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Electrical Power Generated from Tidal Currents and Delivered to USCG Station Eastport, ME

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Acquisition Directorate
Research & Development Center

Electrical Power Generated from Tidal Currents and Delivered to USCG Station Eastport, ME

Final Technical Report
Contract #HSCG32-09-C-R00018

January 21, 2010

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EXECUTIVE SUMMARY

This document is the final technical report for the project, *Electrical Power Generated from Tidal Currents and Delivered to USCG Station Eastport, ME Pier* (Project) (BAA HSCG32-09-R00018).

The US Coast Guard (USCG) Research and Development Center and Ocean Renewable Power Company, LLC (ORPC) signed a contract effective August 26, 2009, under which ORPC delivered services for the Project, which constituted the U.S. government's first practical application of tidal energy.

The Project sought to demonstrate that tidal currents could provide usable power to the USCG's station in Eastport, Maine (Station Eastport). To accomplish this, tidal power harnessed in Cobscook Bay by ORPC's beta pre-commercial TidGen™ power system (Beta TidGen™ System) was used to charge battery banks that were periodically delivered to the USCG pier to be discharged into the USCG's 41-foot Utility Boat (UTB), mainly to heat the UTB's engines.

This effort was accomplished by integrating the USCG Project with ORPC's previously scheduled tidal energy project. This partnership between the USCG and ORPC allowed the Project to utilize ORPC's tidal energy testing infrastructure, the Beta TidGen™ System, comprised of the turbine generator unit (Beta TGU); the *Energy Tide 2* research, testing and deployment vessel; the *Energy Tide 2* mooring system; a tidal energy transfer system consisting of a 20-foot open hull launch used to transport two 24 V battery banks; and a power transfer system at the Station Eastport pier. The Beta TGU's output was first used to power the testing and sampling equipment on the *Energy Tide 2*; excess power was then used to charge the battery banks that were transferred to the pier and used to provide shore power to Station Eastport's response boat.

ORPC deployed the Beta TidGen™ System first at Shackford Head and it was then relocated to Seward Neck, to the west of Eastport Harbor in Cobscook Bay. Typical peak flood and ebb current speeds in these areas were approximately 2.5 m/sec. The Beta TidGen™ System was initially operated off of Shackford Head for a period of 15 days during September 2010. It was then moved to Seward Neck, where it was operated for a period of 42 days.

The Beta TGU operated without mechanical failures over the course of the demonstration period, charging the battery banks 19 times to deliver a total of 191 kilowatt-hours (kWh) of energy to the shore tie connection. The total energy generated by the Beta TGU during the demonstration period was 670 kWh at the Seward Neck site and 582 kWh at the Shackford Head site.

The Project proved that ORPC's Beta TidGen™ System can provide power to Station Eastport, and potentially to other USCG facilities that are adjacent to high tidal or river current areas. It documented the State of Maine, local community and federal processes for approvals and permits for tidal energy testing projects, and applied the USCG Environmental Analysis Checklist for the first time to a tidal energy project. The permitting and approval process was successfully accomplished, and illustrated the importance of early and extensive consultation between the Project team and the various regulatory agencies. The Project also demonstrated the significance of the preliminary work that must be conducted to characterize current speeds in the study area in order to optimize system performance, and to characterize the loads that the system will power. In addition, the Project reaffirmed the view that batteries are a relatively inefficient means of transferring power from tidal energy sites to facilities on shore. It also showed that optimal tidal energy sites may be located too far from USCG Eastport shore facilities to allow for cost-effective transmission via submarine cable. For Eastport, the most immediate opportunity for utilizing tidal power will be to purchase energy from the power grid as local tidal energy projects become grid connected. For potential USCG tidal projects elsewhere, the USCG should identify robust tidal energy sites at close range to station interconnect points, allowing for the shortest possible (and thus most economical) submarine cable to be constructed.

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INTRODUCTION

Ocean Renewable Power Company, LLC (ORPC) and the United States Coast Guard (USCG) Research and Development Center jointly carried out *Electrical Power Generated from Tidal Currents and Delivered to USCG Station Eastport, ME Pier* (Project) to demonstrate the technical feasibility of providing tidal power to the USCG's station in Eastport, Maine (Station Eastport). This was accomplished using ORPC's beta pre-commercial TidGen™ power system (Beta TidGen™ System) deployed from the *Energy Tide 2*, ORPC's research, testing and deployment vessel, in the waters off of Eastport. The Beta TidGen™ System, used primarily to charge house systems on the *Energy Tide 2* in a concurrent ORPC project, also charged battery banks that were periodically transferred to Station Eastport to provide power for the station's primary response vessel, a 41-foot Utility Boat (UTB). The methodology of charging batteries to power the UTB was chosen because 1) the use of a transmission cable was not economically feasible for such a temporary and short-term project, and 2) the proposed installation of a submarine transmission cable would not be feasible within the timeframe of the project due to the permitting process.

The components (systems and equipment) that comprise ORPC's Beta TidGen™ System used in this Project include ORPC's beta pre-commercial turbine generator unit (Beta TGU); ORPC's *Energy Tide 2*, from which the Beta TidGen™ System was deployed; the *Energy Tide 2* mooring system; a tidal energy transfer system with a 20-foot open hull launch that was used to transport two 24 V battery banks, each containing eight 12 V batteries; and an inverter system at the Station Eastport pier.

The Project's contract was awarded to ORPC as a result of a competitive solicitation by the USCG. The Project was integrated into ORPC's existing, private sector beta pre-commercial TidGen™ project (Beta Project), which involved deployment and operation of the largest ocean energy device (Beta TGU) ever deployed in US waters. This integration enabled the modestly funded federal Project to be carried out at the necessary scale, since the Beta Project was able to subsume most of the required costs. The Project was executed in two phases:

Phase I began on September 1, 2009 and was concluded on April 28, 2010. During Phase I, ORPC performed a power quality analysis to determine the UTB's power requirements, and prepared a Test Plan that included Project equipment, test procedures and methodologies. ORPC then conducted tidal current velocity surveys using an Acoustic Doppler Current Profiler (ADCP) to identify a suitable location for the Project in the vicinity of Station Eastport. Based on the ADCP surveys, ORPC selected an appropriate site and then consulted with state, federal and local permitting agencies regarding the site selected and environmental monitoring plans. ORPC then obtained the necessary permits and completed the USCG Environmental Assessment Checklist.

Phase II began on April 29, 2010 and concluded on November 5, 2010. During Phase II, ORPC completed and deployed all of the Project components and successfully carried out the Project's test procedures, charging the battery banks and ferrying them to the Station Eastport pier over the course of the demonstration period. After 57 of the planned 60-day demonstration, the Project was concluded because power demand at the pier exceeded the capacity of the inverter system.

ORPC recorded power data during this period to evaluate the effectiveness of Project equipment and methodologies, and to document lessons learned. This report details these evaluations and lessons learned as well as the events and findings associated with the Project.

PROJECT PHASE I

Power Quality Analysis and Use of Power

In fall 2009, ORPC measured and analyzed initial power demand, average power demand for the UTB and demand variability to confirm the power requirements of the UTB and properly size the inverter that would transfer electricity from the charged battery banks.

An initial inspection of the UTB's electrical layout was performed by a licensed, local electrician under contract with ORPC. The inspection determined that the installation of a power meter would be in compliance with applicable electrical codes and suitable for additional data gathering.

A power quality meter was installed to collect power usage data in five-minute intervals over a seven-day period to determine average, minimum and peak power consumption levels. The power quality meter was used to determine the amount of both the power draw and daily total energy consumption for the UTB. This information helped determine how much each UTB system was drawing.

The results of the power quality analysis indicated there was a consistent power draw with average currents of 50 amps at 120VAC devoted to the heating components of the UTB. It was determined that a 6 kW AC power inverter would be required to convert the DC battery power to serve the UTB.

Based on the energy capacity of each battery bank, it was estimated that 18-20 kWh could be supplied to the UTB per transfer. At winter-use rates that range up to 122 kWh per day, ORPC calculated that battery banks of a size that could be reasonably housed in a 20-ft open boat would provide two to four hours of useful energy per transfer to the heating components, taking into account energy loss via transport, handling and other Project logistics. These calculations served as the baseline for the Test Plan and associated equipment specifications and selection.

Project Site Selection

ORPC chose a mooring site for the *Energy Tide 2* after evaluating numerous factors at different potential sites in the vicinity of Station Eastport. For this Project, the most important feature of a mooring site was a water current flow strong enough to produce the power needed to charge the battery banks in a reasonable amount of time. To minimize time spent ferrying the battery banks back and forth, the site also needed to be as close to Station Eastport as possible.

ORPC began the search for a mooring site by evaluating bathymetry models by the National Oceanic and Atmospheric Administration (NOAA), which showed that the seafloor off the coast of Station Eastport could indeed support the mooring. Next, using an Acoustic Doppler Current Profiler (ADCP) and advice from local mariners, ORPC determined that the best location to explore in depth was located in Friar Roads Bay within sight of Station Eastport, approximately 0.7 miles off the coast (Figure 1). ORPC deployed a bottom mounted ADCP in this location for several weeks to better characterize the current flow in this area, and estimate the amount of energy that could be generated by the Beta TGU at this site. Results of the ADCP analysis indicated that the site did not have sufficient energy potential to provide an effective demonstration of the Beta TGU technology, and would meet neither ORPC's commercial needs nor the Coastguard's need for net energy transfer to Station Eastport. Energy estimates for this and other sites are summarized in Table 1.

The search for a site in Friar Roads Bay stemmed from ORPC's desire to work with the USCG on choosing a site in very close proximity to the pier. On the other hand, existing ocean circulation and energy density models had shown that the Friar Roads area was not a high energy density area.[1] The practical value of these models was borne out by the ADCP data for Friar Roads Bay. The models also showed that higher tidal currents existed at the site where the Project was ultimately located.

Figure 1: Original Site Investigated (Friar Roads Bay)

[1] Xue, H., F. Chai, and N.R. Pettigrew. (1999). A model study of seasonal circulation in the Gulf of Maine. Journal of Physical Oceanography 30:1111-1135.

ORPC then turned to Cobscook Bay to search for areas that could meet both bathymetry and current flow needs while remaining within a reasonable distance of Station Eastport, and identified a potential Project location in Cobscook Bay near Shackford Head, three miles from Station Eastport (Figure 2).

ADCP data from Shackford Head showed current speeds with a maximum of 2.25 m/s, although the highest percentage of time was spent at current speeds between 1 and 1.6 m/s (see Appendix I). ORPC, with concurrence from town officials, local harbormasters, the US Army Corps of Engineers and the USCG, received local mooring permits and moored the *Energy Tide 2* at this Shackford Head site for initial performance tests of the Beta TGU in September 2010.

At the same time, ORPC continued to explore Cobscook Bay using bathymetry and ADCP data. A more desirable site was discovered off Seward Neck, in upper Cobscook Bay between Goose Island and Grove Point in North Lubec, approximately 1.2 miles northwest of the Shackford Head location. The site recorded maximum current speeds of 2.6 m/s, with the highest percentage of time spent at current speeds between 1.4 and 1.8 m/s (see Appendix I). ORPC ultimately relocated the *Energy Tide 2* to the site off Seward Neck, near the Eastport/Lubec border (Figure 2). The relocation process interrupted the Project for 14 days, from September 12 – October 4, 2010. The move stemmed from multiple factors:

- The time spent in the field ground-truthing the circulation model, which ultimately yielded technical information that provided a scientific basis for using the upper Cobscook site (documented by the ocean circulation and energy density model, and ORPC's ADCP deployments)
- A generator maintenance issue (see page 14, *Energy Tide 2* Mooring and Systems Check) that interrupted Project operations and resulted in the *Energy Tide 2* remaining at the Shackford Head site longer than anticipated, thereby creating a potential conflict with the start of the commercial urchin dragging season
- A consensus among local commercial fishermen, the Town of Lubec, and the Maine Bureau of Marine Patrol that use of the upper Cobscook site for tidal energy operations minimized conflicts with other bay users

Table 1 shows a comparison of the expected energy generation available at each of the three sites – Friar Roads, Shackford Head and Seward Neck – based on ADCP data. Energy production depends on tidal cycle parameters at a given location, and can be highly variable. Multiple analytical approaches are available for predicting the energy production by a hydrokinetic turbine at any given site. The data collected by on-board velocity measurements enabled ORPC to produce various performance curves for the Beta TGU, validating the system's performance as a function of water speed (see Appendix II).

Figure 2: Shackford Head and Seward Neck Sites

Energy Produced by Turbine	Friar Roads Bay	Shackford Head	Seward Neck
Per year	13.1 MWh	27.7 MWh	50.0 MWh
Per month	1.1 MWh	2.3 MWh	4.1 MWh
Per day	35.8 kWh	76.0 kWh	137.1 kWh

Table 1: Estimated Energy Production by Beta TGU at Each Site

Permits

ORPC secured all federal and local permits required for this Project and received an opinion from the Maine Department of Environmental Protection that a state permit was not required. These approvals are listed below. Notably, a permit from the Federal Energy Regulatory Commission (FERC) was not required because FERC oversees only private development projects. A FERC permit was also not needed for the separate preparatory testing for the Project involving ORPC because the Project was temporary and not grid-connected.

- City of Eastport – Mooring permits for Shackford Head secured January 22, 2010 and for Seward Neck September 17, 2010
- Town of Lubec – Mooring permits for Shackford Head secured January 22, 2010 and for Seward Neck September 21, 2010
- Maine Department of Environmental Protection – An original opinion letter concluding that a project of this type would not require a permit under the Maine Water Development and Conservation Act (MWDCA) was received November 21, 2008. A further opinion that the Project, with the addition of the USCG's

participation, would not require a permit under the MWDCA was received January 25, 2010.

- US Army Corps of Engineers – Section 10 General Permit for mooring, originally secured October 29, 2009 (extensions granted April 5, 2010 and September 28, 2010)
- US Coast Guard – Private Aids to Navigation, secured September 10, 2010

PROJECT PHASE II

Project Components

ORPC designed, built, deployed and tested its proprietary hydrokinetic power generation system, the Beta TidGen™ System, as the primary component in this first-of-a-kind Project. The Beta TidGen™ System was comprised of the Beta TGU; the *Energy Tide 2* (including the barge and deployment system); the *Energy Tide* 2 mooring system; and the energy transfer system (including the battery charging and discharging equipment and the battery transfer launch), as described below.

Beta TidGen™ System

Beta TGU: The Beta TGU is a fully operational hydrokinetic device that generates grid-compatible electricity from variable tidal currents. It is 46 feet wide by 14 feet high by 11 feet deep, and is suspended approximately 21 feet below the water surface by the *Energy Tide 2* deployment system. Built primarily with composite materials, it requires no lubricants and produces no gas or liquid emissions, including greenhouse gas emissions. The Beta TGU consists of two horizontal advanced design cross flow (ADCF) turbines in tandem on each side of an underwater permanent magnet generator. The ADCF turbines include swept foils adapted to varying turbine diameter with a maximum diameter at mid-span; disks, rings and foils made with vacuum infused E-glass/vinyl ester laminate; and a carbon/E-glass hybrid primary shaft. The turbines and generator are attached to a common drive shaft and all are mounted on a chassis. The Beta TGU is rated for operation at a peak tidal speed of 3.1 m/s. As the tidal speed changes during the course of a tidal cycle, the amount of power generated changes in proportion to the cube of the water speed. The ADCF turbines are designed with a cut-out speed of .5 m/s and a cut-in speed of approximately 1 m/s.

Power Conversion Electronics: The ADCF turbines are directly connected to a permanent magnet generator, which produces 3-phase (3Φ) electrical AC power. Because of the direct coupling, no gears are needed. High strength iron neodymium magnets are mounted on the generator rotor; the interaction of the magnetic field produced by these magnets and the stator wound field generates voltage.

An inverter system is used to perform power conditioning on the variable-frequency, variable-voltage AC power that originates from the Beta TGU's generator. This power is fed to a proprietary boost converter, which provides a direct current (DC) output voltage and boosts the DC voltage. The DC voltage is then fed to a Satcon PowerGate Inverter that outputs constant 60Hz, 480V 3Φ grid-compatible power. This power is fed to a set of four

Victron Energy battery chargers on the *Energy Tide 2*, which in turn charge the house battery system and the USCG battery banks.

The *Energy Tide 2*

The Beta TGU was deployed from the *Energy Tide 2*, ORPC's research, testing, and deployment vessel (Figure 3). Main components of the *Energy Tide 2* include a floating barge, a control room, a propane house generator, and a hydraulic deployment and retrieval system for the Beta TGU.

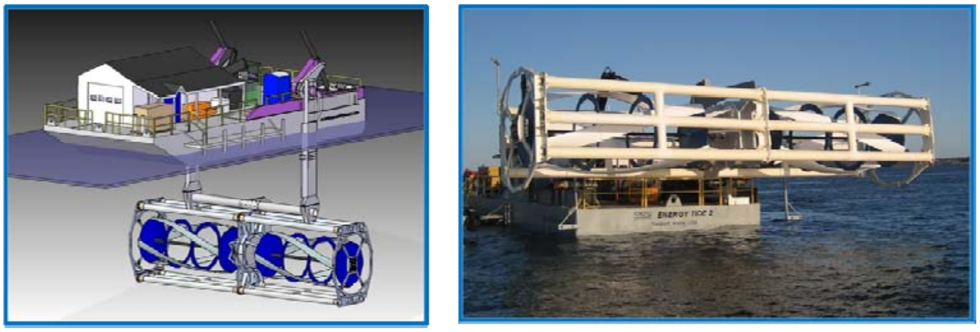

Figure 3: Beta TGU and *Energy Tide 2*

Barge: The barge used for the *Energy Tide 2* is 60' long x 24' wide with a 6' hull side and a displacement capacity of 75 tons. It was built by Morrison Manufacturing in Perry, Maine and is leased from the Eastport Port Authority.

Control Room: The control room aboard the *Energy Tide 2* houses power electronics as well as power conditioning and data acquisition equipment.

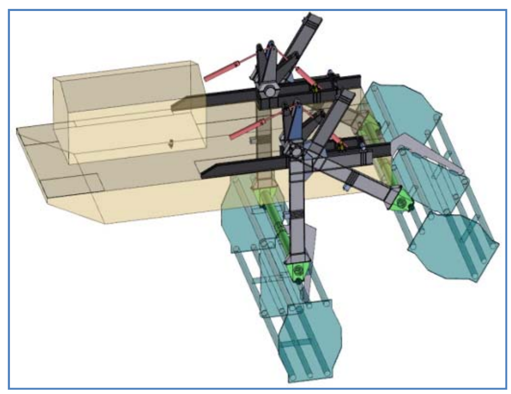

Figure 4: Deployment & Retrieval System

House Generator: Power for the house is supplied by a battery bank comprised of thirty-two 12 V batteries. When these battery banks become depleted, power is supplied by an 8.5 kW propane-powered house generator. The generator starts automatically, supplies house power and charges the battery bank. The generator shuts down when the batteries are charged.

Deployment System: The deployment and retrieval system for the Beta TGU (Figure 4) consists of superstructure elements connected to the *Energy Tide 2* and a set of rotating deployment arms connected to the structural frame of the Beta TGU. Multiple hydraulic actuators provide the means of actuation, which lift and deploy the 26,000-pound Beta TGU in fewer than 10 minutes. Design work for this deployment system included full finite element structural and modal analyses.

The *Energy Tide 2* Mooring System

The mooring system for the *Energy Tide 2* is a variation of a single point mooring, consisting of four primary ground legs connected to a single riser line, which is then connected to a riser float. The ebb and flood current directions serve the primary axis of the system. The ground lines are arranged at 30-degree angles to this primary axis, with both legs on one side of the system forming a 60-degree angle between them. See Appendix IV for an illustration of the mooring system.

Each of the ground legs is comprised of chain sections assembled using standard connecting hardware. A 3,000 pound stockless, Baldt-type anchor is placed at the outer end of each ground leg. Further inbound along the ground line is a second embedment anchor, a 5,000 pound Danforth-type anchor, and a 4,500 lb clump weight. The three anchors are separated by two shot lengths each (standard chain shot = 90 feet). From the innermost clump weight, five sections of chain connect to a common ground ring. The riser line is similarly connected to this ground ring. At the outermost anchor location on each leg, a crown marker buoy is attached via poly-nylon riser line.

The barge is connected to the riser buoy through a three-line bridle. The barge typically orients itself with respect to current and wind direction by pivoting about the central riser buoy.

Energy Transfer System

The batteries selected for this Project were 12 V 2580L sealed AGM lead-acid batteries manufactured by Sun Extender Solar Batteries, a division of Concorde Battery Corp. These batteries were chosen for their overall safety, efficiency and durability, as they are strongly resistant to vibration and shock and will not freeze. Their design also immobilizes electrolyte in glass mats to prevent spillage.

Initially, the Test Plan called for the use of twelve 12 V batteries in each battery bank, with each battery bank weighing approximately 2,000 pounds. Because the knuckle boom crane on the *Energy Tide 2* could not safely accommodate this weight to lift the battery banks into and out of the launch, ORPC reduced the number of batteries in each battery bank to eight, so that each eight-battery bank weighed approximately 1,600 pounds. This resulted in 33% less storage capacity than was originally anticipated.

Figure 5: 20' Launch Containing Battery Bank

The battery banks used to power the UTB were ferried to to the USCG pier aboard a 20' open hull launch (Figure 5). The launch was towed to the pier by a 37' towing vessel.

<u>Methodologies</u>

<u>Charging Batteries onboard the *Energy Tide 2*</u>

Tidal power generated by the Beta TGU charged battery banks onboard the *Energy Tide* 2. A single-line drawing of the battery charging system aboard the *Energy Tide 2* is shown in

Figure 6. In this system, the 3Φ 480V power output by a Satcon PowerGate Inverter is transformed into 3Φ 240V power. The Satcon inverter is a 50 kW-rated system that converts and conditions the DC power generated by the TGU into grid-compatible power. Victron marine battery chargers then use this power to charge the battery banks aboard the *Energy Tide* 2. The battery charging system matches the load drawn by the battery chargers to the tidal current-dependent output of the Beta TGU.

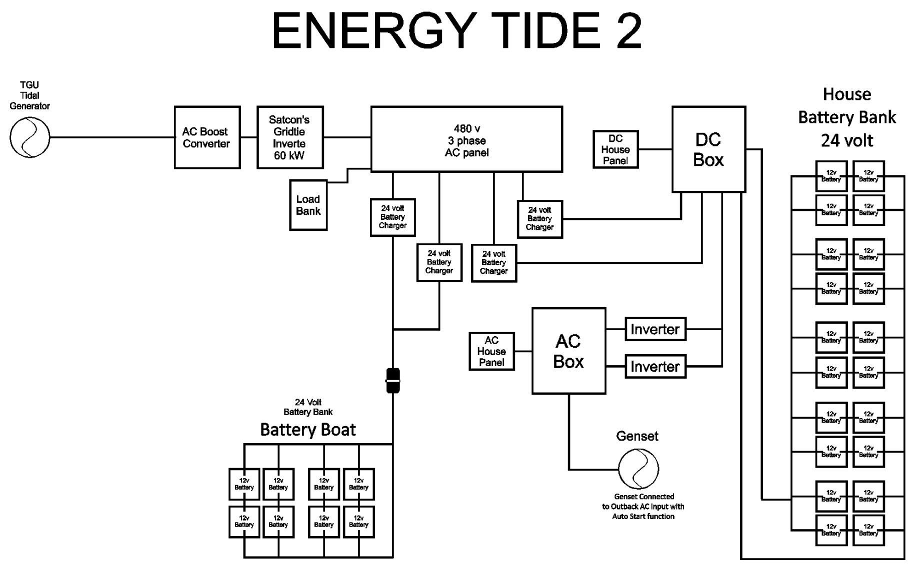

Figure 6: Single Line Diagram - *Energy Tide 2*

<u>Transferring Power from Batteries to USCG Pier</u>

Once charged, the battery banks were then loaded onto the 20-foot launch and towed by a separate 37' vessel from the *Energy Tide 2* to the Station Eastport pier. The battery banks were then connected to the inverter at the pier where power was discharged. The power delivered by the inverter to the designated USCG electrical loads was monitored by the inverter; energy delivered was recorded manually each delivery. The launch would remain at the pier until the battery bank was discharged, and would then be towed back to the *Energy Tide 2* for battery recharging.

The battery banks were connected to an OutBack Inverter System mounted on the USCG pier (Figure 7). The OutBack system was capable of either passing grid power directly to the UTB loads or supplying power to the vessel loads by inverting the 24V DC power in the batteries to 120V AC and transmitting that power to the UTB loads. The OutBack system was programmed to supply power to the UTB from the battery banks whenever a charged battery bank was connected to the system.

Each battery bank was used as the sole power source until the battery voltage reached a prescribed discharge level, at which point the power supply for the vessel was transferred back to the grid until a charged battery bank was again delivered and connected to the shore inverter system. ORPC installed a green light on the OutBack system housing to indicate when power was being supplied to the UTB by the tidally charged battery bank

(Figure 8). A manual transfer switch was also installed to allow the OutBack system to be completely bypassed should a fault occur to compromise power supply to the UTB.

Figure 7: USCG Pier Electrical Panel and Connection

Figure 8: USCG Pier Electrical Panel and Indicator Lights

Data Acquisition

Various instruments were deployed on the Beta TGU to measure parameters such as tidal flow speed, generator rpm, voltage, and current. On board, the power electronics chain measured system efficiency from the water input energy to energy dissipated in the electrical loads. All data were logged on board at 1 to 3 second intervals, and were transmitted to shore on regular intervals. The parameters that were measured and recorded are listed in the Test Plan (See Appendix IV), along with instrument requirements and locations. Multiple power measurements were obtained: the AC 3Φ voltage and current from the generator; the DC rectified voltage and current inputs to the Satcon inverter; and the average 3Φ voltage, current, power factors and power delivered by the Satcon inverter.

Data Collection and Interpretation

The data was logged from the BMV-602 battery meter on each battery bank into a laptop computer that read and recorded readings every minute. Main data collected were voltage level, state of charge, amp (A), amp hour (Ah) and time. Meters were zeroed and synchronized at the start of every delivery.

Site Safety Plan

All Project operations adhered to appropriate safety measures. In March 2010, ORPC developed a Site Safety Plan that addressed potential risks associated with marine operations such as falls; weather related hazards; interaction between and among vessels; crane operations; potential of periodic noise hazards; and the use of equipment, tools, batteries and electrical systems. The Site Safety Plan also outlined emergency response procedures. The Site Safety Plan applied to all ORPC employees, contractors, Project partners and visitors to the work area. Either the site manager or an appropriate designee began each shift with a safety briefing that reviewed any identified risks and required safety measures. This briefing was documented daily, with signatures from all who attended the briefings. All personnel treated safety as a priority. No safety incidents or emergencies were experienced over the course of the Project.

Phase II Execution

Energy Tide 2 Mooring and Systems Check

With the Beta TGU in the stowed position, ORPC moved the *Energy Tide 2* to the initial Shackford Head mooring site on March 1, 2010 and attached it to its mooring. ORPC then performed a complete systems check on the Beta TGU, and discovered an electrical short in the generator. ORPC removed the generator from the Beta TGU and returned it to the shop for repair. However, further maintenance inspection determined that there was an opportunity to substantially improve the overall operation of the generator rather than simply fixing the short, and ORPC chose to make these improvements. The generator rebuilding process began in late April 2010 and delayed the start of the demonstration period until August 17, 2010. While the initial maintenance issue was unfortunate, it arose as a result of real-time demonstration Project activities, and serves as an example of how testing in real marine environments is vital for advancing technology development.

Demonstration Period

After rebuilding the generator and reassembling the Beta TGU, ORPC deployed the Beta TGU and began generating power from tidal currents at the Shackford Head site. Regular battery bank transfers from the *Energy Tide 2* to the USCG pier occurred at varying intervals for the planned 60-day demonstration period beginning August 17, 2010.[2] Over the course of this period, 19 complete transfers were successfully completed and documented (see Table 2 below), for a total of 191.1 kWh delivered to the UTB. Notably, it was not the Project's goal to maximize power delivered to the UTB, but merely to demonstrate the technical feasibility of delivering power from the Beta TGU to the UTB. Accordingly, the 191.1 kWh constitutes only a small portion of the total energy generated during the demonstration period by the Beta TGU (1,252 kWh), which itself was operating in a testing mode rather than a maximum power mode for the majority of this period. During the demonstration period 1,252 kWh was produced by the Beta TGU. The TGU was operating in a constant voltage output mode during the demonstration period in order to more effectively charge batteries, and was not operating in the Maximum Power Point Mode, and consequently the system was operating at a lowered efficiency.

2 The Project's demonstration period was temporarily halted for a period of 14 days from September 12, 2010-October 4, 2010 while the *Energy Tide 2* was relocated from the Shackford Head site to the Seward Neck site, and for a total of 11 down days due to inclement weather, namely high winds.

Transfer	Battery Bank Eleanor or Franklin	Date	Energy Delivered Kilowatt-hours (kW-h)
#1	F	8/17/10	16.8
#2	F	8/21/10	19.1
#3	E	8/24/10	15.1
#4	E	9/8/10	20.9
#5	F	9/11/10	18.6
#6	E	9/12/10	17.5
#7	F	9/21/10[3]	3.2
#8	E	10/5/10	11.9
#9	F	10/9/10	4.0
#10	E	10/12/10	4.9
#11	F	10/13/10	7.9
#12	E	10/14/10	11.6
#13	E	10/20/10	11.3
#14	F	10/21/10	7.4
#15	F	10/26/10	6.5
#16	E	10/28/10	8.4
#17	F	10/29/10	4.0
#18	E	11/1/10	1.7
#19	F	11/4/10	0.2
Total Delivered Kilowatt Hours			**191 kWh**

Table 2: Battery Bank Summary

Lessons Learned and Recommendations

ORPC recorded and interpreted power data during the demonstration period in order to evaluate the effectiveness of Project equipment and methodologies. The following section outlines lessons learned through this Project and recommendations that will help the USCG design more effective tidal energy projects in the future.

Power Quality Analysis

Through the power quality analysis performed in fall 2009, ORPC determined that the UTB would use an average of 40-50 kW/hours (kWh) per day. For the purposes of the Test Plan, ORPC speculated that winter use rates would average 122 kWh per day. In reality, while the UTB drew an average of 71 kWh per day in October, this climbed to over 135 kWh per day by early November. Additionally, in October 2010, power data showed that the UTB was drawing close to 300 instantaneous amps from the battery banks, or 7.2 kW (300 amps

[3] This battery bank was charged and remained on-board the *Energy Tide 2* for several days during the relocation to Seward Neck before being transported to the USCG pier.

x 24 volts). Since the rating for the wire and fusible links was only 250 amps, the batteries could not keep up with this draw. Whereas in mid-August, the battery banks had supplied the UTB with six to ten hours of power, by October they were providing only 23 minutes of power (see Table 2, Battery Bank Summary, above). ORPC has since determined that the discrepancy between the fall 2009 power analysis and the actual power demands in fall 2010 was due to the significantly cooler air and water temperatures that occurred in fall 2010. This caused the UTB's block heaters to be used more frequently and for longer durations (See Appendix III, Station Eastport Power Usage). For future projects, ORPC recommends that initial power analyses incorporate a wider range of weather data to more accurately specify the energy transfer system.

Energy Transfer System

During the last five battery bank transfers (October 26 – November 4, 2010), the cool air and water temperatures increased the UTB's power demand to the point where it actually exceeded the capacity of the batteries and inverter equipment. This caused the Project to begin experiencing equipment failures, including the loss of fusible links and automated battery bank switching capability. When the overall Outback system could no longer revert to grid power automatically, it had to be manually bypassed with the disconnect switch. This required diligent in-person monitoring of the Outback system at the Station Eastport pier. The combination of equipment damage and lack of automation created safety issues for ORPC and USCG personnel as well as the UTB. As a result, ORPC concluded the demonstration period after 57 operating days rather than the intended 60.

The above situation highlights a problem with the energy transfer system configured for this Project. At UTB winter load levels, the battery banks are discharged within approximately 1.5 hours, a time period that does not justify the effort put into charging and ferrying them to the UTB. Expanding the battery system to accommodate UTB winter loads would require a larger battery supply with multiple, shorter wire runs to handle the large electrical currents needed by the inverter system. The inverter would also need to have a slave inverter to be able to increase its output during peak times when the UTB load exceeded 6 kW. To ensure necessary power to the UTB, a redundant automatic transfer switch would likely also have to be installed.[4]

Even if the above modifications were made to the energy transfer system used for similar purposes in the future, this Project reaffirmed that battery banks are a relatively inefficient means of storing and transporting tidal energy. While the battery banks effectively transferred power from the *Energy Tide 2* to the USCG pier, demonstrating the technology's technical feasibility and validating the concepts of off-grid battery charging and inverter-based systems, they could not economically or reliably scale to a larger grid-tied project. For any such larger project in the future, ORPC recommends that the USCG investigate the

[4] This is because the OutBack inverter's internal transfer switch failed to return power supply to the UTB when the DC fuse from the batteries to the inverter blew, causing total inverter shutdown and a failure to activate the internal transfer switch of the inverter.

use of a submarine power transmission cable as an alternative to batteries. Where this is not possible, the USCG can purchase energy from a power grid that is already receiving electricity from an existing tidal energy project.[5]

Before the USCG installs any renewable energy system, ORPC recommends that it perform an energy audit on the station to be served, to identify and implement simple means of reducing energy consumption at the station. In winter, the UTB system alone uses over 6kW of power to run engine block heaters and other ancillary systems, approximately five times the average daily energy consumption of a residential house in Maine.

Siting

Locating an optimal deployment site took substantially longer than expected in this Project. This reaffirmed the complex nature of site selection, which requires the careful study of circulation models and bathymetrical data as well as the time commitment to deploy and inspect ADCP instrumentation in the field and analyze all ADCP data once it has been collected.

Permitting

This Project was the first tidal energy project to ever go through the USCG Environmental Checklist process, so extra time was spent auditing the permitting process as the USCG gained familiarity with state, local and federal requirements. ORPC recommends that in the future, consultations among the permitting agencies, the USCG environmental team and others involved in permitting occur early in the Project process, with regular follow-up to ensure adequate progress.[6]

[5] The entire Eastport-Lubec region will actually be making use of the electricity generated from grid-connected tidal energy because, as a practical matter, electronics flow to the nearest load. This provides a great opportunity to market the area – and highlight the USCG Eastport Station - benefitting from this type of sustainable resource.

[6] Different states across the country will have different approaches to tidal energy permitting. There may be regional variability as well.

Future Commercial Opportunities

ORPC is developing sites and obtaining pilot project licenses from the Federal Energy Regulatory Commission to install a TidGen™ Power System as part of ORPC's TidGen™ Power System Commercialization Project. The TidGen™ Power System is a complete power generating system comprised of an array of TidGen™ devices, which each consist of a single TidGen™ TGU and a bottom support frame (See Figure 9). Each TidGen™ device will be connected via underwater cable to an underwater junction box, which will connect to the on-shore interconnection facility through a single underwater transmission line.

Because this particular project will connect to the power grid in Lubec, Maine, the USCG in Eastport will have the option of purchasing tidal power through the grid, and will not have to permit an underwater cable to and from the TidGen™ Power System. The projected performance curve for the TidGen™ device is provided in Appendix II.

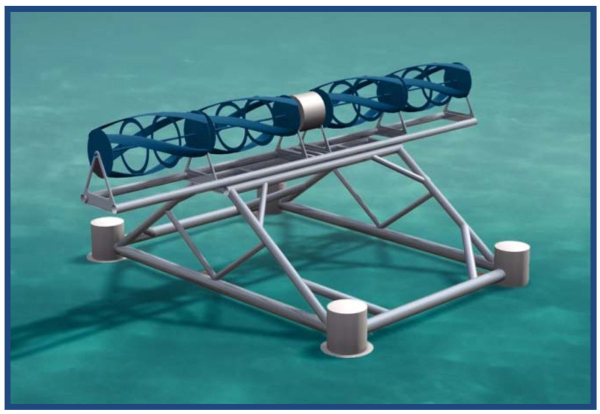

Figure 9: TidGen™ device

CONCLUSIONS

Through the Project, the USCG and ORPC collaborated on a first-of-its kind renewable energy research and development effort that supplemented grid-tie shore-side power used by Station Eastport's UTB. The Project constituted the U.S. government's first practical application of tidal energy, and successfully demonstrated the technical feasibility of using tidal energy at a USCG facility. This report provides the USCG with an initial guide to the development of tidal energy. Although this first-of-a-kind project faced several challenges and produced some unanticipated outcomes, it is precisely this type of leading and exploratory effort that facilitates technical advancement.

The USCG's Sustainability, Environmental & Energy Policy Statement states that "seeking alternatives that maximize use of renewable energy sources" [7] is consistent with the Service's environmental stewardship and protection goals. Currently, one of the Northern Sector's goals is to make Station Eastport the most energy self-sufficient federal facility in the United States using a combination of renewable resources.[8] The Project demonstrated that tidal energy has the potential to be one of these resources, not only for Station Eastport but for other stations situated in remote locations around the country.

This Project provides information on the performance of the ORPC Beta TidGen™ System that can guide potential future USCG tidal energy applications. Lessons learned in this small-scale demonstration Project can also be applied to the development of tidal energy technology in a wide range of larger-scale USCG applications. It is highly recommended that the USCG develop an inventory of stations with nearby tidal energy velocities conducive to project development. Potential next steps might include the incorporation of a bottom-mounted tidal energy device or even an array of bottom-mounted tidal energy devices at sites adjacent to USCG stations. Continued pursuit of tidal energy as a viable clean power source for USCG facilities will help the USCG retain its position as a national leader in the pursuit of energy independence and security.

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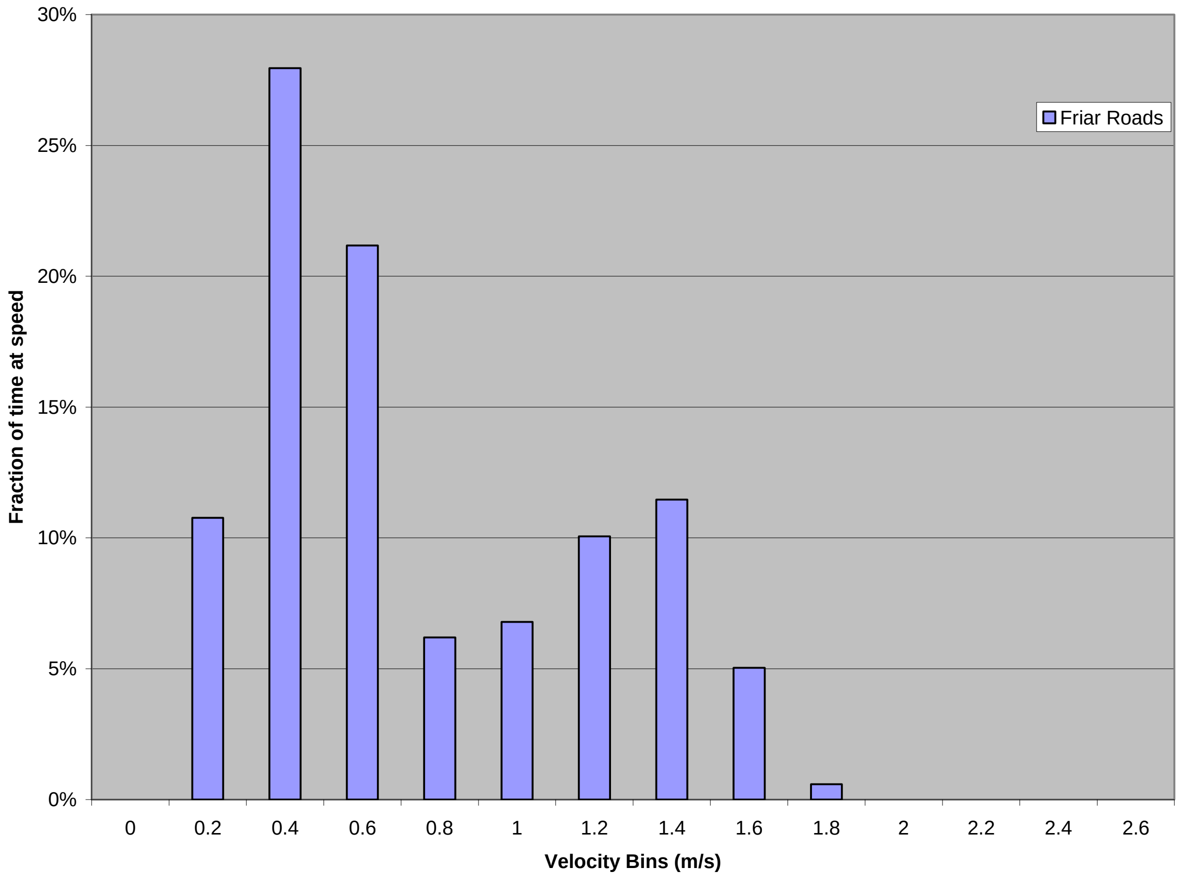
[7] See www.uscg.mil/seniorleadership/announcements/Environmental_and_Energy_Policy_Statement.pdf, last viewed December 24, 2010.

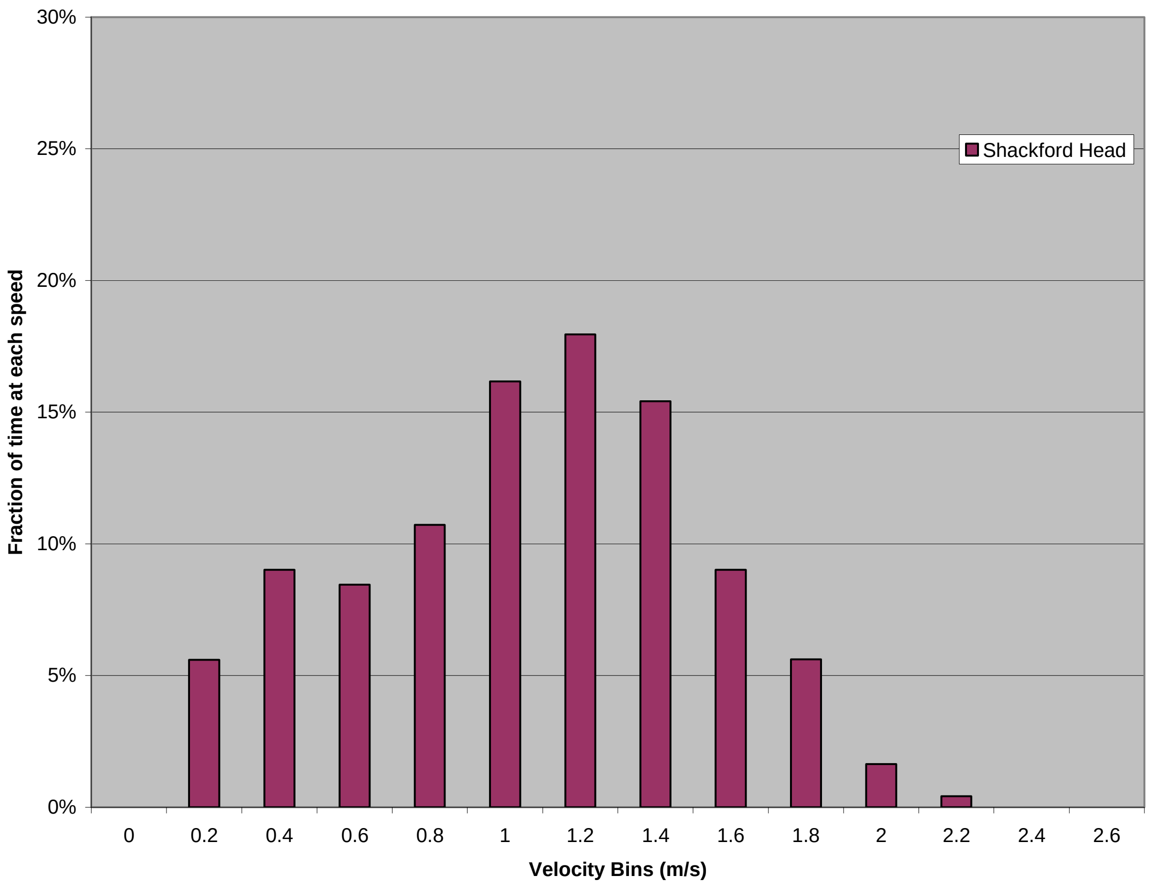
[8] Project interview with Capt. James B. McPherson, Commanding Officer, Northern Sector, USCG District 1, December 17, 2010.

Appendix I - Water Speed Histograms

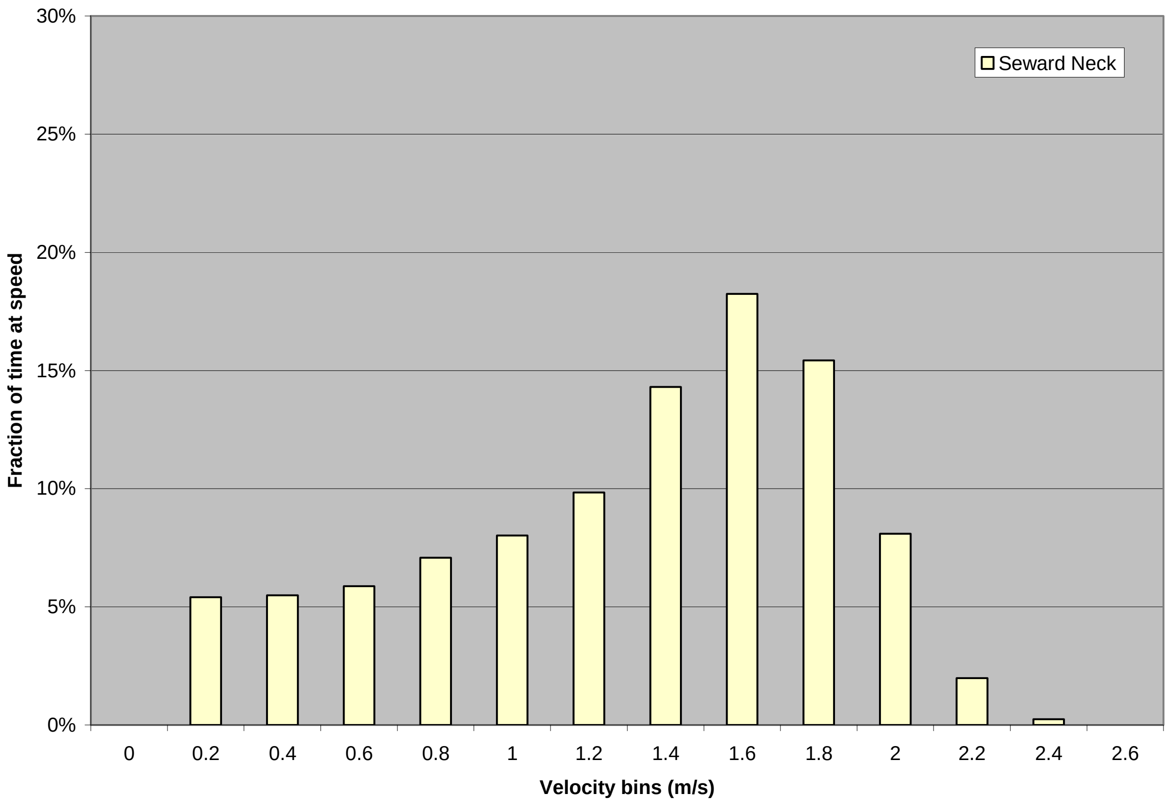
Friar Roads Bay Water Speed Histogram



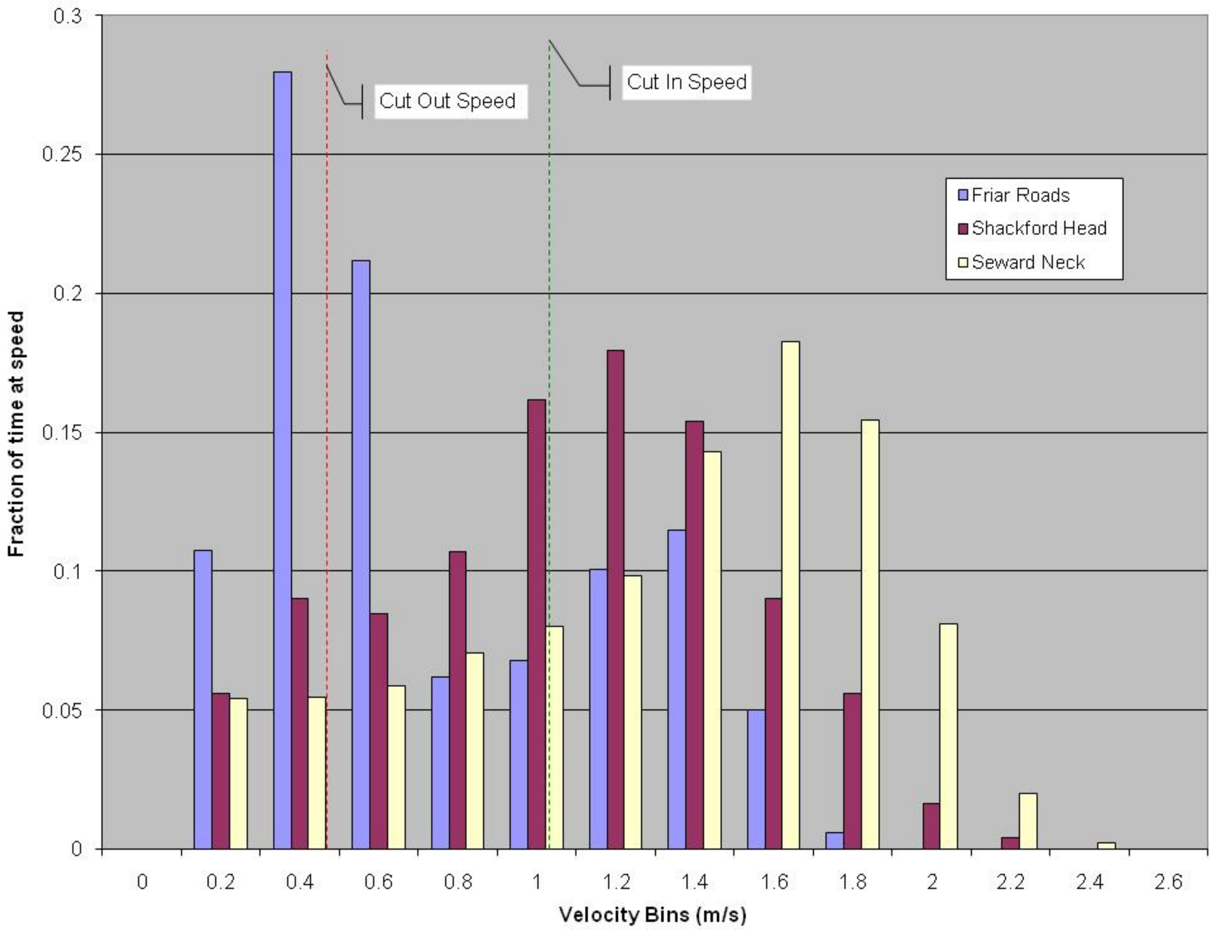
Shackford Head Water Speed Histogram



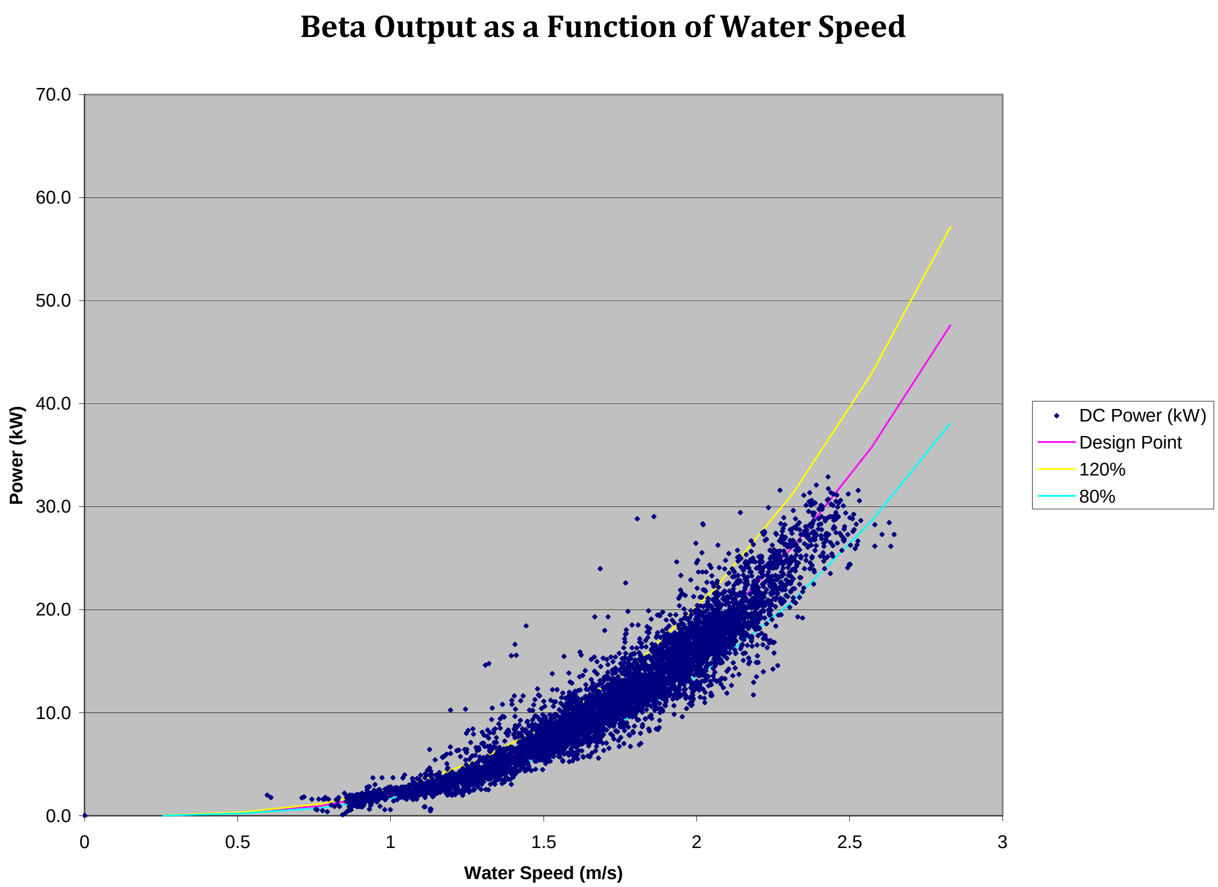
Seward Neck Water Speed Histogram



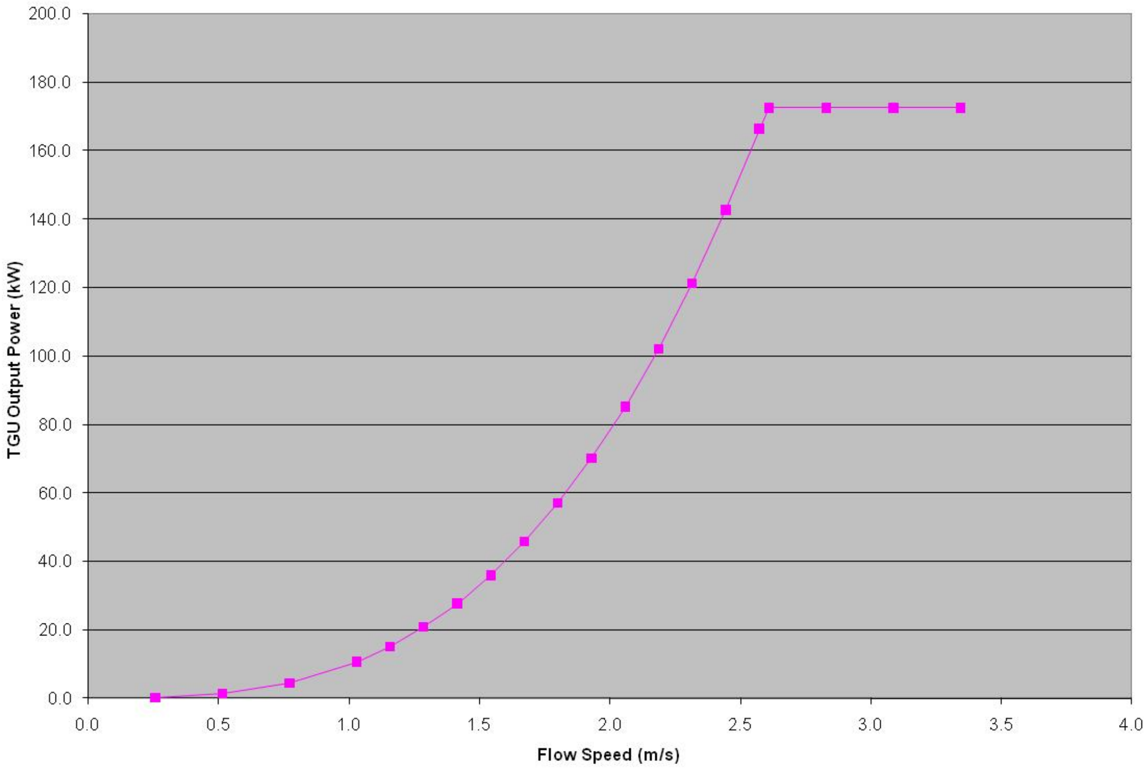
Water Speed Histogram Summary



Appendix II - Power Curves



TidGen™ Power System Projected Performance Curve

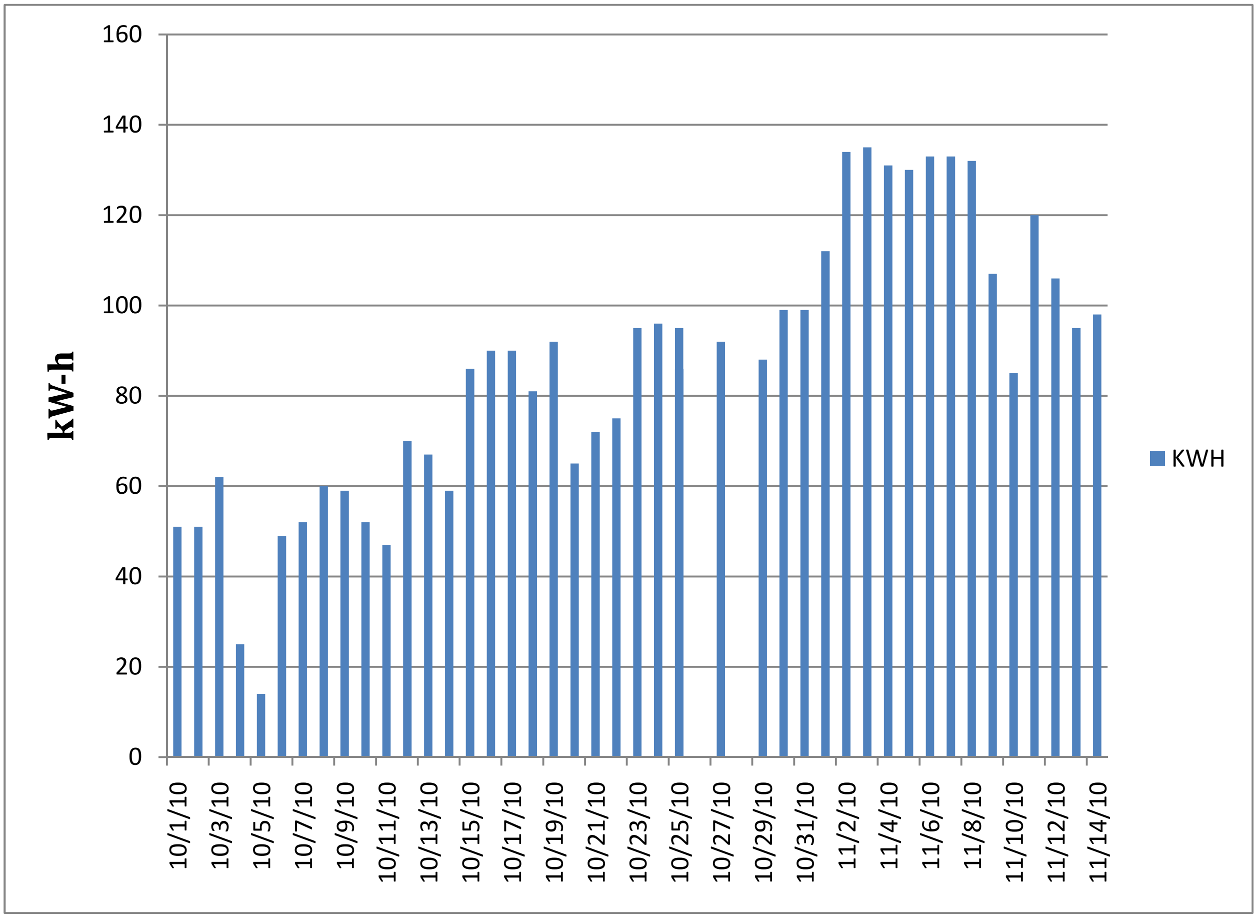


TidGen™ Performance Specification

Flow Velocity (m/s)	0.3	0.5	0.8	1.0	1.2	1.3	1.4	1.5	1.7	1.8	1.9	2.1	2.2	2.3	2.4	2.6	2.6	2.8	3.1	3.3
TGU Power (kW)	0.2	1.3	4.5	10.6	15.2	20.8	27.7	35.9	45.7	57.1	70.2	85.2	102.2	121.3	142.6	166.3	172.5	172.5	172.5	172.5

Appendix III - Power Usage

Station Eastport Power Usage



Appendix IV – Test Plan

ELECTRICAL POWER GENERATED FROM TIDAL CURRENTS AND DELIVERED TO USCG STATION EASTPORT, ME PIER

BAA HSCG32-09-C-R00018

Eastport Breakwater and United States Coast Guard Station Eastport

Prepared by Ocean Renewable Power Company
For
United States Coast Guard Research and Development Center
February 3, 2010

Executive Summary

The US Coast Guard (USCG) and Ocean Renewable Power Company (ORPC) signed a contract effective August 26, 2009 under which ORPC will deliver services for the project *Electrical Power Generated from Tidal Currents and Delivered to USCG Station Eastport, ME Pier* (the "Project") (BAA HSCG32-09-R00018).

Within the Scope of Work (SOW), ORPC was required to develop a Test Plan for the Project, defined in the SOW as:

"ORPC will confirm power requirements with the USCG in order to determine what will be powered and then will establish a Test Plan. The Test Plan will include the theory of operation, test procedures, a basic schematic drawing showing electrical connections, the schedule of battery charging & ferrying, the types of batteries being used, the method for transferring power from batteries to the USCG Station or pier, the electrical & other permits needed, all equipment needed, and any other applicable details on electrical connections, procedures and system operation."

The format of this Test Plan follows the language of the SOW and includes all of the information requested by the SOW, as well as additional details that the USCG project team has requested and that ORPC feels is important for a full understanding the Project. It provides a sound approach to ensure a technically sound, safe and ultimately successful demonstration Project.

The test site will be located in Cobscook Bay, adjacent to Shackford Head and Deep Cove (Map of site is shown in Figure 1). The area is proximate to existing commercial marine infrastructure such as a public boat ramp and pier, the Maine Marine Technology Center (MMTC) which ORPC uses as a fabrication and storage facility, and the Eastport Port Authority's Estes Head Terminal.

The project will make use of ORPC's Energy Tide 2 testing barge and the company's Beta Pre-Commercial Turbine Generator Unit (TGU). The Energy Tide 2 will be moored at the Cobscook Bay site through services provided by the Eastport Port Authority and local contractors. With the Energy Tide 2, ORPC will maintain two 20-foot open launches that will each contain 24 V battery banks, comprised of 12 V batteries. For the demonstration project, ORPC will:

- Charge the battery bank modules.
- Periodically relocate the modules to the USCG pier by towing the launch via a 37-foot vessel captained by a licensed local mariner. (Pier facility and USCG station shown in Figure 2).

- Provide supplemental power for approximately two hours daily to the shore-tie for the 41-foot search and rescue vessel berthed at the pier.
- Maintain the two separate launch vessels and battery module systems and follow a once a day rotation and ferrying schedule (taking into account any weather-related delays changes).

The project will be fully dedicated to safety and all project operations will adhere to appropriate safety measures. The Site Safety Plan for the Test Plan will address risks associated with marine operations, and use of equipment, tools, batteries and electrical systems, and outline emergency response procedures. Because this project involves ORPC, the USCG, the Eastport Port Authority and other local contractors, a collaborative approach to site safety will be implemented and daily site safety briefings will be documented.

ORPC has secured local, state and federal permits for the project, which are described below:

Permitting Requirements

JURISDICTION	AGENCY	REQUIREMENT
Local	City of Eastport (Harbormaster) Town of Lubec (Harbormaster)	Mooring Permits (test site is approximate to boundary of each community)
State	Maine Department of Environmental Protection	Letter providing opinion that the project requires no Maine Waterway Development and Conservation Act permit and therefore no State Coastal Zone Management Act consistency review is necessary
Federal	US Army Corps of Engineers U.S. Coast Guard	Section 10 Programmatic General Permit for mooring PATONS approval for mooring and barge

No permit is required from the Federal Energy Regulatory Commission (FERC) because the commission oversees private development projects only. (Also, any separate testing in preparation for the USCG project involving just ORPC requires no FERC permit because the project is temporary and without a grid connection.)

All permits were obtained following consultation with the relevant agencies regarding potential environmental effects. At the federal level, the National Marine Fisheries Services (NMFS) provides guidance to the U.S. Army Corps of Engineers (USACOE). The USACOE

Programmatic General Permit (PGP) requires ORPC to monitor ambient and operational noise during testing operations and to document the presence of seals at the site, along with their behavior in response to testing. This information will be coordinated and shared with the NMFS. At the state level, the Maine Department of Environmental Protection has provided the opinion that the project is not expected to have any adverse environmental impact and no Coastal Zone Management Consistency permit is required.

Throughout the permitting process ORPC conferred with the Environmental Branch Chief of the Civil Engineering Unit Providence for guidance on proper completion of the USCG Environmental Analysis Checklist.

During the development of the test plan, the ORPC and USCG project teams conferred several times to review testing options and technical data. The USCG project team included representation from the Research and Development Center in New London, CT; Station Providence, RI; Station Belfast, ME; and Station Eastport, ME. The test site was selected following an analysis of a current velocity survey using both mobile transect data and fixed, bottom-mount data provided by an Acoustic Doppler Current Profiler (ADCP). The test plan focus on providing supplemental power to the USCG shore-tie that feeds the 41-foot search and rescue vessel was finalized after completion of a power analysis study. This study included the installation of a power quality meter by a licensed electrician that allowed the documentation of power demand.

In addition to demonstrating how the USCG may use tidal energy at its Eastport station, this test plan will also provide educational background material for USCG personnel regarding tidal energy research and development and the process for planning and implementing a tidal energy demonstration project. The document can serve as a template for any future tidal energy demonstration effort undertaken by the USCG.

Table of Contents

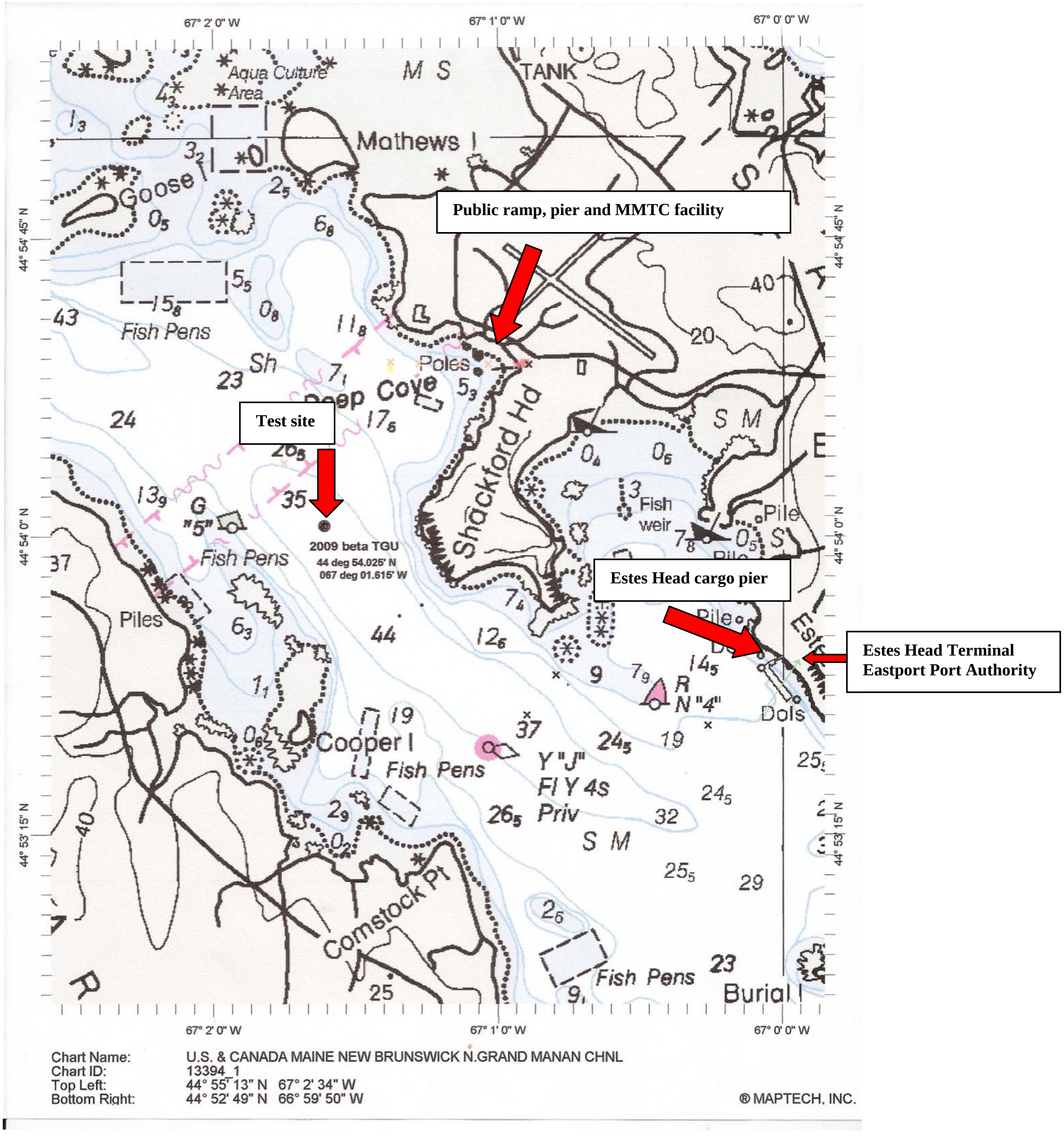


Figure 1: Map of Cobscook Bay test site

Figure 2: Eastport Breakwater and United States Coast Guard Station Eastport

Theory of Operation

The ORPC Pre-Commercial Beta Turbine Generator Unit ("Beta TGU") uses a hydrokinetic cross flow turbine based on Darrieus turbine technology as its prime mover. The TGU is the core of ORPC's proprietary technology and it uses hydrokinetic advanced design cross-flow ("ADCF") turbines to drive a permanent magnet generator located between the turbines and mounted on the same shaft. ORPC continues to develop improvements to its proprietary designs of the ADCF turbine, the underwater permanent magnet generator and the TGU, and has filed utility and Patent Cooperation Treaty (PCT) patent applications covering these designs. ORPC has developed preliminary designs of power generation systems based on its technology for deployment in river, tidal and ocean current applications. Extensive testing of the commercial design of the TGU in actual tidal currents in Cobscook Bay while it is deployed from the *Energy Tide 2* is a critical next step in commercialization of ORPC's technology.

Turbine Theory

Cross flow turbines have been proposed as a competitive design approach for extracting hydrokinetic energy due to their favorable geometric layout and ability to work in bi-directional flows. Axial flow turbine concepts have also been proposed for such devices which have benefited from extensive development in the wind turbine industry. The power coefficient (a measure of energy extraction effectiveness) is defined as follows:

$$C_p = P_{turbine} \Big/ \frac{1}{2} \cdot \rho \cdot A \cdot V^3$$

$P_{turbine}$ is the power developed by the turbine; V is the free stream velocity of the fluid; ρ the density, and A is the cross stream area of the device.

Axial flow wind turbines have demonstrated power coefficients to an estimated 48% which approaches the theoretical "Betz" limit of 59.3%. Cross flow turbines have been demonstrated with as high as 35% power coefficient which makes this configuration competitive with axial flow turbines; however, the development of cross flow turbines has been limited.

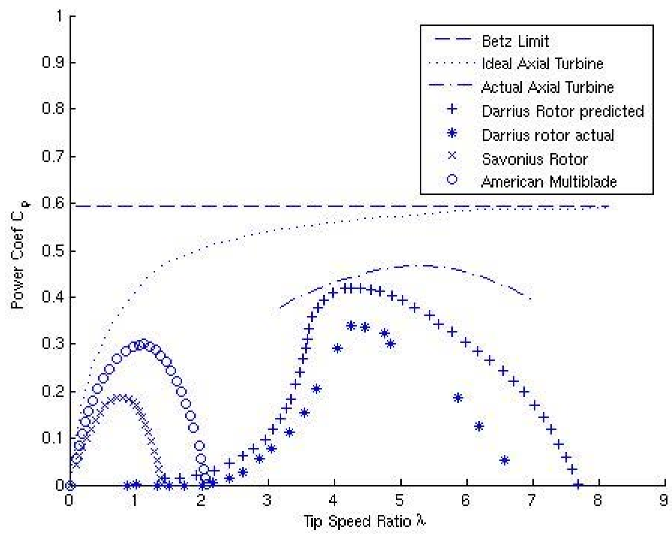


Figure 3: Performance of various types of turbines

Figure 3 shows the efficiency map of various types of fluid kinetic energy extraction devices as compared to the theoretical Betz limit and the single rotor limit as a function of tip speed ratio from Kahn et al. Though axial flow turbines exceed power coefficients of 0.4, the cross flow turbines are in a similar efficiency range.

ORPC's Beta TGU consists of two ADCF turbines mounted horizontally in a support frame, and directly coupled to a permanent magnet generator (See Figure 4). Due to the nature of cross flow turbines, the rotational direction is the same irrespective of free stream flow direction.

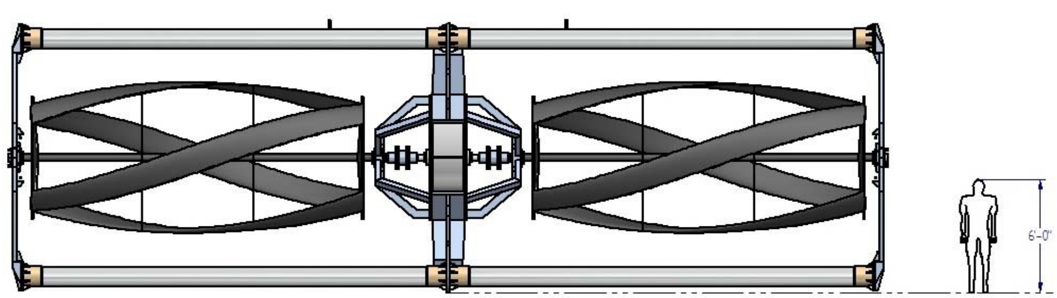


Figure 4: ORPC Beta TGU

Fluid motion past the foils generates a lift force on the foils, which in turn creates a torque on the turbine causing it to rotate. The magnitude of the lift force is dependent on the magnitude of the relative flow velocity, and the lift coefficient for the foil, which in turn is dependent on the angle of attack of the foil to the flow, and the Reynolds number of the flow.

Foils for the ORPC TGUs consist of airfoil shaped sections, where the span of the airfoil is twisted through an angle of 90°. Additionally a barrel shaped profile is imposed on the blade span. ORPC has filed patents related to this particular implementation of cross flow turbine technology. Twisting the foil in this manner reduces torque pulsations on the turbine by evening out the forces acting on the turbine as the foils rotate. This reduces vibration and loading levels on the bearings and support structure considerably. In addition a turbine foil is always located in a favorable starting position so that units can self start in low flow speeds.

ORPC makes a deliberate design choice to operate these turbines with low tip speeds, again reducing vibration, bearing wear and noise, as well as reducing the potential impact on fish species and mammals. The rotational speed of the turbine is directly proportional to the tidal stream velocity and this is expresses as a constant *Tip Speed Ratio.*

Technical advantages of ORPC's proprietary technology include:

- The electricity generated (from 100 percent renewable resources) is emission-free.
- TGUs have simple, robust power trains.
- TGUs have one moving part (the turbines and generator rotate on a single shaft), requiring no gears and therefore eliminating the leading cause of failure in axial flow turbine generator units.
- The turbines rotate in one direction only, regardless of the direction of current flow, so no equipment repositioning is required in tidal currents.
- The turbine blade tip speeds are slower than those of axial flow turbines, reducing wear and tear, noise, vibration, and potential for impacts on sea life.
- Twisted blade design provides self starting capability and provides a smooth continuous torque output from the turbine.
- Barrel shaped blades have lower stress and higher hydrodynamic performance than straight blades.
- TGUs have a very low vertical profile allowing "stackability" of multiple TGUs, allowing power systems to be configured to fit a variety of project sites.

- The modular and stackable features of TGUs provide a variety of deployment configurations, allowing modules to be installed at a wider range of sites (shallow to very deep water) than other technologies of the same scale.

- The major equipment components can be shop fabricated. Projects can be installed with minimal field work, and total installed project costs will be less than alternatives.

- There are no lubricants required so there is no possibility of unwanted liquid discharges.

- The TGUs are held in place well below the water surface so the visibility and environmental impacts will be minimal and the likelihood of obtaining permits and local community acceptance is greatly increased.

- The TGU has only one moving part (no gears) so the life-cycle operating and maintenance costs will be lower than competing mechanically complex technologies.

- The TGUs can be scaled as required to provide a desired level of output power given a known current flow regime.

Generator Operation

The ADCF turbines are directly connected to a permanent magnet generator which produces 3 phase (3Φ) electrical AC power from the hydrokinetic resource. Because of the direct coupling, no gears are required, enhancing the system reliability dramatically. High strength iron neodymium magnets are mounted on the generator rotor and the interaction of the magnetic field produced by these magnets and the stator wound field generates voltage.

From fundamental electromagnetic theory the voltage and frequency produced by the generator is directly proportional to the rate of change of magnetic flux through the coils and in turn to the rotational speed of the turbine. Electrical current is directly proportional to the torque applied by the turbine to the generator. Figure 5 shows the beta generator with the stator being wound.

Because the tidal stream velocity changes continuously, the output voltage and current from the generator also will vary. For the Beta TGU, the output voltage will vary from 0 V to 480 V and frequency will vary from 0 – 30 Hz.

For this output to be useful, the power must be conditioned such that the voltage and frequency are compatible with the electrical grid. An inverter system is used to perform this power conditioning. Under normal grid connected operation, variable voltage and frequency electricity is supplied to the inverter which conditions the power and converts it to fixed 480 V, 60 Hz, 3Φ power. For the barge mounted Beta TGU, there is no electrical grid with which to synchronize. ORPC designed the barge systems such that two different electrical output configurations are possible: one where the inverter output is connected to a resistive load bank and where voltage varies from 0V to 480 V AC as the tide conditions change; and the second option where an artificial grid is created by modulating the load. This second option is the configuration which will be used in the battery charging mode. The first option is technically simpler to implement and will allow the turbine to operate over a wide range of conditions. The second option is technically more complicated, may require substantial effort to tune the control systems, and may not allow the turbine to operate at low rotational speeds.

Figure 5: Stator for Beta TGU permanent magnet generator being wound

Selection of Test Site

The Beta TGU is rated for operation at a peak tidal speed of 3.1 m/s (6 knots). As the tidal speed changes during the course of a tidal cycle, the amount of power generated changes in proportion to the cube of the water speed. However the ADCF turbines are not able to operate below speeds of 1 m/s (~2 knots) and so only when the speed is greater than 1 m/s is power actually generated.

Energy production depends on tidal cycle parameters at a given location and can be highly variable. Multiple analytical approaches are available for predicting the energy production from a hydrokinetic turbine at any given site. The use of a *time varying current analysis* allows for a more accurate representation of temporal changes in power and energy delivery using data collected by bottom mounted Acoustic Doppler Current Profiler (ADCP) technology.

A bottom mounted ADCP was placed at 44°54'1.00"N, 67° 1'36.00"W in Cobscook Bay, Maine. The location of the ADCP deployment site and the proposed location for the beta TGU test is shown in the *Google Earth* image below (Figure 6).

Figure 6: Cobscook Bay deployment site

During the ADCP survey current velocity data was collected over a 17- day sampling period, representing monthly tidal ranges and speeds. The results showed that:

- The average peak current speed was 2 m/s (4 knots).
- The estimated peak power production would be approximately 18 kW per day.
- This peak power production is only available a few hours a day.

The velocity measurements from the ADCP are processed by ORPC's proprietary analysis code to determine the amount of available energy at the proposed beta site from the Beta turbine (See Figures 7 & 8).

- For this sampling period, the amount of energy generated is equivalent to 84.3 kWh per day.
- On board power systems consume 52 kWh per day.
- Net energy available for battery charging is 32 kWh per day
- Accounting for inefficiencies in the charging process it's expected to deliver 24 kWh per day to the battery bank.

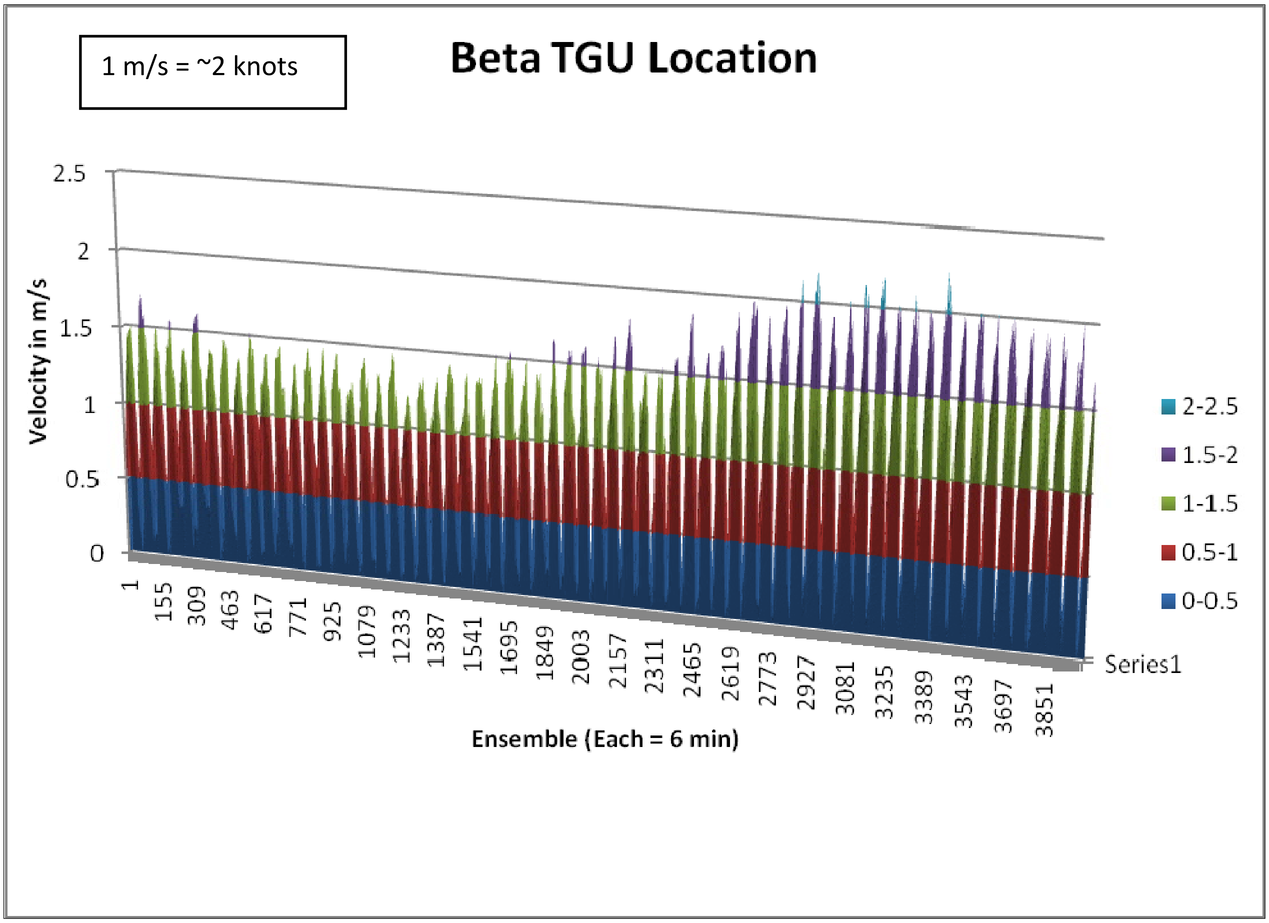


Figure 7: Cobscook Bay deployment site current velocity summary

Time Period	*Energy produced by Beta Turbine at Beta site*
Per year	30.7 MW-hr
Per month	2.6 MW-hr
Per day	84.3 kW-hr

Figure 8: Cobscook Bay deployment site energy production summary

Operation of Deployment System

The Beta TGU is barge mounted and is deployed and retracted by means of hydraulically actuated cylinders and arms. The vessel is known as the Energy Tide 2 (ET2) and the deployment system is illustrated in Figures 9 and 10.

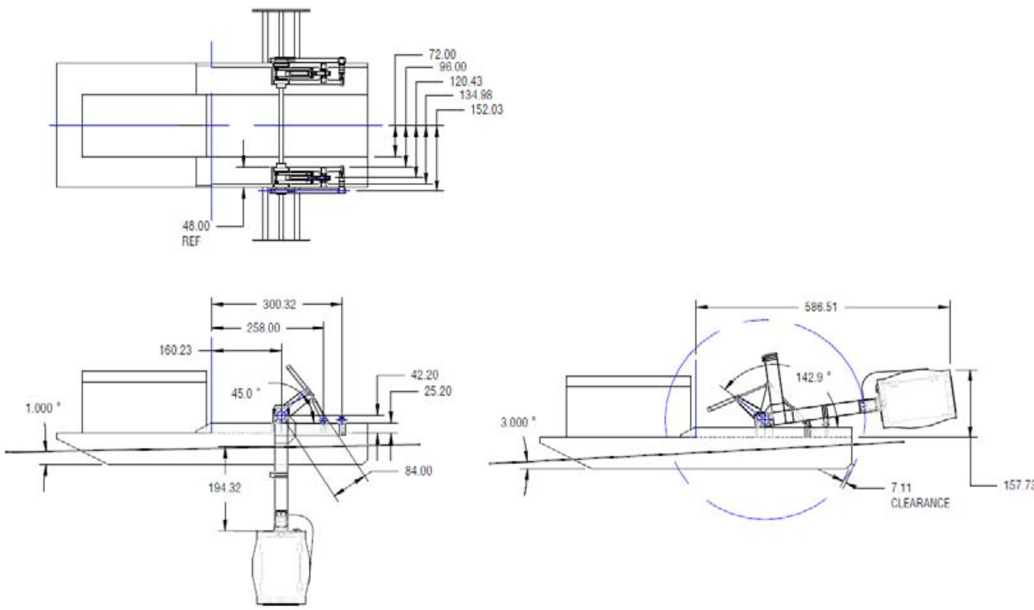


Figure 9: Beta TGU deployment system

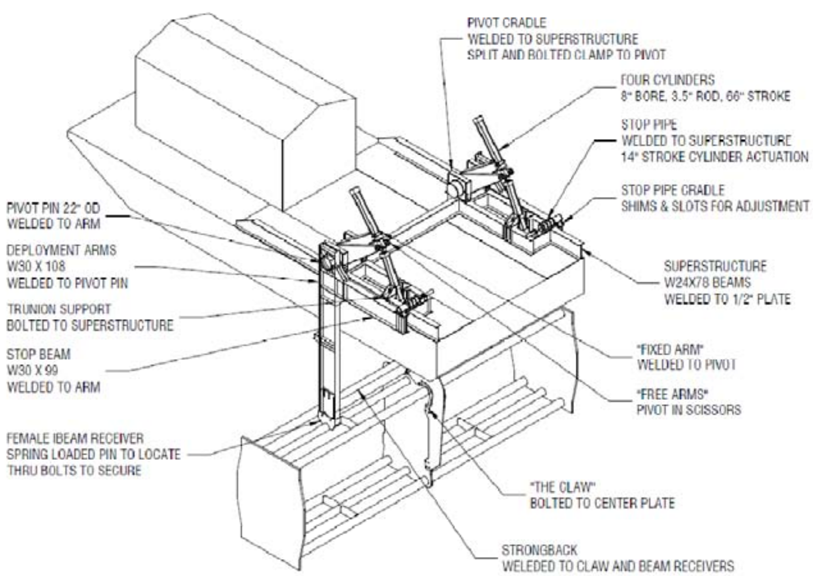


Figure 10: Beta TGU deployment system – Isometric view

Mooring System

The mooring system is a variation of a single point mooring, consisting of four primary ground legs connected to a single riser line, which is then connected to a riser float. The ebb and flood current directions serve the primary axis of the system. The ground lines are arranged at 30 degree angles to this primary axis, with both legs on one side of the system forming a 60 degree angle between them. See Appendix II for an illustration of the mooring system.

Each of the ground legs are comprised of chain sections assembled using standard connecting hardware. A 3,000 lb stockless, Baldt-type anchor is placed at the outer end of each ground leg. Further inbound along the ground line there is a second embedment anchor, a 5,000 lb Danforth-type anchor, and then a 4,500 lb clump weight. The three anchors are separated by 2-shot lengths each (standard chain shot = 90 feet). From the inner most clump weight, there will be 5 sections of chain that connect to a common ground ring. The riser line is similarly connected to this ground ring. At the outermost anchor location on each leg, a crown marker buoy will be attached via poly-nylon riser line.

The barge will be connected to the mooring riser through a four-painter bridle. The barge will typically orient itself with respect to current and wind direction by pivoting about the central riser buoy.

Data Acquisition

Test data will be acquired and stored continuously using an on board LabView Data Acquisition System. Signals generated by the instruments are routed to the A/D converter boards inside the DAQ computer and are stored locally. Data are transmitted to shore on regular intervals via a cell phone connection.

The parameters to be measured and recorded are listed in Appendix I along with instrument requirements and locations.

Power measurements are obtained using multiple measurements: the AC 3Φ voltage and current from the generator; the DC rectified voltage and current inputs to the SatCon inverter; and the average 3Φ voltage, current, power factors and power delivered by the SatCon inverter.

Direct measurement of the DC power flowing to the USCG battery bank will be made and logged concurrently with the rest of the data streams. These power measurements will be processed to determine the amount of energy delivered to the battery bank.

Test Procedure

The test procedure for the Beta TGU will consist of the following methodology:

1. With the TGU in the stowed position, the *Energy Tide 2* will be moved to the mooring site and attached to the single point mooring.

2. The TGU will be lowered into position (deployed).

3. Output from the TGU will be maximized by the SatCon inverter control electronics based on the measured free stream flow. The controls will provide a constant tip speed ratio.

4. All data will be measured and stored by the on board data acquisition systems. The data will be transmitted to shore on a daily basis by means of a cell phone link.

5. Two battery bank launches will be utilized in a rotating pattern of at least 24 hour period.

6. The first based battery launch will be tied-up to the barge and electrical connection made between the charging system and the battery bank.

7. The battery bank will be charged for at least 24 hours.

8. The battery bank will be electrically disconnected from the barge. The second battery bank launch will be tied-up to the launch and electrically connected to the charging system.

9. The battery bank launch will mate up to a tow vessel, untied from the barge, and towed to the USCG float.

10. The battery bank launch will be tied-up to the USCG float and electrically connected to the inverter system on the USCG float.

11. While the first battery bank launch is delivering energy to the coastguard pier the second launch will be charging on the barge.

12. Electrical system will be visually checked and the inverter energized.

13. Data will be examined and analyzed on a daily basis.

14. The barge and test systems will be inspected daily, weather permitting.

15. The TGU will be retracted and inspected on a weekly basis.

16. The TGU will be operated for a period of 60 days at the mooring site.

17. In the event of malfunctions with the TGU, barge, deployment system, or instrumentation, the test may be stopped and repairs/ modifications carried out.

Battery Charging System

A basic schematic drawing of the proposed battery charging system aboard the ET2 is shown in Figure 11. The Beta TGU is electrically connected to the SatCon grid tie inverter. Outputs from the inverter are fed to a breaker panel which feeds the load control devices. These devices are modulated such that the output voltage from the Satcon inverter remains constant at 480 V AC. The 3 phase 480 V power is used by standard forklift battery chargers to charge a bank of batteries on the barge, and in the launch adjacent to the barge. Each launch will contain 24 V battery banks, comprised of 12 V batteries. The on-board battery bank is connected to an inverter system which provides 120 V, single phase, AC power for the barge house systems. Excess power from the TGU is dissipated in a load bank connected to the load controllers.

Types of Batteries

The selected batteries are environmentally friendly 12 V 2580L sealed AGM batteries manufactured by Sun Extender Solar Batteries, a division of Concorde Battery Corp. While technically lead acid based, the batteries were chosen because of overall increased safety, efficiency and durability. They are strongly resistant to vibration and shock and will not freeze. The battery design immobilizes electrolyte in glass mats to prevent spillage. Concorde supplies batteries to the U.S. Navy and leading yacht manufacturers such as the Hinckley Company.

Method for Transferring Power from Batteries to USCG Pier

The battery bank will be transferred from the Energy Tide 2 to the USCG pier by a 20-foot launch towed by a separate vessel contracted from a local mariner who carries a 100 ton Master, Near Coastal License. The contractor will provide either a 37-foot vessel or vessel of equivalent capability. The proposed battery bank will weigh approximately 2,000 lbs, plus any cabling, framework and required restraints. The launch transporting the batteries will have the rated capacity for carrying the weight needed.

The battery bank launch will be tied under the ramp on the inside of the USCG pier (See Figure 12 for shore-side location). The battery bank will be connected to a grid tie inverter. The grid tie inverter will be connected in parallel to the USCG electrical service on the pier.

Schedule of Battery Charging & Ferrying

The USCG battery banks will be ferried to the USCG pier and connected to the inverter at the pier. Power delivered by the inverter to the designated USCG electrical loads will be monitored by the inverter and energy delivered will be recorded manually each day. The inverter will be capable of measuring total energy delivered to the USCG pier over the course of the project.

It is anticipated that battery banks will be transported from the Energy Tide 2 to the USCG Pier on a once per day rotational schedule, depending upon weather conditions. Each day a launch containing fresh batteries will be connected at the pier and the power discharged. The launch will remain on site throughout the day and will be replaced the following day by a second launch, with the first launch being towed back to the Energy Tide 2 for battery charging.

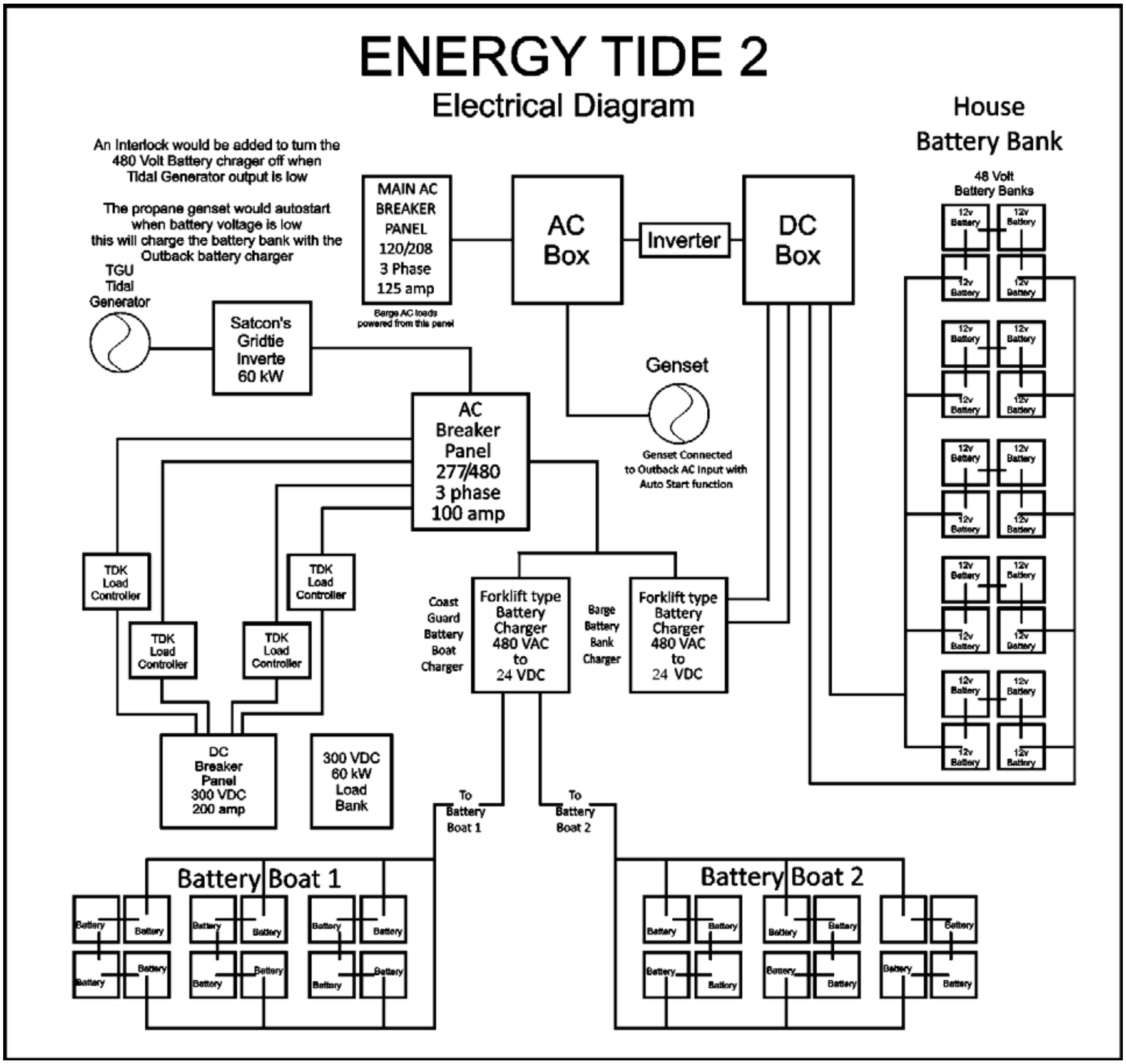


Figure 11: Proposed barge battery charging system

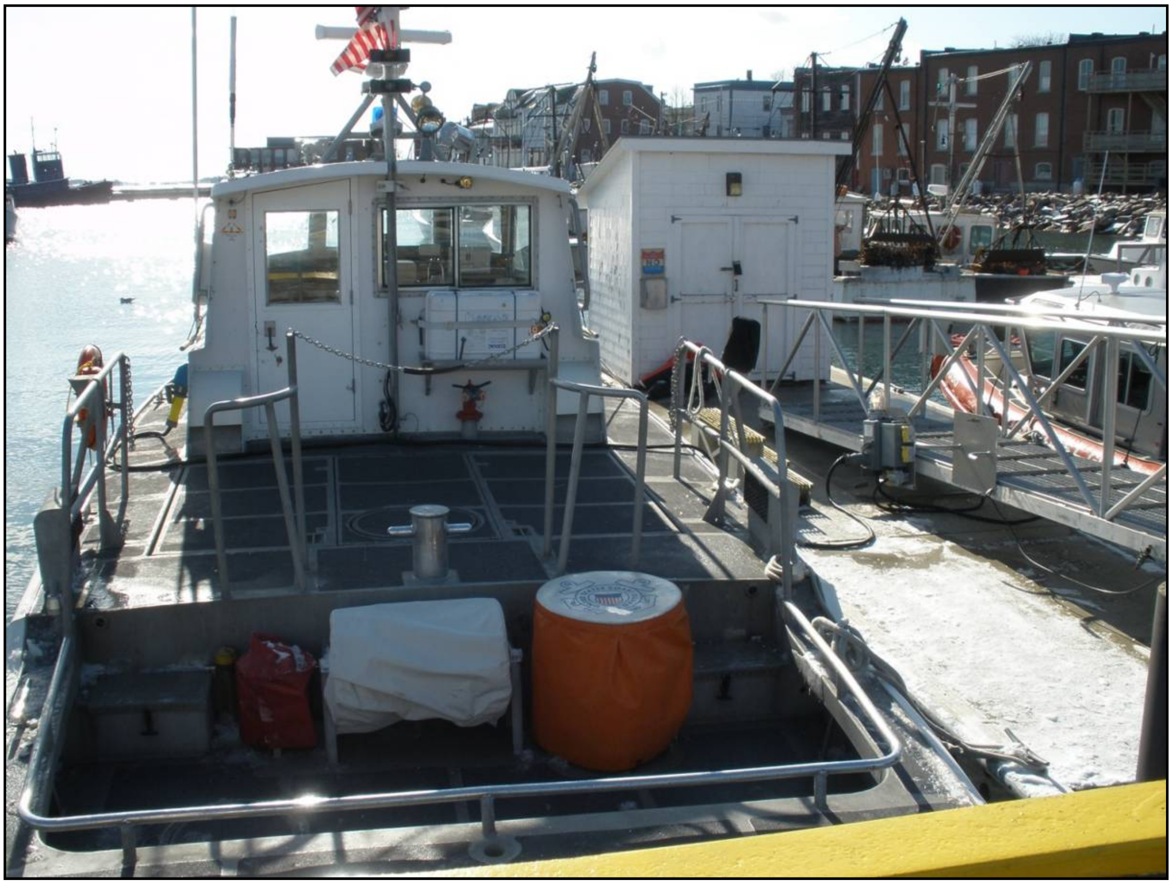


Figure 12: Shore-tie location

Power Quality Analysis and Use of Power

To confirm power requirements at the USCG 41-foot vessel's shore-tie, measurement and analysis of initial power demand, average power demand and demand variability was necessary. This additional power data was necessary to properly size the inverter which will provide the shore-tie with the electricity from the charged battery modules.

An initial inspection of the shore-tie electrical layout by a certified, local electrician contracted by ORPC determined the installation to be in compliance with applicable electrical codes and suitable for additional data gathering. (See Figure 13, a single-line wiring diagram of the existing electrical layout.)

Through the installation of a power quality meter, power usage data, collected in five minute intervals over a minimum of seven days, produced data for the average, minimum and peak power consumption levels. Daily boat runs by the USCG provided further information on the load distribution and average power use levels.

The results of the power quality analysis assessment indicate consistent power draw with average currents of 50 amps devoted to the heating components of the 41-foot vessel.   A 6 kW AC power inverter to convert the charged battery power to serve the shore-tie will be required. A modification of the pier-side electrical system is illustrated in Figure 14, showing the integration of the inverter into the electrical system.

Based on results of the power data analysis ORPC estimates that the battery modules will provide approximately 24 kW/h of gross energy per transit to the shore-tie. At winter use rates that range up to 122 kW/h per day, the modules would provide up to approximately four hours of useful energy per transit to the heating components, taking into account energy loss via transport, handling and other project logistics.

Electrical Permits

The Code Enforcement Officer from the City of Eastport has advised that local permits are not required and the project is consistent with uses allowed in the General Development (SGD) and Harbor Districts.

All associated electrical work will be performed by a certified electrician and work will be completed to all local standards.

Safety

The project will be fully dedicated to safety and all project operations will adhere to appropriate safety measures. Shore personnel and the tow vessel operator will monitor VHF Channel 16 as a way of maintaining constant contact and initiating emergency procedures. In case of emergency, ORPC will directly contact USCG Eastport Station by VHF Channel 16 or dial 9-1-1. A site safety plan will be developed and maintained, and daily updates will be provided and documented. The site safety plan will address risks associated with marine operations, and use of equipment, tools, batteries and electrical systems, and outline emergency response procedures. Because this project involves ORPC, the USCG, the Eastport Port Authority and other local contractors, a collaborative approach to site safety will be necessary.

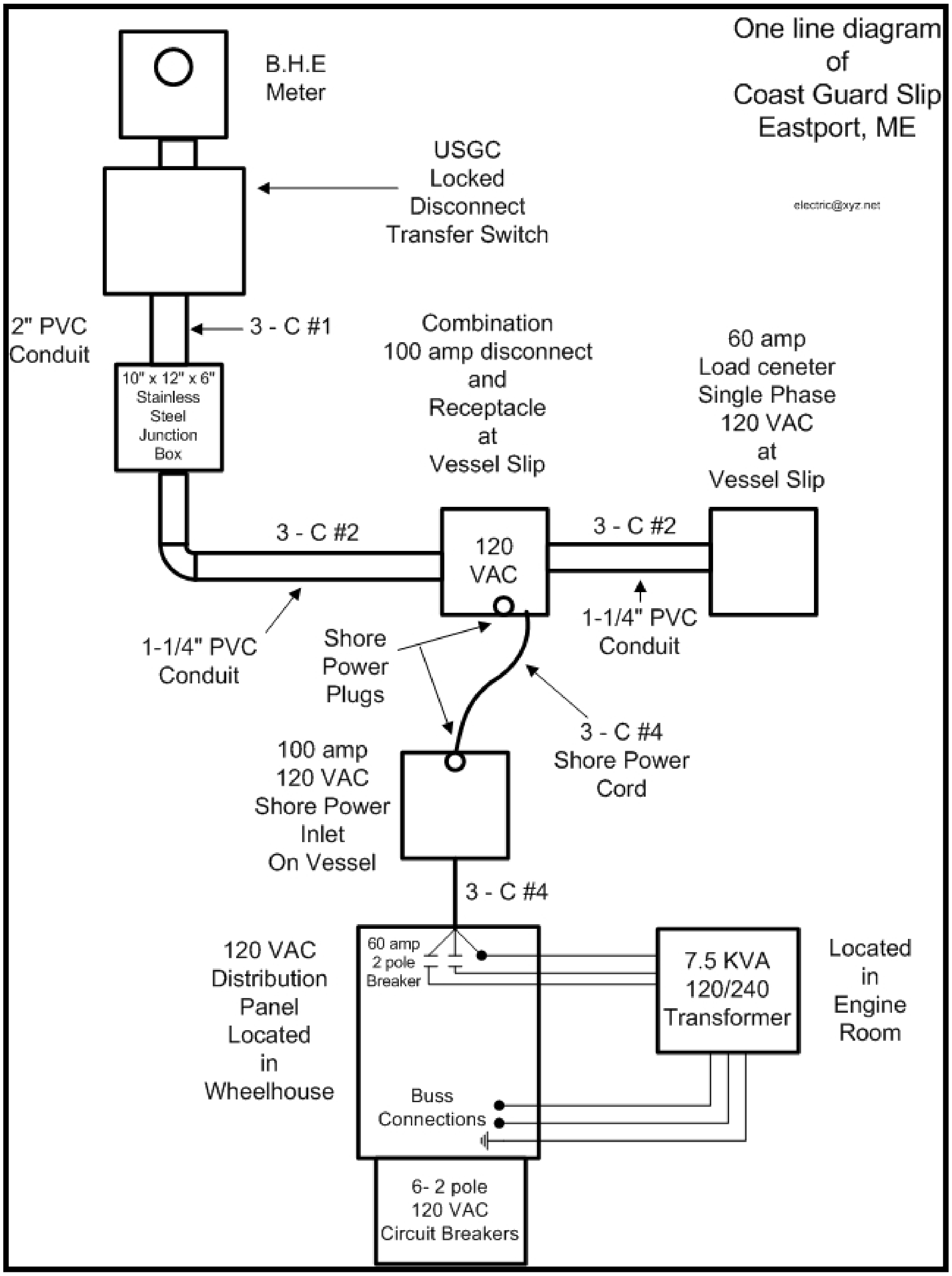


Figure 13: Existing pier-side electrical layout

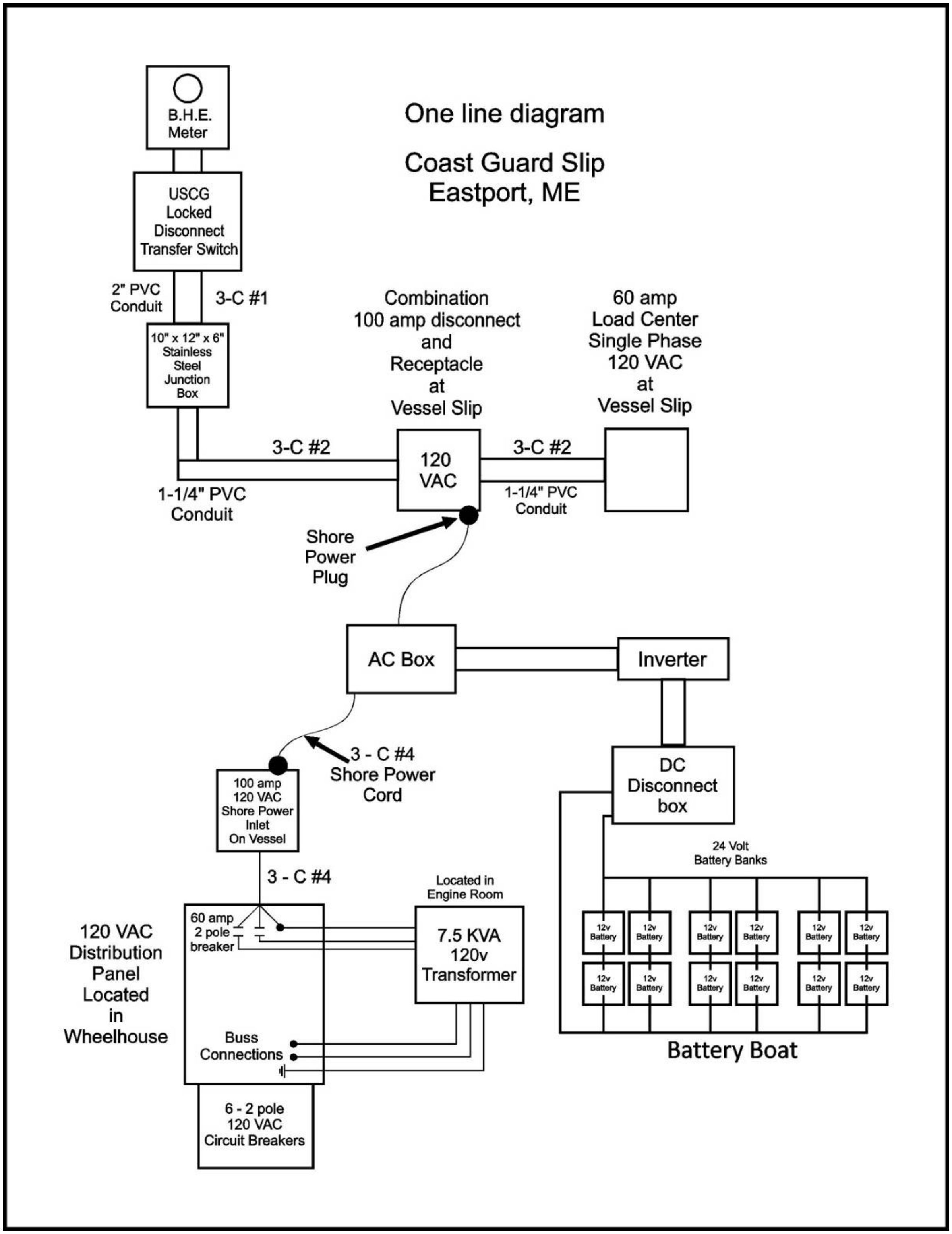


Figure 14: Proposed pier-side electrical layout

Appendix I

Data acquisition and control requirements for test and control of Beta TGU

Environmental

Variable	*Instrument*	*Mounting position*
Time	Computer clock	DAQ computer
Air Temperature	Barge weather station	
Water Temp.	RTD/ Thermocouple	TGU Frame
Water density	Pressure Transducer	TGU Frame
Sea conditions	Qualitative text	
Tide condition	Qualitative text	
Weather	Weather station	

Barge

Variable	*Instrument*	*Mounting position*
Water Speed	1 x Airmar speed meter 1 x Valeport speed transducer	Mounted from barge forward of turbine
GPS position	Weather station	Barge
Tilt and Roll	Tilt and roll sensors	Barge

Deployment System

Variable	*Instrument*	*Mounting position*
Swing Arm position	Visual Indicator	Deployment arm pivot
Swing arm strain	Strain gauges	Deployment arm

Turbine

Variable	*Instrument*	*Mounting position*
RPM	Gear tooth and proximity sensor	End of turbine shaft
Video	2 x Video (color) 2 x Video (bw)	TGU frame
Speed through water	4 x Airmar speed meters	4 units, 1 each mounted ahead (fore and aft) of each turbine

Generator

Variable	*Instrument*	*Mounting position*
Frequency		
Winding Temp	RTD	Generator
Voltage 1 -2	Fluxcore Voltage meter	Power panel
Voltage 2- 3	Fluxcore Voltage meter	Power panel
Voltage 3- 1	Fluxcore Voltage meter	Power panel
Current 1	Fluxcore current meter	Power panel
Current 2	Fluxcore current meter	Power panel
Current 3	Fluxcore current meter	Power panel
Excitation voltage	0 – 150V DC Volt meter	Power Panel
Excitation current	0-10A DC Current meter	Power Panel
Generator RPM	5 x Hall effect sensors	Generator stator
Leak sensor	1 wire sensor/pressure sensor	Generator housing

Power Electronics

Variable	*Instrument*	*Mounting position*
Avg Voltage	SatCon MODbus	SatCon Inverter
Avg Current	SatCon MODbus	SatCon Inverter
Avg PF	SatCon MODbus	SatCon Inverter
Avg Freq	SatCon MODbus	SatCon Inverter
DC In V	SatCon MODbus	SatCon Inverter
DC in A	SatCon MODbus	SatCon Inverter
Error state	SatCon MODbus	SatCon Inverter

AC/DC Rectifier

Variable	*Instrument*	*Mounting position*
DC voltage	DC voltage meter	Power Panel
DC current	DC current meter	Power Panel
DC power	Calculated	Power Panel

Appendix II

Mooring System