# Tidal Energy Potentials in the United States

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## Abstract

This research focuses on applications and potential implementation of tidal turbine power generation systems. Tidal currents are more predictable and consistent than wind. There is an enormous amount of potential energy waiting to be harnessed from oceans and rivers through the use of underwater turbines that work in a manner similar to wind turbines. Since this is a newer technology more research needs to be conducted and better designs need to be implemented to improve the efficiency and cost worthiness of these systems. This project analyzes potential areas in the United States that could produce power from these turbines. Using data from each of the active sites where NOAA has implemented water current tracking systems, the potential energy was calculated and several suitable locations were identified. Calculations were made to estimate the theoretical power a single turbine could produce based off of the analyzed velocities for that location. Different turbine styles and designs will also be analyzed. After calculating the theoretical power for all locations with available data values for current velocities, the top five were highlighted as good potential locations for underwater turbines. The mouth of the St. Claire River, Cameron Fishing Pier on Lake Charles, Jacksonville Port, North Chesapeake Bay, and Jacksonville's Mayport Basin were identified as good locations.

## Introduction

Earth is made up of around 72 percent water, making it one of the most widely available renewable resources in the world. With every country having rivers and possibly shorelines, this creates thousands of miles of flowing water or current that can potentially be harnessed to produce electricity through the use of things like turbines. These water turbines work very much like the wind turbines seen spread out around the world, using a consistently flowing fluid to operate the turbine blades that the generators use to create power. Using water turbines rather than wind turbines is much more practical in theory because the water currents are more predictable and consistent. However, due to this being a newer concept, there is a lot of room for improvement and study for these applications.

## Objectives

The objective of this project is to research and use data analysis for the use of ocean and river renewable energy in the United States, specifically using underwater turbine systems. The potential energy waiting to be harnessed in these rivers and along the coast can be calculated in many areas in the United States. This data can then be used to find areas that produce enough energy to justify the implementation of these turbines and provide estimated power production using certain turbine designs.

## History

Using tides to create power can be traces back to the 10th century, where a dam was built across a basin and filled with the rising tide. As the tide fell, the water in the basin was then released passing through a waterwheel or other energy-conversion device creating power to process grains. In the mid 1960's, the first commercial-scale tidal power plant was built near St. Malo, France. Instead of using a waterwheel, this power plant uses more efficient 10 MW low-head bulb-type turbine generator sets. In 1982, the second commercial-scale tidal power plant was built at Annapolis Royale, Nova Scotia, Canada. This power plant demonstrates the use of Escher-Wyss's invention, the 16 MW STRAFLO turbine [1], which is a redesigned and more efficient low-head straight flow turbine [2].

Few other tidal plants have been built, and those that have are not intended for commercial use. This can be attributed to several different factors that limit the building of these commercial tidal power plants. First, the barrages crossing the basins block traffic of vessels and would need to have locks installed to allow the passing of boats. This is costly and a slow alternative. Second, tidal power plants pose environmental concerns such as altering fish migrations and changing the intertidal zones, and because of this many environmental groups often oppose new projects to build these types of power plants. However, underwater turbines have far less impact on the environment they are installed in and will be furthered discussed in this report [1].

## Theory/ Background

The basic concept of these underwater turbines is very similar to the wind turbines being used all over the country. The turbines are typically placed on the ocean floor with a very heavy base to keep the unit in place. As the oceans current flows past, the force of the flowing water causes the blades to rotate which in turn powers the generator producing electricity. This electricity is then transferred to on shore substations that connect to the power grid providing electricity to homes and businesses. An illustration is provided in Figure 1.

The equation for calculating the theoretical power that a turbine can produce is given as [3]:

$$P = \frac{1}{2}\rho A V^3 \mathrm{C_P}$$

Where P is power, $\rho$ is the density of water, A is the cross sectional area for which the blades spin, V is the velocity of the current, and $C_p$ is the coefficient of power.

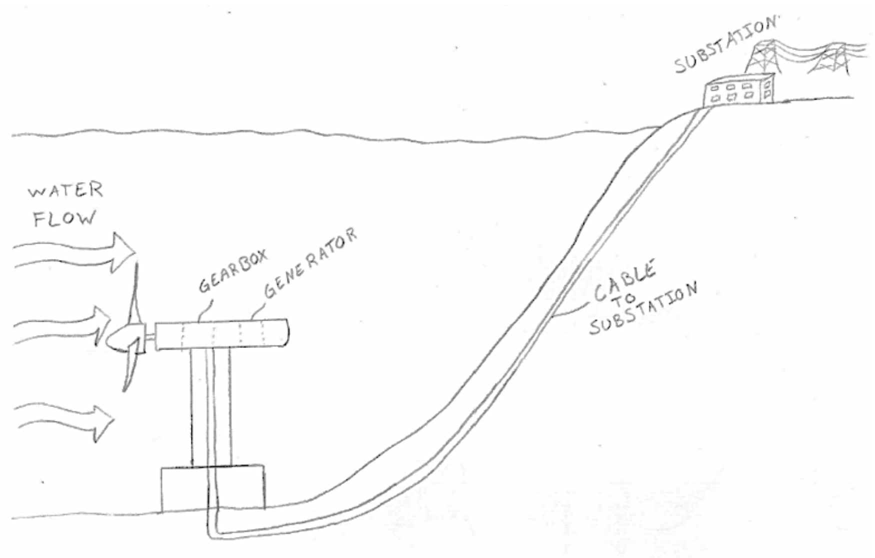

**Figure 1 – Concept of Underwater Turbine**

Figure 2 shows the calculated theoretical power output of a turbine based off of the density of the water, the blade sweep area, and the velocity of water. The x-axis represents the current speed (m/s) and the y-axis represents the potential power output. Please note the present value on the y-axis for a given velocity is calculated using a radius of 1m and a turbine efficiency of 100%. This allows the reader to take this value and multiply it by the desired blade length $(r)^2$ and the efficiency of the turbine to acquire the actual potential power for their specific circumstances.

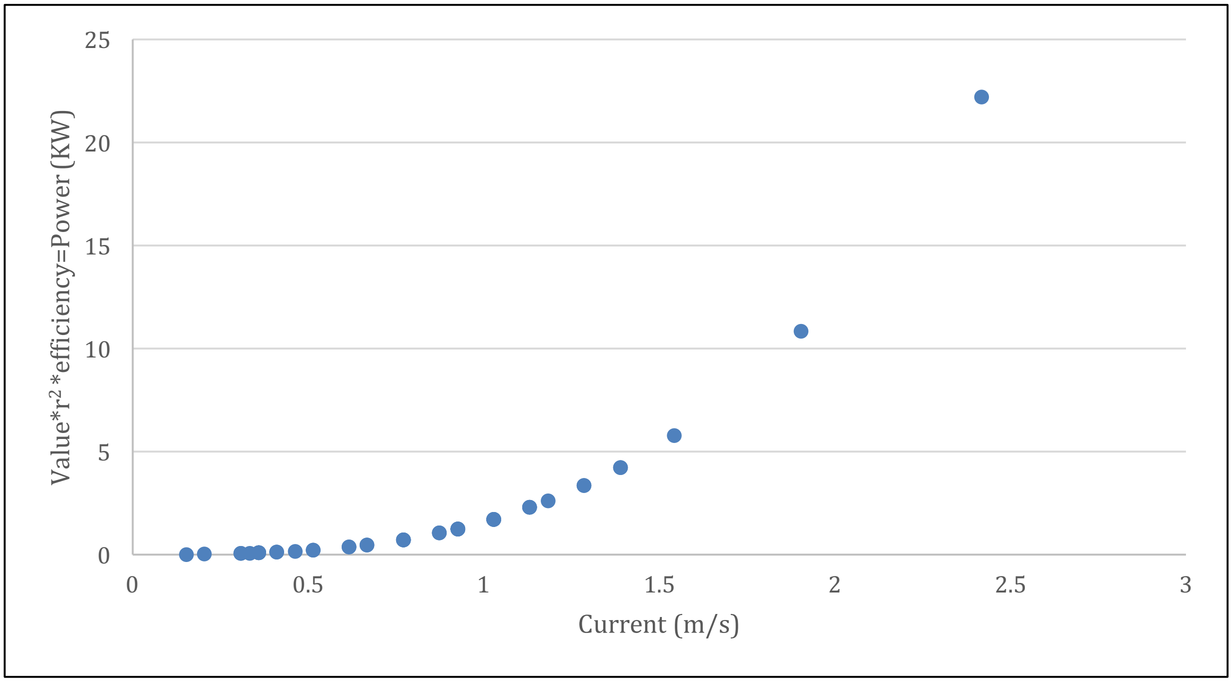

**Figure 2 – Theoretical Power Output**

Sample Calculation

$$\rho_{Water} = Density\ of\ water = 999.9\ \frac{Kg}{m^3}$$

$$V = Velocity\ of\ water = 2.42\ \frac{m}{s}$$

$$r = Radius\ of\ turbine\ blade\ (m)$$

$$A = Blade\ sweep\ area = \pi r^2\ (m^2)$$

$$C_p = Coeficient\ of\ Performance\ (0\ to\ .59)$$

$$P = \frac{1}{2} * \rho * V^3 * A * C_p$$

$$P = \frac{1}{2}\left(999.9\ \frac{Kg}{m^3}\right)\left(2.42\ \frac{m}{s}\right)^3 (\pi r^2)(C_p)$$

$$P \approx 22{,}260 * r^2 * C_p\ \frac{Kg * m^2}{s^3} = 22.260 * r^2 * C_p\ KW$$

**Coefficient of Power and the Betz Limit**

Imagine a circular plane covering the radius of the turbines blades. The fluid that flows through this plane contains the potential work that the turbine could use to create power. However, not all of the energy can be harnessed by the turbine as much of the body flowing through the plane does so without assisting the blades movement, and is therefore lost energy. The coefficient of power (Cp) is a calculation that shows how efficiently these turbines harness the energy of this flowing fluid to create power. The equation used to calculate the Cp is [4]:

$$C_p = \frac{\text{power produced by turbine}}{\text{total energy available}}$$

German physicist Albert Betz performed extensive studies and calculations on the efficiencies of wind turbines. He concluded that no more than 59.3% of the kinetic energy of the wind could be converted into energy by the turbines. This is the theoretical maximum coefficient of power for turbines and is referred to as the “Betz Limit” [4].

Underwater turbines usually operate at 25-30% efficiency. This is partially due to the lack of drag utilization in the turbine. However, newer designs, such as the transverse horizontal axis water turbine which will be discussed later in this report, have shown in lab tests to reach efficiencies of up to 55% with the potential to exceed the Betz Limit [5].

**Designs**

There are several designs of these underwater turbines currently available. To begin, Figure 3 shows a variety of configurations for mounting these turbines to the ocean floor, or in some instances floating bases.

Design 1 from the figure has a varying height base to raise or lower the turbine to different depths which could be useful for harnessing the maximum velocity at different tides, or if the turbine was placed in a bay and needed to be lowered to avoid collision with a passing ship. Design 2 is a design already implemented in some areas that allows the turbine to adjust to certain depths, and is also capable of lifting the turbine above the water level for maintenance. Design 3 uses a funnel type system to funnel the water currents into a smaller area increasing the velocity before reaching the turbine blades, therefore increasing the potential power. Design 4 shows a turbine attached to a floating base. Design 5 is of a turbine mounted to a solid base, the simplest design. Finally, design 6 shows a turbine supported by a cable attached to a solid base, which allows the turbine to self-adjust to the maximum current within its range.

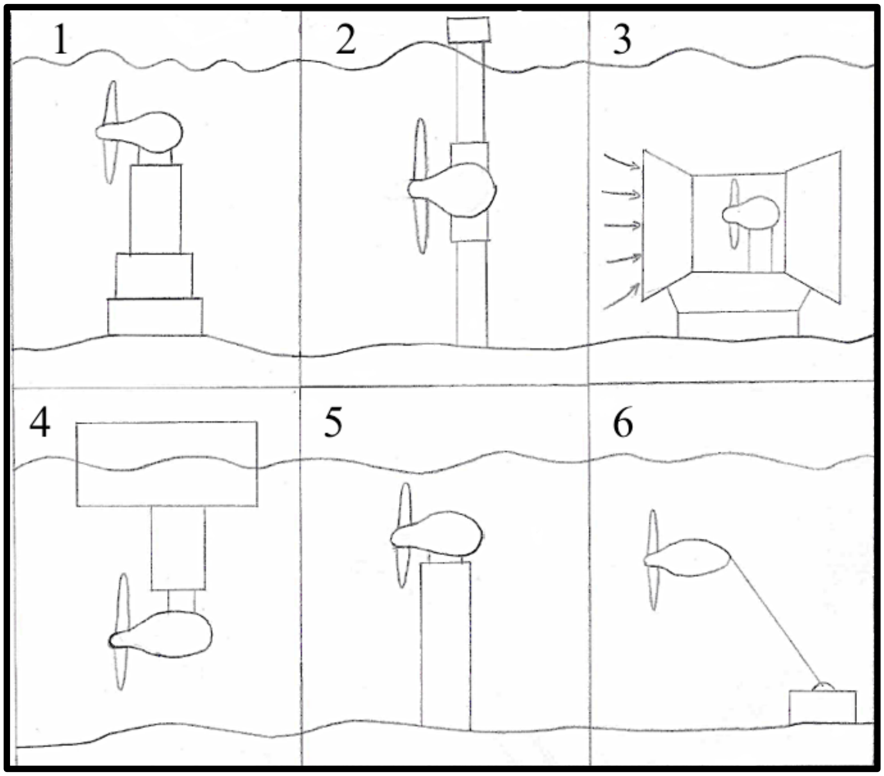

**Figure 3 – Examples of Underwater Turbine Designs**

Another design gaining a lot of attention is the transverse horizontal axis water turbine (THAWT), shown on the right side of Figure 4. This design was conceived by professors at Oxford University, and scale model testing has shown that this design is capable of producing power much more efficiently than previous designs. It is also capable of efficiencies greater than the Betz limit (59.3%) [6]. This design is also more robust and cheaper to build and maintain, making it a great basis for improvements and implementation in the quest for efficient and sustainable renewable energy.

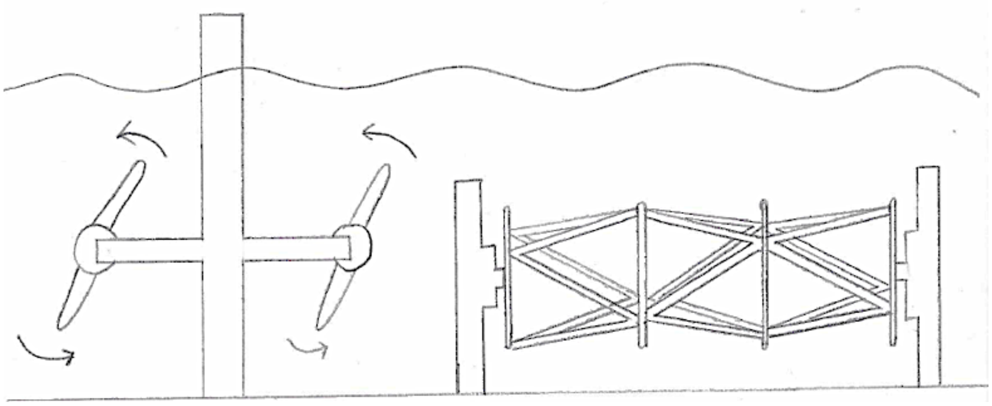

**Figure 4 – Common Turbine vs THAWT**

**Methods**

There are several different types of water turbines that come in various sizes and configurations. These differences in designs are important as they provide a variety of uses in different applications to handle the different environments they are used in to harness this energy. Power equation discussed above will be used to calculate the maximum power that could be generated at locations monitored by The National Oceanic and Atmospheric Administration (NOAA). This data is published online and includes readings from the Great Lakes, the East Coast, Gulf Coast, and the West Coast [7].

**Results**

Data was gathered from current measuring devices deployed by NOAA along the coast of the United States that were recorded for the 48-hour period preceding 4 PM on Wednesday, November 11th, 2015. This data and the related calculations are shown in Table 1. During this time period 45 devices were active. The maximum current for each device during that time period was recorded. More data was obtained and analyzed over the same time period for the top 5 locations. The results obtained from this more accurate and detailed data is summarized in Table 2. For the calculations in Table 2 an efficiency of 50% and a blade length of 1 meter was used. The last row of these tables should be noted. This is the row that shows the average power that could be generated at that location. This takes local current fluctuations into account as well as efficiency so it is more realistic than the theoretical calculation in the last column of Table 1. Note that some locations with slower maximum currents could produce more power than ones with faster maximum current since they are more consistent. For this average power calculation in Table 2, the velocity obtained by averaging the cubes of the currents was used. Plugging in the simple average velocity would have resulted in an inaccurate average power.

The limitations of this data should be noted. These maximum values are useful for calculating the maximum potential to produce energy at that location. However, factors such as the depth of the water, direction of the flow, the acceptable clearances from the ground and surface, and any unevenness of the current at various depths are each factors that would need to be considered before deploying turbines. Each of the top 5 locations with the fastest currents were recorded at a location near a river. At many of these locations the direction of the flow still changed as the tides came in and went out. However, the direction did not change at the location with the fastest current which is located on the St. Clair River at the southern part of Lake Huron.

## Conclusion

The reality that many of the locations with the fastest currents are on or near bays or rivers does not mean that they are locations where tidal renewable energy equipment could not be installed. These turbines can still produce energy with the smaller blade lengths they would most likely use in bays or rivers, although power does increase exponentially with respect to blade length. Further research could be done to determine if it is economically feasible to install turbines in these locations.

Furthermore, the NOAA measuring devices only measure the current velocity at a specific section of water. While each of the devices are considered near surface devices, they are not all oriented the same. Some measure a horizontal cross section, some measure a vertical cross section from the ground to the surface, and others measure from the surface toward the ground [8]. Before implementing real turbines, data in the vicinity of the NOAA devices would need to be gathered and engineering tradeoffs would need to be made between locations with fast current velocities and locations where wider turbine radiuses could be used.

By analyzing the data from Tables 1 and 2, several locations present themselves as good potential locations for underwater turbine farms. The mouth of the St. Clair River feeding into the Great Lakes had the highest maximum current velocity (2.42 m/s) and the highest average power for a standard turbine (7.262 KW) at the time of the data collection. Other locations that recorded high maximum current velocities include Cameron Fishing Pier on Lake Charles (1.90 m/s; 0.48 KW), Jacksonville (1.54 m/s; 0.620 KW), north Chesapeake Bay (1.39 m/s; 0.260 KW), and Jacksonville's Mayport Basin (1.39 m/s; 0.468 KW). More analysis and data recording will need to be done at these locations before deciding to implement underwater turbine farms, but this data shows that these areas have the potential to provide electricity to many homes and businesses in their surrounding areas.

## Bibliography

[1] "History of Tidal Power." *Tidal Electric*. Web. 2 Dec. 2015. <http://www.tidalelectric.com/history-of-tidal-power/>.

[2] "The STRAFLO Turbine." Info Science. Web. 2 Dec. 2015. <http://infoscience.epfl.ch/record/26102/files/straflo_turbine.pdf>.

[3]"Wind Turbine Power Calculations." The Royal Academy of Engineering. RWE Npower Renewables. Web. 8 Oct. 2015.

[4]"Understanding Coefficient of Power (Cp) and Betz Limit." *Kidwind*. Web. 13 Nov. 2015. <http://learn.kidwind.org/sites/default/files/betz_limit_0.pdf>.

[5] Ballard, Stuart. "3rd Generation Tidal Turbines: Too Efficient to Ignore?" Green World Trust. Web. 1 Dec. 2015. <http://www.greenworldtrust.org.uk/Energy/Documents/3rd gen tidal turbines.pdf>.

[6]"Tidal Energy Research Group." Transverse Horizontal Axis Water Turbine -. University of Oxford. Web. 8 Oct. 2015. <http://www.eng.ox.ac.uk/tidal/research/transverse-horizontal-axis-water-turbine>.

[7]"NOAA/CO-OPS ODIN - NOAA Tides & Currents." *NOAA/CO-OPS ODIN - NOAA Tides & Currents*. Web. 14 Sept. 2015.

[8]"PORTS® (Physical Oceanographic Real-Time System)." Tides and Currents. Center for Operational Oceanographic Products and Services, 15 Oct. 2013. Web. 13 Nov. 2015.

**Table 1 : Potential for Tidal Energy at Each of the Active Locations Monitored by NOAA.**

Data was accessed at approximately 4 PM on Wednesday, November 11th 2015. The currents are the fastest observed in the previous 48 hours.

The power in the cell furthest to the right can be modified by $r^2$ and the decimal representation of $C_p$ to get values for any blade length or efficiency. The present value represents the power if the blade length is 1 m and the efficiency is 100%.

Note: The exact location of the station can be viewed in Google Maps or other software by entering the geographical coordinates.

| Rank (Fast to Slow) | Station ID | Station Name | Latitude | Longitude | Project | Maximum Current (knots) | Maximum Current (m/s) | Power (KW) |
|---|---|---|---|---|---|---|---|---|
| 1 | gl0301 | St Clair River | 42.99873 | -82.42527 | Great Lakes Real-Time Currents Monitoring | 4.7 | 2.42 | 22.203 |
| 2 | lc0201 | Cameron Fishing Pier | 29.76414 | -93.34292 | Lake Charles PORTS | 3.7 | 1.90 | 10.832 |
| 3 | jx0301 | Mile Point LB 24 | 30.38275 | -81.45556 | Jacksonville PORTS | 3.0 | 1.54 | 5.774 |
| 4 | cb1301 | Chesapeake City | 39.53053 | -75.82762 | Chesapeake Bay North PORTS | 2.7 | 1.39 | 4.209 |
| 5 | jx0201 | Mayport Basin PC LBB | 30.39889 | -81.39469 | Jacksonville PORTS | 2.7 | 1.39 | 4.209 |
| 6 | g06010 | Galveston Bay Entr Channel LB 11 | 29.34222 | -94.74083 | Houston/Galveston PORTS | 2.5 | 1.29 | 3.341 |
| 7 | jx0701 | Acosta Bridge | 30.32266 | -81.66462 | Jacksonville PORTS | 2.5 | 1.29 | 3.341 |
| 8 | sn0701 | Port Arthur | 29.86708 | -93.93111 | Sabine Neches PORTS | 2.3 | 1.18 | 2.602 |
| 9 | hb0401 | Chevron Pier | 40.7775 | -124.19661 | Humboldt Bay PORTS | 2.2 | 1.13 | 2.277 |
| 10 | jx0501 | Dames Point Bridge | 30.38599 | -81.55786 | Jacksonville PORTS | 2.2 | 1.13 | 2.277 |
| 11 | s06010 | Martinez-AMORCO Pier | 38.03463 | -122.12525 | San Francisco Bay PORTS | 2.2 | 1.13 | 2.277 |
| 12 | cb0102 | Cape Henry LB 2CH | 36.9594 | -76.0128 | Chesapeake Bay South PORTS | 2.0 | 1.03 | 1.711 |
| 13 | cb0701 | Dominion Terminal | 36.96233 | -76.42417 | Chesapeake Bay South PORTS | 2.0 | 1.03 | 1.711 |
| 14 | db0301 | Philadelphia | 39.94623 | -75.1396 | Delaware Bay PORTS | 2.0 | 1.03 | 1.711 |

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| Rank (Fast to Slow) | Station ID | Station Name | Latitude | Longitude | Project | Maximum Current (knots) | Maximum Current (m/s) | Power (KW) |
|---|---|---|---|---|---|---|---|---|
| 15 | mb0301 | Mobile State Dock Pier E | 30.72144 | -88.04278 | Mobile Bay PORTS | 2.0 | 1.03 | 1.711 |
| 16 | sn0301 | Sabine Front Range | 29.758 | -93.8902 | Sabine Neches PORTS | 2.0 | 1.03 | 1.711 |
| 17 | lm0101 | First Street Wharf | 29.92244 | -90.07114 | Lower Mississippi River PORTS | 1.8 | 0.93 | 1.247 |
| 18 | s08010 | Southampton Shoal Channel LB 6 | 37.91625 | -122.42233 | San Francisco Bay PORTS | 1.8 | 0.93 | 1.247 |
| 19 | sn0401 | West Port Arthur Bridge | 29.82361 | -93.96472 | Sabine Neches PORTS | 1.8 | 0.93 | 1.247 |
| 20 | sn0501 | Rainbow Bridge | 29.98111 | -93.87111 | Sabine Neches PORTS | 1.8 | 0.93 | 1.247 |
| 21 | t01010 | Sunshine Skyway Bridge | 27.625 | -82.655 | Tampa Bay PORTS | 1.8 | 0.93 | 1.247 |
| 22 | ps0301 | Northrop Grumman Pier | 30.35978 | -88.56406 | Pascagoula PORTS | 1.7 | 0.87 | 1.051 |
| 23 | t02010 | Old Port Tampa | 27.86287 | -82.55373 | Tampa Bay PORTS | 1.7 | 0.87 | 1.051 |
| 24 | cb0402 | Naval Station Norfolk LB 7 | 36.96238 | -76.33387 | Chesapeake Bay South PORTS | 1.5 | 0.77 | 0.722 |
| 25 | cb0601 | Newport News Channel LB 14 | 36.95602 | -76.41448 | Chesapeake Bay South PORTS | 1.5 | 0.77 | 0.722 |
| 26 | mb0401 | Mobile Container Terminal | 30.66435 | -88.03235 | Mobile Bay PORTS | 1.5 | 0.77 | 0.722 |
| 27 | s09010 | Oakland Outer Harbor LB3 | 37.8082 | -122.34434 | San Francisco Bay PORTS | 1.5 | 0.77 | 0.722 |

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Note: The exact location of the station can be viewed in Google Maps or other software by entering the geographical coordinates.

| Rank (Fast to Slow) | Station ID | Station Name | Latitude | Longitude | Project | Maximum Current (knots) | Maximum Current (m/s) | Power (KW) |
|---|---|---|---|---|---|---|---|---|
| 28 | ps0201 | Pascagoula Harbor LB 17 | 30.21503 | -88.51089 | Pascagoula PORTS | 1.3 | 0.67 | 0.470 |
| 29 | sn0201 | USCG Sabine | 29.72861 | -93.87001 | Sabine Neches PORTS | 1.3 | 0.67 | 0.470 |
| 30 | cp0101 | Cherry Point | 48.8628 | -122.761 | Cherry Point PORTS | 1.2 | 0.62 | 0.370 |
| 31 | lc0301 | Lake Charles City Docks | 30.21783 | -93.24944 | Lake Charles PORTS | 1.2 | 0.62 | 0.370 |
| 32 | cb0301 | Thimble Shoal LB 18 | 37.0111 | -76.24948 | Chesapeake Bay South PORTS | 1.0 | 0.51 | 0.214 |
| 33 | cb0801 | Rappahannock Shoal Channel LBB 60 | 37.67438 | -76.15453 | Chesapeake Bay North PORTS | 1.0 | 0.51 | 0.214 |
| 34 | cb1101 | Chesapeake Channel LBB 92 | 38.98215 | -76.38467 | Chesapeake Bay North PORTS | 0.9 | 0.46 | 0.156 |
| 35 | cb1001 | Cove Point LNG Pier | 38.40283 | -76.38417 | Chesapeake Bay North PORTS | 0.8 | 0.41 | 0.109 |
| 36 | sn0601 | Port of Beaumont | 30.0797 | -94.08625 | Sabine Neches PORTS | 0.8 | 0.41 | 0.109 |
| 37 | lc0101 | Calcasieu Channel LB 36 | 29.69347 | -93.33118 | Lake Charles PORTS | 0.7 | 0.36 | 0.073 |
| 38 | nb0301 | Quonset Point | 41.58363 | -71.39733 | Narragansett Bay PORTS | 0.7 | 0.36 | 0.073 |
| 39 | ps0401 | Pascagoula Harbor LB 10 | 30.19583 | -88.52253 | Pascagoula PORTS | 0.7 | 0.36 | 0.073 |
| 40 | sn0101 | Sabine Bank Channel LBB 34 | 29.62873 | -93.81617 | Sabine Neches PORTS | 0.7 | 0.36 | 0.073 |

**Table 1 : Potential for Tidal Energy at Each of the Active Locations Monitored by NOAA.**

<table>
<tr><td colspan="9">Data was accessed at approximately 4 PM on Wednesday, November 11th 2015. The currents are the fastest observed in the previous 48 hours.</td></tr>
<tr><td colspan="9">The power in the cell furthest to the right can be modified by $r^2$ and the decimal representation of $C_p$ to get values for any blade length or efficiency. The present value represents the power if the blade length is 1 m and the efficiency is 100%.</td></tr>
<tr><td colspan="9">Note: The exact location of the station can be viewed in Google Maps or other software by entering the geographical coordinates.</td></tr>
<tr><th>Rank (Fast to Slow)</th><th>Station ID</th><th>Station Name</th><th>Latitude</th><th>Longitude</th><th>Project</th><th>Maximum Current (knots)</th><th>Maximum Current (m/s)</th><th>Power (KW)</th></tr>
<tr><td>41</td><td>cb0901</td><td>Potomac River MidChannel LWB B</td><td>38.09098</td><td>-76.52975</td><td>Chesapeake Bay North PORTS</td><td>0.7</td><td>0.33</td><td>0.059</td></tr>
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<tr><td>43</td><td>nb0201</td><td>Fall River</td><td>41.6999</td><td>-71.17842</td><td>Narragansett Bay PORTS</td><td>0.6</td><td>0.31</td><td>0.046</td></tr>
<tr><td>44</td><td>nl0101</td><td>Groton Thames River Pier 6</td><td>41.39175</td><td>-72.09233</td><td>New London PORTS</td><td>0.4</td><td>0.21</td><td>0.014</td></tr>
<tr><td>45</td><td>gl0201</td><td>Maumee River</td><td>41.62913</td><td>-83.53022</td><td>Great Lakes Real-Time Currents Monitoring</td><td>0.3</td><td>0.15</td><td>0.006</td></tr>
</table>

**Table 2. Comparison of the Top 5 Locations**

| Location | Maximum Current Velocity (m/s) | Average Current Velocity from Cubes (m/s) | Average Power (KW) |
|---|---|---|---|
| St. Clair River | 2.42 | 2.10 | 7.26 |
| Cameron Fishing Pier | 1.90 | 0.85 | 0.48 |
| Jacksonville | 1.54 | 0.92 | 0.62 |
| Chesapeake City | 1.39 | 0.69 | 0.26 |
| Mayport Basin PC LBB | 1.39 | 0.84 | 0.47 |