeholders onto the critical issues that need to be addressed by future study.

For the same site and scale of development, array layout, navigation concerns, and potential environmental impacts depend greatly on device selection. That is to say, site-specific criteria should have a key role in device selection. For example, in Tacoma Narrows the vertical velocity profile is such that devices deployed high in the water column will produce considerably more power than those moored near the seabed. However, surface piercing piles, which are the best developed mechanism to accomplish this configuration, are incompatible (at large scale) with shipping traffic in a narrow channel.

For Tacoma Narrows, each of the three device deployments have certain desirable attributes, but all also have complications, as evidenced by a review of Table 4.1. From an environmental standpoint, the MCT SeaGen has the smallest footprint on the seabed, smallest surface area of permanent hard substrate, and smallest volume of lubricant, but the surface piercing design creates the greatest conflict with shipping traffic and curtails the maximum size of a commercial array. The Lunar RTT is compatible with shipping and has the longest servicing interval of all devices, but introduces the largest surface area of hard substrate and requires the largest array area to achieve a given rated capacity. The SMD TidEl combines many of the best attributes of the MCT SeaGen and Lunar RTT, but is at an early stage of development and may experience unforeseen technical hurdles during future testing. This is generally reflective of the lack of design convergence in the industry – there are many concepts, but no device configurations optimized for all tidal environments.

Finally, even at the largest scale of development considered, the far-field environmental effects are relatively minimal. For example, modeling suggests that the volume of water exchanged in the South Sound, a particularly stressed region of Puget Sound, would decrease by less than 1% for an array with a rated electrical capacity of 50 MW. Higher levels of power conversion require either that devices be deployed in marginally energetic waters, the efficiency of individual devices improves, or arrays be packed more densely than is assumed for this study. Of these options, the easiest to implement would be a denser array packing, though this requires a better understanding of wake propagation and near-field environmental impacts than presently exists.

These scenarios demonstrate the promise of tidal energy, but also point to a number of unresolved cost-benefit questions which require additional in-water testing. Efforts by the Department of Energy and other agencies to promote device deployment and demonstration are of great benefit to this emerging industry and should be expanded.

Finally, there are a number of key areas of research that could serve the industry as a whole, including;

- Quantification and compilation of electromagnetic field data near subsea cables;
- Quantification and compilation of noise-sources from construction and operation activities;
- Determination and compilation of species threshold studies for electromagnetic and acoustic impacts;
- Assessment of the impacts of navigation lighting on birds and determination of best practices;
- Detailed modeling of tidal energy reduction in the near field and estuary-wide effects of energy conversion.

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