A Hydrokinetic Energy Conversion System for Use at Bridges with the Memorial Bridge as a Case Study

Ian Gagnon
University of New Hampshire, Durham

Follow this and additional works at: https://scholars.unh.edu/thesis

Recommended Citation
https://scholars.unh.edu/thesis/1220

This Thesis is brought to you for free and open access by the Student Scholarship at University of New Hampshire Scholars' Repository. It has been accepted for inclusion in Master's Theses and Capstones by an authorized administrator of University of New Hampshire Scholars' Repository. For more information, please contact Scholarly.Communication@unh.edu.
A HYDROKINETIC TURBINE DEPLOYMENT SYSTEM FOR USE AT BRIDGES
WITH THE MEMORIAL BRIDGE AS A CASE STUDY

BY

IAN GAGNON
BS, Mechanical Engineering, University of New Hampshire, USA, 2015

THESIS

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Master of Science
in
Mechanical Engineering

September 2018
This dissertation has been examined and approved in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering by:

**Thesis Director, Martin Wosnik,**
Associate Professor of Mechanical Engineering

**Erin Bell,**
Associate Professor of Civil Engineering

**Kenneth Baldwin,**
Professor of Ocean Engineering and Mechanical Engineering

**M. Robinson Swift,**
Professor of Mechanical Engineering and Ocean Engineering

on 20 August 2018.

Original approval signatures are on file with the University of New Hampshire Graduate School.
ACKNOWLEDGMENTS

I would like to thank the National Science foundation for supporting the majority of my schooling and research assistantships on this project and the New Hampshire Department of Transportation, the United States Federal Highway Administration, and the United States Department of Energy for supporting the fabrication of this project.

The members of the various senior projects, REU’s, and RETE’s who contributed to this work. All the grad students who provided input and feedback on ideas as well as made my time at UNH fun.

The other Living Bridge Project members whom this work would not be complete without their contributions including but not limited to Eric Doherty, Timothy Nash, Maryam Mashayekhizadeh, Travis Adams, Travis Manning, Chao Yang, Vahid Shahsavari, and especially Kaelin Chancey, who I worked very closely with.

I would like to acknowledge the efforts of both Instream Energy Systems, and New Energy Corporation. They both have been integral to the success of this project.

I would like to thank Dr. Thomas Lippmann for use of the CBASS and processing of transect data, and Mr. Jonathan Hunt for his skills as a professional driver of many vehicles.

My parents John and Katherine Gagnon, my sister Kelsey, and my Oma and Opa for teaching me to work hard on things that you believe in and enjoy.

Finally to my thesis committee members, whom all of which I have worked closely with on this project and I have learned much from. Thanks for entrusting me with this awesome opportunity of a project.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xvii</td>
</tr>
</tbody>
</table>

## CHAPTER

1. **INTRODUCTION** .......................................................... 1
   1.1 Our Energy Future .................................................... 1
   1.2 The History of Tidal Energy in New Hampshire ................. 4
   1.3 The Living Bridge Project ........................................ 7
   1.4 Tidal Energy at Bridges ........................................... 8

2. **BRIEF INTRODUCTION TO THE TIDES** ................................. 10

3. **TIDAL ENERGY RESOURCE ASSESSMENT** ............................... 14
   3.1 Site Description .................................................... 15
      3.1.1 The Great Bay/Piscataqua River Estuary .................... 15
      3.1.2 The Memorial Bridge Test Site .............................. 17
   3.2 Flow Measurement Techniques ...................................... 19
      3.2.1 ADCPs .......................................................... 19
   3.3 ADCP Deployments .................................................. 23
   3.4 Data Analysis ...................................................... 26
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Alternatives Analysis</td>
<td>34</td>
</tr>
<tr>
<td>4.2</td>
<td>Turbine Concept Selection</td>
<td>34</td>
</tr>
<tr>
<td>4.3</td>
<td>Turbine Selection</td>
<td>38</td>
</tr>
<tr>
<td>4.4</td>
<td>Turbine Operating Theory</td>
<td>42</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Power Available in a Flow</td>
<td>42</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Extractable Power</td>
<td>44</td>
</tr>
<tr>
<td>4.5</td>
<td>Energy Production Estimate</td>
<td>48</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Envirogen 025 Series Tidal Turbine Description</td>
<td>50</td>
</tr>
<tr>
<td>5.1</td>
<td>Energy Management Configurations</td>
<td>53</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Off-grid</td>
<td>53</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Off-grid with Storage</td>
<td>55</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Automated Transfer Switch</td>
<td>56</td>
</tr>
<tr>
<td>5.1.4</td>
<td>Net Metered</td>
<td>62</td>
</tr>
<tr>
<td>6.1</td>
<td>Load Determination</td>
<td>67</td>
</tr>
<tr>
<td>6.1.1</td>
<td>Gravitational Loading</td>
<td>67</td>
</tr>
<tr>
<td>6.1.2</td>
<td>Tidal Current Drag</td>
<td>69</td>
</tr>
<tr>
<td>6.1.3</td>
<td>Stability</td>
<td>71</td>
</tr>
<tr>
<td>6.1.4</td>
<td>Wave Loading on Turbine</td>
<td>72</td>
</tr>
<tr>
<td>6.1.5</td>
<td>Wave Loading on Platform</td>
<td>74</td>
</tr>
<tr>
<td>6.1.6</td>
<td>Wind Loading on Above Water Structure</td>
<td>78</td>
</tr>
<tr>
<td>6.1.7</td>
<td>Turbine Torque Loading</td>
<td>78</td>
</tr>
<tr>
<td>6.1.8</td>
<td>Load Summary</td>
<td>79</td>
</tr>
<tr>
<td>6.1.9</td>
<td>Additional Loadings</td>
<td>79</td>
</tr>
<tr>
<td>6.2</td>
<td>Pontoon Racking FEA Study</td>
<td>79</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Pontoon Racking Analysis</td>
<td>82</td>
</tr>
<tr>
<td>6.2.1.1</td>
<td>Structure Classification</td>
<td>82</td>
</tr>
<tr>
<td>6.2.1.2</td>
<td>$M_S$ Load Case</td>
<td>84</td>
</tr>
<tr>
<td>6.2.1.3</td>
<td>$M_P$ Load Case</td>
<td>85</td>
</tr>
<tr>
<td>6.2.1.4</td>
<td>$M_T$ Load Case</td>
<td>86</td>
</tr>
</tbody>
</table>
6.3 Design Considerations .................................................. 88

6.3.1 Guide Post Elevation Determination ................................. 88
6.3.2 Pile Guide Design ...................................................... 90
6.3.3 Vertical Guide Post Vortex Induced Vibrations ..................... 94
6.3.4 Frame Transportation, Corrosion, and Assembly ................... 99
6.3.4.1 Pontoon/Frame Connection ...................................... 99
6.3.5 Ice Loading ............................................................. 102
6.3.6 Instrumentation ......................................................... 105

6.4 Instrumentation Mounts .................................................. 106
6.5 Turbine Pitching Mechanism Design .................................... 107

6.5.1 Requirements ......................................................... 107
6.5.2 Alternatives Analysis .................................................. 107
6.5.2.1 Spanning Beam ....................................................... 108
6.5.2.2 Spanning Beam Supports ......................................... 110
6.5.2.3 Actuation ............................................................. 113
6.5.2.4 Winch Power ......................................................... 120
6.5.3 Analysis ................................................................. 120
6.5.3.1 Winch Sizing ........................................................ 120
6.5.3.2 Interface Bracket .................................................... 121
6.5.3.3 Adapter Bracket Design ........................................... 121

7. FABRICATION AND DEPLOYMENT .................................... 130

7.1 TDP Assembly, Installation, and Commissioning ...................... 130
7.2 TDP Deployment .......................................................... 132
7.3 TPM Fabrication and Assembly ......................................... 134
7.4 Additional Buoyancy Section ............................................. 136
7.5 Electronics Shelter Assembly ............................................ 137
7.6 Turbine Assembly .......................................................... 137

8. CONCLUSIONS AND FUTURE WORK ................................. 142

8.1 Conclusions ............................................................... 142
8.2 Future Work ............................................................... 143
8.2.1 Turbine Wave Forcing ................................................ 143
8.2.2 Turbine Performance .................................................. 143
8.2.2.1 Fender Wake ......................................................... 144
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>ADCP operating parameters</td>
<td>24</td>
</tr>
<tr>
<td>3.2</td>
<td>ADCP survey operating parameters</td>
<td>31</td>
</tr>
<tr>
<td>6.1</td>
<td>&quot;M number&quot; determination</td>
<td>66</td>
</tr>
<tr>
<td>6.2</td>
<td>Buoyancy calculations</td>
<td>68</td>
</tr>
<tr>
<td>6.3</td>
<td>Drag load calculations</td>
<td>70</td>
</tr>
<tr>
<td>6.4</td>
<td>Loading assumptions and calculations</td>
<td>80</td>
</tr>
<tr>
<td>6.5</td>
<td>Capacities and demands as per AISC</td>
<td>111</td>
</tr>
<tr>
<td>6.6</td>
<td>Directional loading scenarios</td>
<td>128</td>
</tr>
<tr>
<td>B.1</td>
<td>Boating transit safety</td>
<td>155</td>
</tr>
<tr>
<td>B.2</td>
<td>Turbine safety</td>
<td>156</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>L to R: Cad Rendering of the UNH TDP Gen 1.0 with the turbine in the deployed position. CAD rendering of the UNH TDP Gen 1.0 with the turbine in the removed position. Turbine testing on the UNH TDP Gen 1.0 at the General Sullivan Bridge.</td>
</tr>
<tr>
<td>1.2</td>
<td>CAD rendering and engineering schematics of TDP Gen 1.1 used for testing a turbine at the General Sullivan Bridge and in the Muskeget Channel.</td>
</tr>
<tr>
<td>2.1</td>
<td>Tidal bulges explained by the variation in gravitational tractive force throughout the diameter of the earth (not to scale).</td>
</tr>
<tr>
<td>2.2</td>
<td>Top: Spring tide. Bottom: Neap tide. (not to scale).</td>
</tr>
<tr>
<td>3.1</td>
<td>The Memorial Bridge with pier numbers, deployment site, and shipping channel shown.</td>
</tr>
<tr>
<td>3.2</td>
<td>Map of the Great Bay/Piscataqua River Estuary.</td>
</tr>
<tr>
<td>3.3</td>
<td>Map of the deployment site. To the north is Kittery, ME. To the south is Portsmouth, NH. The Memorial Bridge runs through the center of the map connecting Portsmouth and Kittery. The central lift section is supported by two piers which define the deep water shipping channel. The turbine deployment site is marked. Letter markings are as follows A=Pepperell Cove Marine Services, B = NH Port Authority, C = Granite State Minerals Pier, D = NH Community Fishing Pier, E = Portsmouth Naval Ship Yard (Seavey Island), F = Prescott Park, G = Strawberry Bank, H = Harborwalk Park. For scale, the Memorial Bridge is made up of 3 300ft long truss sections. Imagery ©2017 Google, Map data ©2017 Google.</td>
</tr>
<tr>
<td>3.4</td>
<td>A LinkQuest FlowQuest 1000 ADCP. The piezoelectric oscillators can be seen on the sloped surfaces at the bottom of the image.</td>
</tr>
<tr>
<td>3.5</td>
<td>A bottom mounted ADCP configuration with an external battery pack on a triangular mounting system (L) and a surface mounted ADCP configuration pole mounted over the bow of a floating platform(R).</td>
</tr>
</tbody>
</table>
3.6 An illustration of Doppler shift. ................................................................. 22

3.7 Surface currents for maximum ebb (left) and flood (right) currents plotted over a map of the site. The positions of the HG-14 (red circle) and K-07 (red triangle) ADCP deployments as well as the L-17 flood and ebb transect lines are indicated. The L-17 ebb transect intentionally intercepted the HG-14 ADCP deployment location. Approximate bridge pier locations are indicated by blue squares. ......................................................... 26

3.8 Velocity magnitude maxima for spring flood (top) and ebb (bottom) tides at the Memorial Bridge along transect lines shown in Figure 4. The circle in the bottom plot represents the approximate location of the HG-14 ADCP deployment while the triangle represents the approximate location of the K-07 ADCP deployment. The approximate locations of Pier 2 (Portsmouth side) and Pier 3 (Kittery) are indicated with dashed lines. The bridge pier locations were determined by lines perpendicular to the transect lines in Figure 3.7 that intercept the bridge pier locations. The data for these surveys are an average of the tidal currents recorded over a 24 minute period centered at 15.51 GMT 28 April 2017 for the flood survey and 12:52 GMT 1 May 2017 for the ebb survey. The raw bin sizes for this survey are 0.5m in the vertical direction. Every two bins in the vertical were averaged to produce these plots. ............... 28

3.9 Current speed and direction for the HG-14 (left) and K-07 (right) ADCP surveys. 0 degrees corresponds to true North and the radial increments show speed in m/s. The HG-14 data is from the two consecutive 29.5 day periods from 19 Dec. 2013 to 16 Feb. 2014 and is taken from a bin 12.06 m above the seafloor as this was the highest available bin. During this period the heading of the ADCP varied by less than 3.1 degrees. The K-07 data is from the two consecutive 29.5 day periods from 21 Jun. 2007 to 27 Jul. 2007 and is taken from bin 14 which is approximately 4.5 m below the water surface at MLLW and should be approximately level with the highest bin in the HG-14 survey. ................................................................. 29

3.10 Distribution of tidal current speeds at the HG-14 (left) and K-07 (right) survey sites. Notice the bimodal distribution in the HG-14 histogram that shows the strong variation in flood and ebb tide strengths, whereas the tides are much less asymmetric at the K-07 location. ................................. 33

4.1 Verdant Power’s KHPS, an example of an axial flow turbine. Image reproduced with permission from Verdant Power. ................................. 35

4.2 ORPC’s TideGen® Power System, an example of a crossflow turbine. Image reproduced with permission from ORPC. ......................... 36
4.3 IES’s vertical axis crossflow turbine. Note: this image shows the turbine partially deployed such that one can see the rotor. In the fully deployed position the rotor is fully submerged and the rotating shaft is vertical. Image reproduced with permission from IES. 37

4.4 A rotor sizing tool for the Memorial Bridge deployment site. This chart can be used to determine the rotor swept area necessary to convert a given amount of energy for various turbine efficiencies and cut in speeds at the HG-14 survey site. The blue dot represents a selected design. 41

4.5 A diagram of the stream tube control volume used in one dimensional momentum theory. 43

4.6 Power curve for a representative cross-flow tidal turbine. Turbine rotor efficiency is shown in red, and power produce [kW] is show in blue. 49

4.7 The EVG-025H, a four bladed cross flow vertical axis 25kW (at 3m/s current speeds) hydrokinetic turbine with a direct drive permanate magnet generator. 50

5.1 A diagram of the off-grid energy management configuration. 54

5.2 A diagram of the off-grid with storage energy management configuration. 55

5.3 A diagram of the automated transfer switch energy management configuration. 56

5.4 Energy management system model flow chart. 57

5.5 Energy management system model results. Top: power production (blue) for a representative (6m²) turbine rotor with a constant $C_p$ of 0.35 and cut-in speed of 0.7m/s and consumption (red) profiles with times and amounts of power over produced (magenta) and under produced (black lines). Bottom: battery charge level. The bottom smaller inset figures show typical examples of (bottom left) energy underproduction (switch to backup power source) and (bottom right) overproduction (dissipation of energy). 59

5.6 Energy utilization factor for a range of rotor sizes and battery banks. 60

5.7 A diagram of the automated transfer switch energy management configuration. 62

6.1 Schematic explaining bow-down (left) and results of calculations (right) performed to determine the deck angle and bow pitch distance for a 3 m x 3 m turbine. 71
6.2 Horizontal Wave Force on a Floating Object. Figure reproduced from [19], plotted with results from [23]. .................................................. 75

6.3 Wave force adjustment for relative body length. Figure reproduced [19], plotted with results from [23]. .................................................. 76

6.4 Wave forces for a range of wave lengths. .................................................. 76

6.5 The turbine deployment platform. .................................................. 81

6.6 A visual description of racking. Images are taken from DNVGL [28]. ................. 81

6.7 DNVGL service restrictions taken from [28]. .................................................. 82

6.8 Map of the Lower Piscataqua River with the distance to the UNH Pier marked. .................................................. 83

6.9 Loading for $M_S$ as per DNV GL. .................................................. 84

6.10 $M_S$ Loading condition and moment diagram from SAP2000. ................. 85

6.11 Loading for $M_P$ as per DNV GL. .................................................. 86

6.12 $M_P$ Loading condition and moment diagram from SAP2000. ................. 86

6.13 Loading for $M_T$ as per DNV GL. .................................................. 87

6.14 $M_T$ Loading condition and moment diagram from SAP2000. ................. 87

6.15 Excerpt from HNTB "PIER 2 - RETROFIT PLAN AND ELEVATIONS." ....... 88

6.16 NOAA high and low water exceedances in meters with reference to NAVD88. These water levels do not include wave action [61]. .................................................. 90

6.17 Guide post elevation layout (note: not to scale). .................................................. 91

6.18 Commercially available Merco Marine Chain Pile Guide. ................. 92

6.19 UNH pile guide design (chains and rollers not shown) used to moor the TDP to vertical guide posts. .................................................. 93

6.20 Strouhal numbers for rough and smooth cylinders for a range of Reynolds Numbers [4]. .................................................. 95
6.21 Natural frequency adjustment factors for partially submerged cylinders in crossflow. $d/H_s$ is the ratio between the submerged depth of the cylinder to the total length of the cylinder. $H_s/D$ is the ratio between the total length of the cylinder and the diameter of the cylinder. $\omega_{wet}/\omega_{dry}$ is the ratio between the wet natural frequency of the submerged cylinder to the dry natural frequency of the cylinder. This chart was taken from Lozzo et al 2012 [50].

6.22 VIV SAP results table. ................................................................. 97

6.23 A mass spring damper system. ..................................................... 97

6.24 Frame connections used to enable transportation and galvanization. ............. 100

6.25 A view of the rigid stern joint and the first expansion joint. The stern joint is fixed rigid to the frame. Expansion joint 1 allows expansion and contraction of the pontoons. The expansion and contraction allowed increases with joint number and increasing distance from the rigid stern joint. Note: the decking and decking joists have been removed from this view to improve clarity. ............ 101

6.26 A view of the pontoons joints at 32° F. One should notice the decrease in amount of available travel on the expansion joint as the pontoons have contracted compared to 6.25. Note: the decking and decking joists have been removed from this view to improve clarity. ................................. 102

6.27 AFDD plotted for the Great Bay Reserve with a freezing temperature of 28.4°F ................................................................. 104

6.28 The CTD mounted in the deployed position over the side of the TDP. .............. 106

6.29 TDP v1.0. Left: CAD model of TDP v1.0 with the turbine shown in the deployed position. Middle: CAD model of TDP v1.0 with the turbine shown in the removed position. Right: turbine testing at the General Sullivan Bridge with TDP v1.0 and a Gorlov turbine. Photos taken from [22]. ....................... 108

6.30 TDP V1.0. Left: CAD model of TDP V1.1. Middle: side view engineering drawing showing instrumentation layout. Right: rear view engineering drawing showing instrumentation depths. Photos taken from [67]. ................. 109

6.31 A rendering of the TPM with its major components labeled. ....................... 110

6.32 An early concept of the TPM that used electric actuators to pitch the turbine rotor out of the moon pool. ............................................. 114

6.33 A comparison of three different winch models considered. ....................... 116
6.34  Memorial Bridge elevation drawing taken from [78]. .............................. 117
6.35  Vertical guide post drawing taken from [2]. .......................................... 118
6.36  Solidworks model showing clearance below bridge deck. ......................... 119
6.37  A comparison of four different battery models considered. ..................... 120
6.39  The adapter bracket with components labeled. ...................................... 122
6.40  The adapter bracket tetrahedral mesh used. .......................................... 124
6.41  A convergence study performed on the adapter bracket mesh. ................. 126
6.42  von Mises stress plot for the adapter bracket. ...................................... 127
6.43  Displacement plot for the adapter bracket. .......................................... 127
7.1   A picture of the pontoons at the NH Port Authority. Note: the pontoons are upside down in this picture. ................................................................. 131
7.2   Assembly of the TDP. Top left: frame assembly and joining to pontoons. Top right: joist layout. Bottom left: assembly nearly complete with addition of fiberglass grating. Bottom right: lifting the TDP into the Piscataqua River at the NH Port Authority. ......................................................... 132
7.3   Bound pile guides. Platform shown listing due to the bound pile guides not allowing the TDP to rise with the flooding tides. Inset: close up of bound pile guides. ................................................................. 133
7.4   New pile guides. Left: a rendering of the new pile guides shown wrapped around the vertical guide posts. Right: a picture of the new pile guides shown attached to the TDP with the TDP moored at the UNH Pier. ................. 134
7.5   Assembly of the TPM. Top left: beam cradle installation. Top right: spanning beam lift. Bottom left: pitching mechanism nearly complete, note: winch mounted on strongback which was later moved to be on the TDP deck. Bottom right: completed TPM. ......................................................... 135
7.6   Additional buoyancy modular pontoon sections added to the bow and stern of the TDP. ......................................................................................... 136
7.7 Left: a rendering of the electronics shelter design. Right: a photo of the assembled and deployed electronics shelter with associated power electronics. .............. 137

7.8 The turbine crated and loaded on a flatbed truck in Alberta for shipment to UNH. From L to R, small crate for foils and support arms, biggest crate for turbine, adapter bracket, and resistor, medium crate for electronics shelter with power electronics pre-mounted. The electronics shelter crate was disposed of. The turbine and foils crate was left at the UNH Pier for potential later packaging of the turbine. ................................................................. 138

7.9 Upper Left: turbine drive train as packaged for shipping with crate walls removed. Lower Left: Martin torquing bolts to attach the blade supports to the hubs. Upper Right: clearance check after everything was mounted. Lower Right: turbine lift from the pier down onto the TDP. ................................. 139

7.10 TDP enroute to memorial bridge. A hip tow was used. Note it is important to keep the boat attached far enough aft on the TDP in order to ensure good control during towing. A bridled tow has also been used for towing operations once in open water. ...................................................... 139

7.11 The 25kW resistor bank which is used to dissipate all power generated by the turbine during off-grid testing. ................................................................. 140

7.12 The droop cable. This cable bundle serves as the data and power connection between the bridge and the TDP. ................................................................. 140

7.13 A photo of the installed system including the EVG-025H turbine in the removed position. ................................................................. 141

8.1 Four potential concepts for a larger scale hydrokinetic turbine deployment at bridges. Upper Left: single turbine with one sided contraction. Lower Left: multiple small turbines in a two sided contraction. Upper Right: a larger turbine built into a pier. Lower Right: larger turbines deployed between two bridge piers. ................................................................. 145
ABSTRACT
A Hydrokinetic Turbine Deployment System for use at Bridges with the Memorial Bridge as a Case Study
by
Ian Gagnon
University of New Hampshire, September, 2018

As a part of the Living Bridge Project on the Memorial Bridge between Portsmouth, NH and Kittery, ME a turbine deployment system for use at bridges was designed, built, and deployed. One of the purposes of the Living Bridge Project is to demonstrate that advantages to deploying hydrokinetic turbines at bridges exist. The expected advantages include 1) good hydrokinetic resources are likely to occur at bridges because bridges are typically built at constrictions where the flow tends to speed up, 2) existing bridge structures can be used as mooring points, 3) existing bridge permits can be leveraged to aid in the permitting of auxiliary hydrokinetic systems, and 4) power can easily be transmitted from a turbine to shore via the bridge. A tidal energy resource assessment was performed at the Memorial Bridge crossing the Piscataqua River in Great Bay Estuary in Southeastern New Hampshire. The purpose of the resource assessment was to quantify the kinetic energy that could be converted from the tidal currents to electrical energy, size a turbine for the location based on an estimated energy demand, and investigate potential energy management configurations. A turbine was selected for use at the site. The design loads for a turbine and a deployment platform were determined. Based on these design loads the turbine deployment platform and its moorings were analyzed. A 49 ft. by 18 ft. floating turbine deployment platform was designed. The turbine deployment system, which includes two vertical guide post mooring piles, a pontoon type turbine deployment platform, and the turbine pitching mechanism, was fabricated and deployed. A New Energy Corporation EVG-025H series tidal turbine with associated power electronics was deployed on the system in June of 2018.
CHAPTER 1
INTRODUCTION

1.1 Our Energy Future

Since it’s earliest forms human civilization has relied upon the consumption of energy to provide solutions to its problems. Earlier cave dwellers heated their shelters by combusting plant matter. Fire was used as a tool to clear land, heat and cook food, and provide light. All consuming energy to solve problems. It is believed that in 1831 Michael Faraday built the first homopolar generator, commonly called the Faraday disc. This was the beginning of electrical generators. Shortly after this Thomas Edison invented the first practical light bulb [31] that could produce light for extended periods of time. The electric motor and internal combustion engine as well as a myriad of other inventions spurred us into the industrial revolution where human consumption of energy increased at an exponential rate.

Initially, this increased consumption of energy was beneficial to human society. Global human population increased drastically and technological advances were made at a pace that had never in human history been witnessed before solving an immense amount of human problems. In this flurry of innovation a new problem arose.

The majority of this energy was derived from carbon emitting fuels, which later on in history consisted primarily of fossil fuels. There are a multitude of problems that have arisen since our society has started burning fossil fuels and emitting an increased amount of carbon-dioxide into the atmosphere and these problems are well documented. Bill Gates explains the problem and its possible solution with one equation [38]
\[
P \times S \times E \times C = CO_2 \tag{1.1}
\]

where \( P \) is the number of people on the earth, \( S \) is the amount of services that people use, \( E \) is the amount of energy that those services consume, \( C \) is the amount of carbon dioxide that is produced per energy unit consumed, and \( CO_2 \) represents worldwide carbon-dioxide emissions. Cumulative emissions of \( CO_2 \) into our atmosphere largely determines global mean surface warming and the vast majority of climate scientists agree upon this [44]. In order to decelerate global warming we must bring our \( CO_2 \) emissions to nearly 0.

Looking at the left hand side of Bill Gate’s equation we have a few ways we can do this. We can reduce, or potentially even eliminate our population. Which does not seem to be a viable solution as humans, and all other successful species, are biologically programmed to procreate. We could reduce the services we use and consume, which also does not seem to be a viable solution as this would revert us back into a world were we suffered against all the problems we have already solved by consuming energy. Another potential solution could be to reduce that amount of energy that we consume for each service we perform, which actually does seem to make a bit of sense although the second law of thermodynamics reminds us that there is a limit to this. As we know that by performing work (or completing a service) one will always use some energy. The only way to truly eliminate the emission of carbon-dioxide and slow climate change is to send the \( C \) variable to 0 and eliminate the amount of carbon-dioxide emitted from our energy production sources.

While performing the first public demonstration of the electric light bulb Thomas Edison said "We will make electricity so cheap that only the rich will burn candles." I would like to coin the phrase in this thesis and make it a personal goal for my career that we will make renewable energy so appropriate, that only idiots will burn fossil fuels. Economically this has already partially been accomplished as solar and wind energy are now cost competitive with natural gas and are a significantly cheaper form of energy than coal [82]. Many problems with these technologies still exist.
One such problem, and a problem that will be addressed in this thesis, is the fact that solar and wind energy are unpredictable sources of power. One day the wind may not blow, or the sun may be blocked by clouds and these stochastic processes which drive wind speed or cloud cover cannot be easily predicted with great certainty for more than a few days in advance.

Tidal energy is the conversion of energy obtained from the tides into other useful forms of energy. The tides are the periodic rise and fall of the earth’s oceans due to variations in gravitational pull from the moon and sun. This rise and fall of the earths oceans is caused by the location of the sun and moon with respect to the earth. The positions of these celestial bodies are highly predictable and thus the tides can be predicted with high levels of certainty for many years in advance. If one can predict the tides than one can predict the amount of energy that can be converted from the tides for many years or even decades in advance.

There is potential for tidal energy to be employed on a large scale as a carbon emission free source of predictable electrical energy generation. This will be a unique contribution to coastal electrical grids and empower grid operators to deliver power more efficiently to end users.

The first method employed to harness tidal energy was by the use of a tidal barrage. Tidal barrages convert potential energy differences of stored water into power. To do this a dam is constructed. Turbines are placed in the dam. Water is allowed to flow into the dam as the tides rise. Then as the tides fall the water is forced through the turbine(s) to create power. There is evidence that this method of tidal power has been employed since Roman times [73] and we know that five tide mills operated in Boston using a barrage that ran where Causeway St. now runs [55]. The Rance Tidal Power Station is a modern day tidal barrage that has been in operation since 1966. Thus tidal energy is a proven technology. The problem with tidal barrages is that they typically isolate estuaries from the greater ocean by forming a lagoon which can have detrimental effects to the marine environment.

Another method of harnessing tidal energy is to use a tidal stream generator. Similar to a wind turbine, tidal stream generators convert the kinetic energy of the tidal currents into rotational motion which is used to spin a generator and produce power. From this point forward, unless
explicitly stated when a tidal turbine is discussed it is assumed to be a tidal stream generator and not a turbine installed in a tidal barrage.

1.2 The History of Tidal Energy in New Hampshire

Some of the first settlers in the New World came to the banks of the Piscataqua River in 1623 and settled in Dover, NH, on Dover Point creating what they would call Cochecho Plantation, on the land that is now Hilton Park[70]. It would be seven years before any Europeans settled in nearby Boston Massachusetts and nine years for Portland Maine. In 1623 the Piscataqua River provided good landing locations for early settlers. These early settlers even built mill ponds to run small tidal barages for to harness tidal energy to perform early industrial processes [17], but as the size of ships grew the river’s strong tidal currents prevented shipping traffic from entering the main port in Portsmouth except at slack tides which also prevented the local port from growing to the size of Boston or even Portland. Move time forward to the early 2000’s and a new use for those ports strong tides had been discovered.

In September of 2005, across all sectors, New Hampshire had the third highest electricity prices of any state in the US [32]. At this time the majority of the energy generated in the state came from imported fuel sources and nuclear energy. People began to search for new forms of energy that could be generated locally. The tidal currents of the Piscataqua River caught the attention of Oceana Energy Co. and Underwater Electric Kite [84]. Both tidal energy companies proposed installing tidal energy conversion devices at the General Sullivan and Little Bay Bridges, near Dover Point where the first settlers landed in Dover.

At that time the governor of New Hampshire was John Lynch and he ordered the creation of the NH Tidal Energy Commission to "identify and collect technical and sociological data, and investigate the regulatory requirements necessary to determine the feasibility of building a system for tidal power generation under" the General Sullivan and Little Bay Bridges [34]. After a year of investigation the commission reported that it was questionable whether a commercially viable tidal energy conversion device could be installed at the bridges without interrupting existing boating and
shipping traffic. The commission also recognized that at that time the tidal energy industry had not overcome technological challenges that limit large scale development of tidal energy conversion devices. The commission recommended that the bridges be used as a test environment to perform research with the University of New Hampshire (UNH).

UNH researchers took this recommendation and began developing and testing tidal turbines in the Great Bay/Piscataqua River estuary.

In 2008 a undergraduate team began developing a turbine deployment platform for use at the General Sullivan bridge. The team also began developing the electronics necessary for a tidal turbine test[6].

In 2009 two undergraduate teams continued the work of the 2008 team with one team focused on developing the "Infrastructure," [22] and the other focused on the "Tidal Turbine Performance Analysis" [37]. These two teams managed to perform a tow test of a turbine donated by Lucid Energy Technologies in January of 2009 and a deployment of the same tidal turbine at the General Sullivan Bridge later that spring.

From 2010 to 2011 three undergraduate projects [65] [5] [47] focused on developing their own tidal turbine using variable flux generation [20] a technology developed by Blue Water Concepts.

In 2012 a project worked to develop a force balance to be used to test bidirectional hydrofoils for tidal turbines in a high speed cavitating water tunnel [79]. In 2015 this work later resulted in a
Ph.D. dissertation titled Performance and Cavitation Characteristics of Bi-Directional Hydrofoils [57].

In 2012 after learning of the Memorial Bridge’s closure a group began investigating the potential for developing tidal energy at the Memorial Bridge. The group "concluded that implementing a hydrokinetic research and generation platform is both feasible and recommended for the Memorial Bridge site, as it will provide a unique and invaluable resource for furthering New Hampshire’s commitment to renewable energy research and production, with the potential to generate approximately 21 megawatt-hours yearly per array" [13]. This team predicted relatively closely the amount of power that could be produced by a small tidal turbine and recognized the potential for a tidal turbine to be deployed at this site.

In 2012 UNH deployed a 1 meter scale tidal turbine at the General Sullivan Bridge and in the Muskeget Channel (three times at each site), located between Martha’s Vineyard and Nantucket [27] [68].

In 2013 one project investigated potential turbine designs that could be deployed at the Memorial Bridge [16], while another project developed a tidal energy demonstration channel to be used for education and outreach [41].
In 2014 a project developed a test bed, for investigating the use of wing tips on tidal turbine hydrofoils [21], while another group began to investigate the tidal current resource available at the Memorial Bridge [42].

The towing mechanism on UNH’s tow tank was redesigned and rebuilt, which allowed the use of a newly constructed turbine rotor test bed for testing of rotors, and an actuator line model was developed in OpenFOAM to investigate crossflow vertical axis turbines numerically [10] [11].

Despite the tremendous progress of the nearly ten years of tidal energy research at UNH all of these tests were either performed in the laboratory or were temporary, lasting no longer than 24 hours and converting energy from less than two tidal cycles at a time. The next undertaking in the tidal energy research progression at UNH would be to develop a facility where a tidal turbine could be deployed for an extended period of time (on the order of one year) in the field to allow for long term studies on tidal turbines that are nearly ready for commercial production (DOE TRL 5-7).

1.3 The Living Bridge Project

The Living Bridge Project is a primarily NSF sponsored research project at the University of New Hampshire. The purpose of the Living Bridge Project is to create a self reporting self diagnosing "smart bridge." To do this the Memorial Bridge, a community landmark and vital link, between Portsmouth NH and Kittery Maine has been outfitted with an array of both structural health and estuarine sensors. A tidal turbine has been installed at the bridge to provide renewable energy to the instrumentation as well as the bridge.

Data from the sensors will be analyzed at UNH as well as shared with other researchers. The Memorial Bridge is built with unique structural features, such as gussetless connections. The Memorial Bridge is the first application of gussetless connections in an automobile bridge. Most bridges use gusset plates to join two members. The problem with gusset plates is that they typically are one of the first area’s of a bridge to fail due to corrosion. The corrosion that develops underneath the gusset plate is difficult to inspect and they are time consuming to construct because of the large number of bolts that must be tightened in the connection. The elimination of gusset plates on the
major connections in the Memorial Bridge allowed the bridge to be erected faster and cheaper, and could potentially extend the bridge’s life. To allow for more future applications of the gussetless connection in bridges their performance in the field must be studied and their design must be validated.

The bridge is also situated in one of the most trafficked and developed portions of the Piscataqua River and this location has not been instrumented to provide long term oceanographic data. This additional hydrographic data will be useful when studying the effects of the turbine on the estuary and the bridge as well as potential larger effects such as nutrient pollution and climate change. This will also create a highly monitored living laboratory which will act as an incubator where innovators can test new technologies in a highly monitored environment.

When appropriate, the data generated from the sensors will also be shared with the local community including K-12 educators. A walking STEM museum will be created on the bridge, and an interactive website will be used to share information about the bridge and allow people to access the data generated by the sensors. The goal of this is to create engage and educate the citizen scientist about the United State’s critical energy and transportation infrastructure.

1.4 Tidal Energy at Bridges

Throughout the development of this project four advantages to deploying tidal turbines at bridges were identified.

- Bridges are typically sited in locations where stronger currents exist, due to the advantages of placing a bridge at constrictions in rivers. More power can be produced from faster currents.
- Bridges have existing infrastructure (i.e. piers) that can be used as mooring points or foundations for turbine support structures.
- Bridges already have existing environmental permits that can potentially be appended to include turbines as a part of their own structure reducing permitting effort to deploy a turbine.
• Bridges offer a potential method of connecting to the grid without the need for subsea power and data cables.

The objective of the work in this thesis was to demonstrate that these advantages exist by deploying a tidal turbine for an extended duration of time at the Memorial Bridge. This project will also create a facility where turbine developers can readily test turbines with the ultimate goal of providing a readily available test platform to help accelerate the progress towards bringing these turbines to commercial production. To do this a turbine deployment platform capable of deploying a turbine with a rotor up to $9m^2$ in size was designed.
CHAPTER 2
BRIEF INTRODUCTION TO THE TIDES

This chapter has been adapted from a combination of John Boon’s Secrets of the tides [18] and a section of Mathew Rowell’s master’s thesis that describes tidal theory[67].

Tides are predominantly driven by the gravitational forces of the moon and sun. As the two masses orbit around the earth they exert varying amounts of gravitational force on the earth and it’s oceans. This force is quantified by Newton’s law of universal gravitation

\[ F_g = G \frac{m_1 m_2}{r^2} \]  \hspace{1cm} (2.1)

where \( G \) is the gravitational constant \( (6.674 \times 10^{-11} \ \text{Nm}^2/\text{kg}^2) \), \( m_1 \) and \( m_2 \) represent the masses of two objects, and \( r \) is the distance between the centers of mass of the two objects. The gravitational force between two forces varies directly with the product of the two masses and inversely with the square of the distance between them. Generally the moon rotates around the earth, but more precisely, the earth and moon are rotating around their shared combined center of mass, called a barycenter. For the earth and moon this barycenter is located slightly within the earth’s crust. As the earth and moon rotate around this point they experience two equal and opposing forces at their own centers of mass. The first force acting on each body is the gravitational pull between the two masses that acts in the direction towards the other object. The second force acting on each body is the centrifugal force acting on the mass of each body pulling it away from the barycenter. This force is given by

\[ F_c = \frac{m v^2}{r}. \]  \hspace{1cm} (2.2)

These two forces are balanced at the center of the earth but they vary throughout the diameter of the earth. As one moves closer to the side of the earth closest to the moon the gravitational
force from the moon increases as the $r$ in Newton’s law of universal gravitation decreases. As one moves to the side of the earth farthest from the moon the centrifugal force remains constant, but the gravitational force from the moon decreases as the distance to the moon has increased. These net forces are called tractive forces. This increase in gravitational force on the near-moon side of the earth and decrease in force on the far-moon side of the earth results in the moons gravitational pull elevating the oceans on the near and far moon sides of the earth. The sides of the earth perpendicular to a line drawn from the center of the earth to the center of the moon will experience lowered sea levels as they experience a balance between the centrifugal forces and gravitational forces and thus no net force to lift the water away from the center of the earth.

![Diagram of Earth with labels for centrifugal and gravitational forces.](image)

**Figure 2.1:** Tidal bulges explained by the variation in gravitational tractive force throughout the diameter of the earth (not to scale).

These two bulges of elevated sea levels and areas in between of lowered sea levels explain why in most places on the earth there are two tides per lunar day. A lunar day is the amount of time between successive moonrises, which happens to be about 24 hours and 50 minutes. When a location experiences two high tides (caused by the elevated sea levels) and two low tides (caused by the lowered sea levels) every lunar day, the area is said to be experiencing semidiurnal tides. The Great Bay/ Piscataqua River Estuary experiences semidiurnal tides.

Even though the sun is far from the earth, its very large mass allows it to still play a role in the earth’s tides. Solar tractive forces created by the sun’s gravitational pull are less than half as strong as the lunar tractive forces. The combined lunar and solar tractive forces create the spring-neap
cycle of the tides. When the earth moon and sun are all in line with one another their tractive forces act parallel to each other and create larger tidal effects as seen in the top portion of Figure 2.2. When this happens, these higher high tides and lower low tides are called spring tides. When the moon is at a right angle, perpendicular to the earth-sun connecting line, the lunar and solar tractive forces act perpendicularly to each other and offset each other’s tidal effects. This creates lower high tides and higher low tides called neap tides which are illustrated in the bottom portion of Figure 2.2. The moon orbits the earth every 29.53 days with respect to the sun. This is also the time interval that a spring-neap tidal cycle takes to occur.

In addition to the lunar and spring neap cycles there are multiple other periodic tidal cycles and each one of these cycles can be described mathematically by what are called harmonic constituents. Each of the \( m \) harmonic constituent consists of a frequency \((\omega)\), amplitude \((R)\), and phase \((\phi)\).
Harmonic constituents can be summed and taken with respect to mean sea level \((h_0)\) and any known non-astronomical water level effects \((\sigma(t))\) to predict tidal elevations at a given location.

\[
h(t) = h_0 + \sum_{j=1}^{m} R_j \cos(\omega_j t - \phi_j) + \sigma(t)
\]

In the open ocean the variations in tractive forces on the earth’s oceans tend to only cause vertical motion of the water as it raises and lowers. Locations with constrictions tend to cause resistance on the horizontal movement of the water. This resistance to horizontal movement of the water causes differences water elevation which cause the water to flow horizontally from locations of higher water elevation to lower water elevation. These horizontal water flows are called tidal currents. The harmonic constituents used to predict periodic variations in tidal elevation can also be used to create forecasts or even hindcasts of tidal currents. The kinetic energy of the tidal currents is what the turbines described in this thesis aim to convert into electrical energy.
CHAPTER 3
TIDAL ENERGY RESOURCE ASSESSMENT

The International Electrotechnical Commission (IEC) has established a technical specification, TS 62600-201, which outlines a methodology for performing a tidal energy resource assessment and characterization [1]. The resource assessment presented here utilized two acoustic Doppler current profiler (ADCP) field surveys to characterize the tidal current resource at the turbine deployment site. Although the ADCP surveys pre-date publication of TS 62600-201, IEC technical specification was followed as closely as possible.

One of the goals of the Living Bridge Project is to demonstrate that tidal energy is a feasible energy conversion technology for installation at an estuarine bridge and inspire interest, particularly in young people, about our country’s critical energy infrastructure [69] [81]. To responsibly deploy a tidal turbine the expected currents at the Memorial Bridge must be understood.

The Piscataqua River has some of the fastest currents of a commercial port in the Northeastern United States [51], and it is generally believed that tidal energy extraction could be feasible in this estuary. A freely available model of the tidal currents throughout the US [48] shows a mean current of 1.2 m/s at the memorial bridge, suggesting that tidal energy conversion is feasible at this site. All major shipping traffic passes through an 80 m wide shipping channel under the center lift span of the bridge, which still leaves two 90 m wide sections of river outside of the shipping channel on either side of the center lift span where a turbine could be placed. In the summer of 2007 a NOAA/NOS/CO-OPS ADCP field study of the entire estuary was performed as a part of the National Current Observation Program [46]. A maximum tidal current of 2.09 m/s was recorded at the Memorial Bridge site. The measurements obtained in 2007 at the Memorial Bridge were located in the center of the shipping channel where a turbine could not be placed owing to possible obstruction of shipping traffic. Due to local bathymetric changes across the river channel, the tidal
energy resource would be expected to vary in the sections outside the shipping channel. As a result, additional ADCP observations were obtained in potential deployment locations outside of the shipping channel as part of this study. The ADCP survey for this resource assessment was performed for the southern-most section of the bridge. This survey was performed to assess the tidal energy resource for a turbine rigidly fixed to the Portsmouth face of the Portsmouth pier (Pier 2, as it is referred to in the bridge structural drawings and shown in Figure 3.1). This survey was necessary to size the turbine, determine if a battery should be used, and determine how much energy will be produced. Without properly quantifying the available resource the project could fail to produce a reasonable amount of energy and the technology could be seen as infeasible at scale. If a battery bank is improperly selected or sized, power interruptions to the instrumentation could occur. Even worse, without properly understanding the forces that the tidal currents impart on the deployment structure, a structural failure could occur [52].

![Image of the Memorial Bridge with pier numbers, deployment site, and shipping channel shown.](image)

**Figure 3.1:** The Memorial Bridge with pier numbers, deployment site, and shipping channel shown.

### 3.1 Site Description

#### 3.1.1 The Great Bay/Piscataqua River Estuary

The Great Bay/Piscataqua River Estuary is a tidally dominated estuarine system extending about 20km inland located in southeastern New Hampshire (see Figure 3.2). With a nominal range on the order of 2.5 meters, the estuary has a surface area on the order of 11 km² at low tide and 23
$km^2$ at high tide. The Great Bay is connected to the Gulf of Maine via the Piscataqua River. The tide is dominated by the M2 lunar harmonic constituent, a semidiurnal signal that provides two full tidal cycles per lunar day. The seabed of the Lower Piscataqua River, where the Memorial Bridge is located, consists primarily of gravel and sandy gravel [85] and the shorelines are primarily developed with industrial and commercial activity. Although several rivers empty into the Great Bay and Piscataqua River, the ratio between river discharge and tidal prism is typically <1% [33]. The estuary has a horizontal salinity gradient ranging from 30-0 ppt from the mouth of the river to the upper reaches of the tidal tributaries and parts of the Great Bay depending on tidal cycle, seasonal, and rainfall conditions [45].

![Figure 3.2: Map of the Great Bay/Piscataqua River Estuary.](image)

Approximately 5.5 $km$ from the river’s mouth, the river runs East/West where the Memorial Bridge connects Portsmouth, NH (to the South) and Kittery, ME (to the North). Shown in Figure 3.1, the Memorial Bridge is a vertical lift bridge with a 300 $ft.$ center lift truss section supported by two piers spanning a deep-water shipping channel with two side fixed truss spans each at 91 $m$ long [78]. In the center of the shipping channel the water is 20.6 $m$ deep and at the deployment
The water is 17.6 m deep at MLLW [62]. The mean tide range near the Memorial Bridge is 2.47m [59]. The tidal energy conversion system (TECS) will be deployed outside of the shipping channel, moored to the Portsmouth side of pier 2 on the Memorial Bridge.

### 3.1.2 The Memorial Bridge Test Site

The Memorial Bridge is an exceptional site for a demonstration tidal energy conversion project in the Great Bay/Piscataqua River Estuary. Although it is does not exhibit the fastest tidal currents in the estuary, it still reaches tidal current speeds well above 2 m/s making it a good "nursery" (DOE TRL 5-7) site for tidal energy where turbine developers can test their turbines as well as demonstrate the feasibility of their technology in real currents with reasonably high velocities. Tidal energy resources sufficient for hydrokinetic energy conversion are often located in more remote locations, inaccessible to the public and requiring significant transit time for marine support. The fact that the lower Piscataqua River has some of the fastest currents of any commercial port in the Northeastern United States makes it an excellent location to capitalize on these strong currents located near the support infrastructure of a commercial port for tidal energy conversion device development. The port has locally-based marine construction and commercial diving crews who frequently work in the area and are familiar with the estuary. 3.3 shows various facilities and places in the vicinity of Memorial Bridge. The New Hampshire Port Authority (A) is approximately 1km from the Memorial Bridge and provides staging areas for on the water construction, as well as emergency docking space. The Granite State Minerals Pier (B) is also approximately 0.5km for the Memorial Bridge and can be used for staging on the water construction. The New Hampshire Community Fishing pier (C) is also less than 0.5 km from the Memorial Bridge and provides a place of safe harbor as well as access to local fishermen for stakeholder engagement. Directly across the river approximately 0.5 km from the deployment location is the Portsmouth Naval Shipyards (D) where many of the US Navy’s nuclear submarines are refueled and repaired. This tidal energy site represents a good location to demonstrate the emerging technology to the
US Navy as a potential energy source as well as to rely on the marine expertise of the shipyard’s employees.

Figure 3.3: Map of the deployment site. To the north is Kittery, ME. To the south is Portsmouth, NH. The Memorial Bridge runs through the center of the map connecting Portsmouth and Kittery. The central lift section is supported by two piers which define the deep water shipping channel. The turbine deployment site is marked. Letter markings are as follows A=Pepperell Cove Marine Services, B = NH Port Authority, C = Granite State Minerals Pier, D = NH Community Fishing Pier, E = Portsmouth Naval Ship Yard (Seavey Island), F = Prescott Park, G = Strawberry Bank, H = Harborwalk Park. For scale, the Memorial Bridge is made up of 3 300ft long truss sections. Imagery ©2017 Google, Map data ©2017 Google.

Rebuilt in 2013, the Memorial Bridge has newly poured concrete pier caps that are a strong mooring point for a turbine to be anchored to [52]. Possibly the strongest reason for deploying tidal energy conversion devices at the Memorial Bridge is the exposure of the new technology to the large number of people who frequent the bridge area. The Memorial Bridge is positioned on the edge of downtown Portsmouth and residents and visitors often walk the bridge as a form of recreation. The bridge is one of the few places in downtown Portsmouth where the public can ex-
perience being over the river without owning a boat. Harborwalk Park (E) is a recently constructed public deck that directly overlooks the tidal energy site. Adjacent to the bridge is Prescott Park (F) where large audiences gather on a weekly basis in the summer to watch performances, with views of the bridge crossing the Piscataqua River. Prescott Park abuts Strawberry Bank (G), an authentic outdoor historical museum. The people that visit these attractions can now also easily observe the science and engineering involved with a tidal energy project.

3.2 Flow Measurement Techniques

Accurate measurements of tidal current flows at a tidal energy site are necessary to reliably predict the amount of energy that can be converted from tidal currents into electrical energy. To measure the currents various instruments have been used. Rudimentary measurements are often taken by measuring the amount of time it takes a floating object to travel a given distance in a measured amount of time. Propeller style current meters have been used for point measurements of currents over a longer time period. By placing multiple current meters on a anchored line with a float on the top one can begin to measure a profile of the flow of water.

3.2.1 ADCPs

Acoustic Dopper Current Profilers (ADCP) are the modern day standard for field measurements of water currents. They were developed in the late 1970’s and early 1980’s to enable robust water current profile measurements.

Two ADCP deployment configurations are typically used. Bottom mounted ADCPs are mounted on the seafloor looking upwards towards the surface of the water. This configuration generates velocity profiles that are in reference to the seabed. Typically one must provide batteries and a retrieval system for bottom mounted deployments. ADCPs can also be deployed in a surface mounted configuration where they are mounted through the hull of a ship or over the side of a vessel. In the surface mounted configuration the ADCP is facing downwards towards the seabed. The surface mounted configuration creates velocity profiles that are in reference to their near surface mounting location. The water surface moves with wave and tidal action and the response of the
mounting structure with respect to the movement of the water surface is difficult to predict. The floating structures that ADCPs are typically mounted to are often changing position. When using surface mounted ADCPs one typically must correct for the position (both horizontally and vertically) and attitude of the ADCP. Other auxiliary instruments are can be used to provide correction factors for surface mounted ADCPs, as well as some ADCPs come equipped with internal attitude and location sensing instruments to make their own corrections.

ADCPs operate upon the principle of measuring the Doppler shift of reflected or "back-scattered" sound. When an ADCP operates it uses piezoelectric oscillators to transmit sound pulses of a known frequency through the water. The sound that is transmitted into the water gets scattered by suspended particles in the water. Some of this scattered sound ends up getting reflected back to the piezoelectric oscillators. The piezoelectric oscillators sense the frequency of that reflected sound. reflected sound is the Doppler shift. By measuring the Doppler shift of reflected sound one can determine the speed of the object that scattered that sound. When an object is moving towards
the sound emitting source it will reflect sound at an increased frequency directly proportional to the speed of the object. When an object is moving away from the sound emitting source it will reflect sound at a decreased frequency directly proportional to the speed of the object. By assuming the particles suspended in the water column have the same speed as the water in which they are suspended one can determine the speed of the water.

To determine the velocity of the water, which includes both speed and direction, one must use multiple piezoelectric oscillators to generate multiple beams of sound. By pointing at least three, but typically four, beams in different known directions and analyzing the trigonometric relationships between the speeds measured along each of those beams, the instrument can determine three dimensional velocity components. Because the beams are all angled away from one another they are all measuring the current in different places. The trigonometric relationships assume homogeneity across all beams in order to correctly compute velocity. This typically is a reasonable assumption in most river and ocean flows. ADCPs have the ability to generate current profile measurements. To do this the ADCP uses temporal gating. By measuring the amount of time it takes for sound to reflect back to the piezoelectric oscillators the ADCP can determine how far away that sound is coming from. The ADCP determines a velocity measurement from the sound it senses over a very small time interval. Each of these velocity measurements taken over very small
time intervals creates a velocity measurement at a given depth determined by the amount of time it took for that sound to return to the piezoelectric oscillators. Because the measurements have to be performed over very small intervals, the measurements of velocity are an average measurement of velocity over a given depth bin instead of being a point measurement of velocity. Although it can be set up to perform in many custom configurations the ADCP is performing this operation of pinging out a burst of sound and then listening for backscattered sound from throughout the water column approximately every two seconds. The instrument is obtaining velocity measurements at every ping instance. The uncertainty involved with these measurements is too high to meet most measurement requirements so a series of velocity measurements from individual pings is typically ensemble averaged to achieve an estimation of the velocity with more certainty. ADCPs can also
be accompanied with a range of other sensors to give more meaning to the velocity measurements that they make. Pressure sensors allow the user to determine the ADCPs distance from the water surface. Gyrocompasses, synchros, and GPS allow the user to determine the ADCPs attitude and position. Additional beams can be added to the ADCP to track the bottom, allowing the user to determine the distance from the ADCP to the seafloor as well as the velocity of the ADCP with respect to the seafloor. Additional beams may also enable a user to measure turbulence in the water. ADCPs often measure water temperature to help correct for variations in sound speed. [74]

3.3 ADCP Deployments

The data from three acoustic Doppler current profiler (ADCP) surveys was used in this assessment. The first survey was performed in 2007 as a part of a NOAA/NOS survey of the currents throughout the Piscataqua River and will be referred to as the K-07 survey [36] [60]. The second survey was performed in 2013/14 specifically for a potential TECS installation at the Memorial Bridge deployment site, and will be referred to as the HG-14 survey [42]. The K-07 and HG-14 surveys were bottom mounted ADCP deployments. The third ADCP survey was performed in 2017 from a vessel mounted ADCP and will be referred to as the L-17 survey.

The data from the K-07 and HG-14 surveys were analyzed to investigate the temporal variations in the tides. The K-07 survey deployed the ADCP in the middle of the shipping channel. The ADCP for the HG-14 survey was located close to the TECS deployment location, a short distance upriver owing to limitations caused by the bridge clearance and the deployment vessel). The locations of the ADCP deployments are shown in Figure 3.7. The distance directly between the K-07 and HG-14 ADCP deployment locations was about 64 m, and about 56 m when measured parallel to the bridge (approximately perpendicular to the tidal currents). During the 123 day HG-14 survey a construction barge moored directly over the ADCP from day 27 to day 57. The data recorded prior to and during the period when the barge interfered with the survey will not be used in this assessment and is not shown in any plots. This resulted in a 66 continuous day period of acceptable data that was used for the results presented here. The K-07 ADCPs used 30 range bins
Table 3.1: ADCP operating parameters

<table>
<thead>
<tr>
<th>Survey Method</th>
<th>K-07</th>
<th>HG-14</th>
<th>L-17</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bottom Deployed, Upward</td>
<td>Bottom Deployed, Upward</td>
<td>Through Hull Transsects,</td>
</tr>
<tr>
<td></td>
<td>Facing</td>
<td>Facing</td>
<td>Downward Facing</td>
</tr>
<tr>
<td>Latitude [deg. N]</td>
<td>43.0795</td>
<td>43.0791</td>
<td>-</td>
</tr>
<tr>
<td>Longitude [deg. W]</td>
<td>-70.75283</td>
<td>-70.7534</td>
<td>-</td>
</tr>
<tr>
<td>Model</td>
<td>RDI Workhorse Sentinel</td>
<td>RDI Workhorse Sentinel</td>
<td>RDI Workhorse Sentinel</td>
</tr>
<tr>
<td>Frequency [kHz]</td>
<td>600</td>
<td>1200</td>
<td>600</td>
</tr>
<tr>
<td>Bins [#]</td>
<td>30**</td>
<td>50</td>
<td>Varies w/ depth</td>
</tr>
<tr>
<td>Bin Length [m]</td>
<td>1</td>
<td>0.25</td>
<td>Vertical: 0.5 (raw)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Horizontal: 7.5</td>
</tr>
<tr>
<td>Blanking Range [m]</td>
<td>0.88</td>
<td>0.8</td>
<td>0.45</td>
</tr>
<tr>
<td>Sampling Rate [Hz]</td>
<td>0.5</td>
<td>0.5</td>
<td>0.97</td>
</tr>
<tr>
<td>Ensemble Length [min]</td>
<td>6</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>Deployment Depth [m]</td>
<td>20.5 Approx.</td>
<td>16 Approx.</td>
<td>0 (Surface)</td>
</tr>
</tbody>
</table>

*Only 59 days (two consecutive 29.5 day periods from 19 Dec. 2013 to 16 Feb. 2014) of data was used from this survey.

** Only the 18 lower bins are available from this survey.
each with 1 m height to sample the currents throughout the entire water column. Only the 18 lowest bins were published from that survey and used in this analysis. The HG-14 survey recorded only data below the tidal range to avoid collecting data in regions that would at times be above the water’s surface. At the time of this survey a bottom mounted turbine support structure was under consideration, and the turbine would not have operated in the highest levels of the water column. A 15 minute ensemble length was selected to allow the ADCP to record for a long period of time. Data from both the K-07 [60] and HG-14 [43] surveys are publicly available. The L-17 survey was performed to investigate the spatial distribution of the currents across the river at the bridge. The L-17 survey was obtained with the Coastal Bathymetry Survey System (CBASS) [49], a Yamaha Waverunner based survey system equipped with a hull-mounted, downward looking Teledyne RD Instruments 600 kHz Sentinel Workhorse ADCP, differential GPS positioning, dual-transducer 192 kHz single-beam echosounder, and custom navigation system. Instantaneous currents are sampled at about 1 Hz and discretized into vertical cells ranging 0.5 m in height. Vessel motion is removed from the current’s velocities using Teledyne RD Instruments (RDI) built-in bottom tracking algorithms. Observations from 10 cross-river transits (taking approximately 24 minutes to complete) are then binned into spatially overlapping 15 m wide sections, and then further bin-averaged in depth across 2 adjacent depth cells. Currents estimated with the CBASS compare well with traditional observations obtained at a fixed location with coincident bottom-mounted ADCPs within the transect, with current magnitudes within +/- 4.5 cm/s ($r^2 = 0.96$) and directions within ± 17 deg. ($r^2 = 0.97$) [54]. CBASS surveys were conducted at the maximum spring flood and ebb currents, each about 75-100 m upstream of the Memorial Bridge. The surveys were conducted for about 4 hours each time, with 10 transits averaged each 24 minutes or so to produce a time series of changes in the average current magnitudes leading up to, during, and just after maximum flow. The current transects when the strongest 25-minute averaged currents were observed at maximum flood and ebb spring tide are presented herein. The survey performed on the ebb tide passed directly over the HG-14 survey location.
3.4 Data Analysis

The L-17 survey investigated the spatial distribution of the tidal currents. The velocities reported from this survey were averaged over 24 minutes (for multiple transects), during which the maximum velocities were approximately constant. The surface tidal current speeds and directions are shown in Figure 3.7. Velocity magnitude contours for the transects are shown in Figure 3.8. This
survey showed that on flood tides the strongest currents (1.75 m/s) occurred around the Kittery side bridge pier (Pier 3, as it is referred to in the bridge structural drawings and can be seen in Figure 3.1) with weaker currents (1 m/s) occurring near the Portsmouth side pier (Pier 2). During the ebb tides the strongest currents (slightly exceeding 2 m/s) occurred at the Portsmouth side pier while more moderate currents occurred near the Kittery pier (1.75 m/s). Notice the large variations of tidal current strength at the Portsmouth side pier compared to the Kittery side pier as well as the small variations in tidal current velocity magnitude in the flows near the surface.

The L-17 survey indicated that both the Kittery and Portsmouth piers could be reasonable candidate locations for a tidal turbine installation. The Kittery side pier has less ebb/flood asymmetry than the Portsmouth pier, but the Portsmouth pier has faster maximum currents. The Portsmouth pier is a better location for a demonstration turbine deployment since it has the faster maximum currents which are desirable for testing of tidal turbines and since it can be more easily viewed from shore.

To quantify the tidal energy conversion potential at the Memorial Bridge site, representative bins from the HG-14 and K-07 ADCP surveys were analyzed. A tidal turbine would be placed near the surface to take advantage of the fastest currents, outside of the bottom boundary layer. For the HG-14 survey, the uppermost bin recorded was used. In the initial stages of project planning a bottom-supported tidal energy conversion system was being considered, thus the HG-14 survey only measured currents up to 12.1 m above the seafloor, whereas the water reached a maximum depth of 18.4 m during the survey. It was assumed that the currents in the uppermost bin of this ADCP survey would be representative of the flow any turbine installation, bottom-mounted or floating. For the K-07 survey a bin was selected that was approximately at the same depth in the water column as the uppermost HG-14 bin. Current speed and direction for these data are shown in Figure 3.9.

Four metrics were calculated from the HG-14 and K-07 surveys to quantify the tidal energy resource in a way that can be compared to other locations. Following the work of previous tidal energy resource assessments [64] the mean kinetic power density (W/m²), mean kinetic power
Figure 3.8: Velocity magnitude maxima for spring flood (top) and ebb (bottom) tides at the Memorial Bridge along transect lines shown in Figure 4. The circle in the bottom plot represents the approximate location of the HG-14 ADCP deployment while the triangle represents the approximate location of the K-07 ADCP deployment. The approximate locations of Pier 2 (Portsmouth side) and Pier 3 (Kittery) are indicated with dashed lines. The bridge pier locations were determined by lines perpendicular to the transect lines in Figure 3.7 that intercept the bridge pier locations. The data for these surveys are an average of the tidal currents recorded over a 24 minute period centered at 15.51 GMT 28 April 2017 for the flood survey and 12:52 GMT 1 May 2017 for the ebb survey. The raw bin sizes for this survey are 0.5m in the vertical direction. Every two bins in the vertical were averaged to produce these plots.

asymmetry (dimensionless), peak velocity (m/s), and direction asymmetry (°) were calculated, and the uncertainty in these measurements was determined based on the specified accuracy of the ADCP used. The data from a 59 day period from 19 December 2013 to 16 February 2014 and the bin recorded closest to the water’s surface of the HG-14 survey was used to capture two spring/neap
Figure 3.9: Current speed and direction for the HG-14 (left) and K-07 (right) ADCP surveys. 0 degrees corresponds to true North and the radial increments show speed in m/s. The HG-14 data is from the two consecutive 29.5 day periods from 19 Dec. 2013 to 16 Feb. 2014 and is taken from a bin 12.06 m above the seafloor as this was the highest available bin. During this period the heading of the ADCP varied by less than 3.1 degrees. The K-07 data is from the two consecutive 29.5 day periods from 21 Jun. 2007 to 27 Jul. 2007 and is taken from bin 14 which is approximately 4.5 m below the water surface at MLLW and should be approximately level with the highest bin in the HG-14 survey.

tidal cycles. For the K-07 ADCP survey one 29.5 day period from 17:36 21 June 2007 UTC to 10:23 July 9 2007 UTC was used. Mean kinetic power density $K$ is defined by

$$K = \frac{1}{2} \rho |U^3|$$

where $\rho$ represents the density of seawater, and $U$ is the horizontal tidal current velocity. Mean kinetic power density gives a quantitative time averaged measure of the amount of energy available in the flow. The mean kinetic power density for the HG-14 location, representative of the turbine deployment location, was calculated to be 0.668 kW/m$^2$. The mean kinetic power density for the K-07 location was slightly higher at 0.766 kW/m$^2$. 

The mean kinetic power asymmetry, $\phi$ can be calculated by taking the ratio of the mean kinetic energy in the ebb tides, $K_{\text{ebb}}$ to the mean kinetic energy in the flood tides, $K_{\text{flood}}$.

This metric shows the ratio of energy available during an ebb tide to the amount available during the flood. The mean kinetic power asymmetry at the turbine deployment location is 5.39. This strong mean kinetic power asymmetry is due to channel bathymetry, there is a shallow area just to the northeast of Four Tree Island (shown in Figure 3.3), which causes the flow to move to the Maine side of the river on the flood tide at the bridge. No such obstruction is present for ebb tides. Evidence of this can also be observed in the surface velocity vector plots in Figure 3.7 and the velocity contours in Figure 3.8, measured during spring ebb and flood tides. Sites with strong tidal asymmetries typically necessitate a large energy storage system if power is to be continuously provided by the local tidal energy resource.

It is evident from Figure 3.7, Figure 3.8, and Figure 3.9 that a much stronger ebb tide exists at the turbine deployment location. The fastest current measured in the highest bin over the 59 day period of the HG-14 survey was 2.06 $m/s$. This maximum velocity should be used when determining drag loads on the structure. The mean kinetic power asymmetry at the center of the shipping channel (K-07 location) is less pronounced with a value of 1.72, also showing stronger ebb tides than flood tides. The fastest current in the representative bin of the K-07 survey was 1.93 $m/s$. It should be noted here that the maximum velocities measured are also a function of averaging time, or ensemble length of each ADCP velocity record. This ensemble length is often driven by criteria such as desired deployment length and ADCP battery capacity. As the averaging time is decreased, we expect to measure somewhat higher maximum velocities. This will be studied in more detail once instruments are deployed directly at the site. One can also observe in Figure 3.9 a small ebb/flood directional asymmetry, defined as the difference between the average angle of ebb and flood tidal currents.

$$\bar{\theta}_{\text{flood}} - \bar{\theta}_{\text{ebb}} - 180^\circ \quad (3.2)$$

30
At the HG-14 survey location, the directional asymmetry was calculated to be -5.04 degrees. Such a small directional variation in tides will typically have little effect on turbine performance. A vertical axis crossflow turbine was selected because of its commercial availability and its potential to reduce maintenance by keeping power train out of the water. The performance of crossflow turbines is not affected by flow direction as long as the flow remains approximately perpendicular to the axis of rotation. A fixed yaw axial flow turbine’s performance would be decreased by a large ebb/flood directional asymmetry. The directional asymmetry at the K-07 survey location was -7.04 degrees. While the directional asymmetry at the turbine deployment site is small, the directional variation of the tidal currents is important for this TECS design: the bridge pier and its attached fenders act as hydrofoils at an angle of attack, and depending on flow angle can produce a separated wake flow. Depending on its placement, the turbine may have to operate within this wake. This wake could introduce error into the estimation of the time averaged metrics for both the magnitude and the direction of the currents. It is difficult to estimate this error at this time without measurements of the currents within this wake.

Table 3.2: ADCP survey operating parameters

<table>
<thead>
<tr>
<th>Site Characterization Metrics</th>
<th>K-07</th>
<th>Accuracy</th>
<th>HG-14</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Kinetic Power Density [kW/m²]</td>
<td>0.766 ±0.00689</td>
<td>0.668 ±0.00601</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Kinetic Power Asymmetry</td>
<td>1.72 ±0 (Within instrument’s velocity resolution)</td>
<td>5.39 ±0 (Within instrument’s velocity resolution)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Current [m/s]</td>
<td>1.93 ±0.0058</td>
<td>2.06 ±0.006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ebb/Flood Directional Asymmetry [°]</td>
<td>-7.04 ±2</td>
<td>-5.04 ±2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The estimated error in the time averaged metrics (Table 3.2) are based on the Teledyne RD Instrument’s specifications sheet for the Workhorse Sentinel ADCP where a velocity accuracy of
0.3% of the water velocity relative to ADCP and compass directional accuracy of ±2° is specified [75]. These estimations of error are low, non-conservative estimations of the amount of error due to the fact that none of the ADCP deployments were performed at the exact turbine deployment location. Small scale flows, such as the wakes coming off the bridge piers and fenders could increase or decrease the power production potential of the turbine. The ADCP was not measuring in this location since these flows are too small to resolve with an ADCP. In summary, the K-07 location in the center of the channel appears to have a slightly better tidal energy resource than the HG-14 location near the turbine deployment site. The K-07 site exhibits a slightly lower maximum current, but a much lower mean kinetic power asymmetry, resulting in a slightly higher mean kinetic power density. The ebb/flood directional asymmetry is slightly higher at the K-07 site, but comparable to the HG-14 site. However, the K-07 site is directly in the center of the shipping channel in a location where it would be difficult to obtain permits to deploy a TECS as it could interfere with shipping traffic in and out of the port. This demonstrates the difference between a technically available resource and a practically achievable resource. These two surveys also demonstrate the potential difference in resources that were observed in two different locations only 64 m away from each other. At the HG-14 survey site the tidal current speeds range from 0 to 2.06 m/s with a bimodal distribution. The first peak in the distribution corresponding to the flood tides is centered approximately on 0.75 m/s and the second peak in the distributions corresponding to the ebb tides is centered approximately on 1.42 m/s. The two distinct peaks for flood and ebb tides in the velocity histogram also manifest themselves in the strong mean kinetic power asymmetry, and are due to channel bathymetry, as discussed previously.
Figure 3.10: Distribution of tidal current speeds at the HG-14 (left) and K-07 (right) survey sites. Notice the bimodal distribution in the HG-14 histogram that shows the strong variation in flood and ebb tide strengths, whereas the tides are much less asymmetric at the K-07 location.
CHAPTER 4
TURBINE SELECTION AND SIZING

4.1 Alternatives Analysis

A hydrokinetic turbine could be deployed in various configurations at a bridge. Previously deployed configurations of tidal energy conversion systems could all be adapted to work at a bridge. A bottom mounted turbine with various forms of foundations could be used. The turbine could be fixed rigidly to the bridge pier and located at some depth in the water column. The turbine could also be deployed in a floating configuration.

4.2 Turbine Concept Selection

Unlike modern wind turbines and their three bladed, horizontal axis, axial flow, with a tubular pole tower design, tidal turbine designs have not yet converged to a best configuration. Many drastically different designs of tidal turbines are currently under development around the world.

An axial flow turbine uses a rotor with its rotating axis aligned in the direction of the oncoming flow of fluid. One example of a tidal turbine using this technology is Verdant Power’s Kinetic Hydropower System (KHPS) Figure 4.1.

An axial flow turbine rotor can only produce power from flows in one direction unless it either either pitches its blades or yaws its entire rotor to take advantage of bidirectional tidal currents. This necessitates additional moving parts and possibly an additional seal, all of which could possibly fail in the challenging marine environment. The advantage of using an axial flow turbine rotor in tidal energy is the ability to take advantage of the knowledge of rotor performance known from the wind industry.
Figure 4.1: Verdant Power’s KHPS, an example of an axial flow turbine. Image reproduced with permission from Verdant Power.
Although some tidal turbines are using axial flow rotors, a rebirth of the use of crossflow rotors has been seen. A cross flow turbine has its axis of rotation perpendicular to the flow of oncoming fluid. Crossflow rotors can produce power from flows in any direction so long as the flow is perpendicular to the rotor’s axis of rotation. This eliminates the need to yaw the rotor in a different direction as the tides change between ebb and flood, and reduces the number of moving parts that could fail. A disadvantage of crossflow rotors is the constant unsteady loading of their blades greatly increases the fatigue loading of the blades. An example of a crossflow tidal turbine is Ocean Renewable Power Company’s (ORPC) TideGen® Power System which is shown in Figure 4.2.

Crossflow turbines can be oriented horizontally as ORPC’s TideGen® Power System is, or they can also be oriented vertically. Instream Energy System’s (IES) vertical axis crossflow turbine is an example of this and can be seen in Figure 4.3. One advantage of using a vertically oriented rotor is that it allows sensitive components such as the gearbox and generator to be placed above the waterline to avoid flooding and eliminate the need for waterproofing sensitive components of the turbine such as the generator and gearbox.
Figure 4.3: IES’s vertical axis crossflow turbine. Note: this image shows the turbine partially deployed such that one can see the rotor. In the fully deployed position the rotor is fully submerged and the rotating shaft is vertical. Image reproduced with permission from IES.
4.3 Turbine Selection

After considering various turbine deployment options, it was decided to deploy a tidal turbine from a floating platform moored to the bridge pier. This mooring configuration allows the turbine to be floated in and out of the deployment location, and avoids mooring to the estuary bottom. UNH has significant experience testing tidal turbines deployed from floating platforms [27] [68]. A floating platform enables the turbine to be deployed near the surface where currents are the fastest, where it can be viewed by the public and more easily accessed and studied by researchers. The floating platform can be towed to a sheltered location with access to lifting equipment for installing turbines, as well as for safe harbor during extreme weather events. Both axial and cross-flow turbines can be deployed from a floating platform; a cross-flow turbine would be simpler since it does not need to yaw into the flow. Further, a vertically oriented cross-flow turbine would allow the power train to be placed above water. Only a few companies in North America make cross-flow turbines of this type and at a scale appropriate for this project and have demonstrated viability of their product via credible in-water testing. These companies include New Energy of Calgary, AB [15] and Instream Energy Systems of Vancouver, BC [40]. Another provider of vertical axis cross-flow turbines, Lucid Energy of Portland, OR, who produced the Gorlov Helical Turbines, recently exited the tidal/riverine instream energy conversion market and is now focusing on spherical cross-flow turbines in gravity driven pipes [12]. A vertical axis crossflow turbine was selected as the turbine configuration that would initially be deployed and tested.

Multiple turbine developers were contacted and asked to provide a turbine for the project. Initially Instream Energy Systems (IES) was selected to provide the turbine based off the performance of their turbine in a past deployment as well as their responsiveness to correspondences. The UNH team worked closely with IES from August of 2015 to November of 2017 teleconferencing regularly to discuss the technical development and preparation of the turbine for this project. Unfortunately, as is presently common in marine hydrokinetic device development, in November of 2017 IES’s financial situation changed such that they would not be able to provide a turbine to the
project without additional funding. After much consideration the UNH team decided they would have to procure a turbine from another developer.

New Energy Corporation Inc. (NECI) was contacted to determine if they could supply a turbine. NECI informed UNH that they could provide a turbine in approximately 3 months. In December of 2017 the Living Bridge Project entered into an agreement with NECI that stated NECI provide an Envirogen 025 (EVG 025H) Series turbine to the project.

The NECI turbine would have to be slightly modified for the Living Bridge Project’s application. Since the TDP intended to deploy the turbine was already fabricated the NECI turbine rotor would have to be decreased from its standard 3.4 m diameter to a 3.2 m diameter to enable the rotor to fit into the moon pool of the TDP. The NECI turbine would also have to be marinized as this would be its first installation in a marine environment. NECI changed some of the coatings and materials used on their turbine to adapt it to the marine environment and agreed to work with UNH to study its performance in the marine environment.

The NECI turbine uses a direct drive permanent magnet generator. This type of generator eliminates the use of a gearbox between the rotor and generator which simplifies the construction of the turbine and eliminates moving parts which could be a point of failure. A direct drive generator also necessitates power factor correction. Due to the high inductance of a direct drive generator the generator produces an alternating current waveform which lags behind the voltage waveform produced. This creates a situation where voltage and current are not phase matched and the true power generated is much less than the apparent power. The power factor is defined as the ratio between the true power and apparent power. When the apparent power is equivalent to the true power, an optimal power factor of 1 is achieved. To phase match the current with the voltage capacitors are used to balance the inductive load of the generator and phase match the voltage and current. This works well when the generator is run at a constant speed as inductance is correlated with generator frequency, but in a tidal environment the tidal current speeds are highly variable which means the generator frequency will be highly variable. This gives rise to the need for many different capacitance values for all of the different frequencies the generator will operate at based
on different tidal current speeds. On average this leads to sub-optimal power generation by a
turbine of this type in tidal applications. NECI is in the process of developing an active rectifier
which would eliminate the need for capacitors to perform power factor correction. At present this
solution is not available and the turbine will operate sub-optimally in the variable tidal current
flows. NECI is committed to developing an active rectifier for the UNH installation but it was
believed that evaluating the turbine on its performance without this key technology would be an
unfair representation of its performance thus a representative turbine was used to estimate annual
energy production.

In the results reported below, a generic representative cross-flow turbine with performance
specifications similar to other commercially available turbines will be used. It is believed that the
NECI turbine will perform similarly to this representative turbine once it is paired with an active
rectifier. With the turbine type selected, the rotor size still needed to be determined. Commer-
cially available vertical axis cross-flow turbines have rotor diameters ranging from 1.5 - 5 meters.
A common rotor diameter, for a range of power ratings, available from the companies referenced
earlier, is 3 meters (nominally). For a vertical axis turbine, the height of the rotors can be in-
creased to achieve higher power ratings in slower currents. Using the HG-14 ADCP survey data
a turbine rotor size selection chart was created, shown in Figure 4.4. This tool allows designers
to estimate the amount of energy that could be converted from a given resource based of various
turbine characteristics, such as power coefficients and cut-in speed. Figure 4.4 was produced using
the uppermost bin of the survey as a representative bin. It should be noted that if ADCP bins are
available and the resource changes appreciably with depth, then an increasing number of bins (i.e.,
increasing depth) should be used in the rotor sizing calculation as the rotor height is increased for
a fixed diameter turbine rotor to increase rotor area. Note also that vertically varying flow would
introduce nonlinearity or discontinuities in the slope of the lines shown in Figure 4.4, when the
rotor extends into bins that recorded slightly faster or slower currents.
Figure 4.4: A rotor sizing tool for the Memorial Bridge deployment site. This chart can be used to determine the rotor swept area necessary to convert a given amount of energy for various turbine efficiencies and cut in speeds at the HG-14 survey site. The blue dot represents a selected design.
4.4 Turbine Operating Theory

The following section was based on the derivations performed in [10] and class notes from Martin Wosnik’s ME 706/806 Renewable Energy: Physical and Engineering Principles course.

Tidal stream generators turbine rotors operate mostly under the same theory as wind turbine rotors. A model to predict the power generated, thrust on the rotor, and effect of the rotor operation on the local wind (or tidal current) field of an ideal turbine was developed by Albert Betz in 1920 [14]. To begin developing simple equations to predict power generation, rotor thrust, and the effects of the turbine on the local fluid flow field, one can use one dimensional momentum theory which models the turbine rotor as an actuator disk in a stream tube. An actuator disk is a mathematical tool that acts as a turbine rotor and imparts a force on the fluid to extract power from it. The fluid interacting with the turbine rotor can be modeled as the fluid encapsulated within a stream tube. This stream tube acts as a control volume when performing one dimensional momentum theory. It is assumed that fluid properties are constant across cross sections of the stream tube at any stream-wise location, and that fluid only enters and exits at the ends of the stream tube. A diagram of this stream tube model is shown in Figure 4.5.

4.4.1 Power Available in a Flow

To determine the available power in a flow, or for the case of a turbine, the flow that flows through a streamtube, one must first look at the relationship between energy and power

\[ P = \frac{dE}{dt} \]  \hspace{1cm} (4.1)

where \( P \) is the power available in a flow, \( E \) is energy, and \( t \) is time.

The energy available in a moving flow that can be converted by a tidal stream generator is the kinetic energy which can be written as

\[ E = \frac{1}{2} m V^2 \]  \hspace{1cm} (4.2)
Figure 4.5: A diagram of the stream tube control volume used in one dimensional momentum theory.
where $m$ is mass and $V$ is velocity. Equation 6.12 can be substituted into Equation 6.5 to get

$$P = \frac{dE}{dt} = \frac{d}{dt}(\frac{1}{2}mV^2).$$  \hspace{1cm} (4.3)

One can apply the chain rule to differentiate and get

$$P = \frac{1}{2}(V^2\frac{dm}{dt} + 2Vm\frac{dV}{dt}).$$ \hspace{1cm} (4.4)

When the fluid speed is constant

$$\frac{dV}{dt} = 0$$ \hspace{1cm} (4.5)

which results in

$$P = \frac{1}{2}(V^2\frac{dm}{dt}).$$ \hspace{1cm} (4.6)

where $\frac{dm}{dt}$ is the mass flow rate of the fluid through the turbine rotor. If the density of the fluid is $\rho$ and the cross sectional area of the turbine rotor is $A$, then the mass flow rate of the fluid through the turbine rotor can be written as

$$\frac{dm}{dt} = \rho AV$$ \hspace{1cm} (4.7)

by substituting Equation 6.21 into Equation 6.14 the result is

$$P = \frac{1}{2}\rho AV^3.$$ \hspace{1cm} (4.8)

This equation for available power is useful when analyzing a potential tidal current resource. It represents the maximum amount of power available in a flow.

4.4.2 Extractable Power

When analyzing a control volume one typically uses Reynolds transport theorem which states
\[
\frac{dN}{dt} = \frac{d}{dt} \int_V \eta \rho dV + \int_A \eta \rho (\vec{V} \cdot \vec{n}) dA
\] (4.9)

where \(N\) is any extensive property of the system, \(V\) is the volume of the system, \(\eta\) is parameter that corresponds with \(N\) to compute the instantaneous value of \(N\) in the control volume. To conserve mass throughout the streamtube

\[
\rho A_1 V_1 = \rho A_2 V_2 = \rho A_3 V_3 = \rho A_4 V_4 = \dot{m}
\] (4.10)

where \(\rho\) is the density of the fluid, the \(A\)’s are the cross sectional areas marked at their respective locations on the streamtube and the \(V\)’s are the velocities at their respective locations marked on the streamtube. It should be noted that \(A_2\) and \(A_3\) since they are right before and after the turbine rotor are equal to each other and representing the rotor cross sectional area as well as \(V_2\) and \(V_3\) are equal.

The rate change of momentum must be equal to the sum of all the forces applied. The force applied across the rotor is the difference in pressures over the rotor area.

\[
\rho V_1 A_1 - \rho V_4 A_4 = F_{thrust} = (P_2 - P_3) A_{rotor}
\] (4.11)

where the \(P\)’s are the pressures at their respective locations and \(A_{rotor}\) is the flow intercepting area of the rotor.

The pressure drop across the rotor can be expressed using Bernoulli’s equation (Equation 4.12)

\[
P_2 - P_3 = \frac{1}{2} \rho (V_1^2 - V_2^2) + P_1 - \frac{1}{2} \rho (V_4^2 - V_3^2) - P_4
\] (4.12)

Since \(P_1 \approx P_4\) and \(V_2 = V_3\) Equation 4.12 simplifies to

\[
P_2 - P_3 = \frac{1}{2} \rho (V_1^2 - V_4^2)
\] (4.13)

By substituting Equation 4.10 into Equation 4.11 and combining conservation of mass and momentum
\[(V_1 - V_4)\dot{m} = (P_2 - P_3)A_{\text{rotor}}.\]  \hfill (4.14)

By substituting Equation 4.13 into Equation 4.14

\[(V_1 - V_4)\dot{m} = \frac{1}{2}\rho(V_1^2 - V_4^2)A_{\text{rotor}}.\]  \hfill (4.15)

Substituting \(\dot{m} = \rho V_2 A_{\text{rotor}}\) and simplifying Equation 4.15 yields

\[V_2 = \frac{1}{2}(V_1 + V_4).\]  \hfill (4.16)

One can define an axial induction factor to describe the normalized decrease in velocity of the fluid in the streamtube from 1 to 2 as

\[a = \frac{V_1 - V_2}{V_1}.\]  \hfill (4.17)

Solving Equation 4.17 for \(V_2\) yields

\[V_2 = V_1(1 - a)\]  \hfill (4.18)

Equation 4.18 can be substituted into into Equation 4.16 and solved for \(V_4\) to find

\[V_4 = V_1(1 - 2a)\]  \hfill (4.19)

This equation shows that the velocity downstream of the rotor, \(V_4\), must always be greater than 0 if \(V_1\) is greater than 0. Thus the axial induction factor, \(a\) must always be less than \(\frac{1}{2}\).

The since power is \(FxV\) and recalling Equation 4.13, the power at the disk can be written as

\[P = F_{\text{thrust}} * V_2 = \frac{1}{2}\rho A_{\text{rotor}}(V_1^2 - V_4^2) * V_2\]  \hfill (4.20)

Substituting into Equation 4.20 with Equations 4.18 and 4.19 yields
\[ P = \frac{1}{2} \rho A_{rotor} V_1^3 \ast 4a(1 - a)^2. \]  

Equation 4.8 can be used to describe the available power in the fluid. A rotor can only extract a fraction of this total available power. This fraction is the non-dimensional power coefficient, \( C_P \), which is defined as

\[ C_P \equiv \frac{P}{P_{available}} \equiv \frac{P}{\frac{1}{2} \rho A_{rotor} V_3^3} = 4a(1 - a)^2. \] (4.22)

Naturally, one would be interested in determining what the maximum possible \( C_P \) achievable is. To do this, \( C_P \) can be written as

\[ C_P = 4a(1 - a)^2 = 4a - 8a^2 + 4a^3. \] (4.23)

To find the maximum the roots of the derivative of the function can be found

\[ \frac{dC_P}{da} = 12a^2 - 16a + 4 = 0. \] (4.24)

The roots of this quadratic equation are

\[ a_{1,2} = \frac{16 \pm \sqrt{16^2 - 4 \ast 12 \ast 4}}{2 \ast 12} = \frac{16 \pm \sqrt{64}}{24} = 1(nonphysical, a < \frac{1}{2}), \frac{1}{3} \] (4.25)

Therefore the maximum \( C_P \) occurs at \( a = \frac{1}{3} \). Substituting \( \frac{1}{3} \) into \( a \) in Equation 4.23 yields

\[ C_{P_{max}} = 4 \left( \frac{1}{3} \right)^2 \left( 1 - \frac{1}{3} \right)^2 = \frac{16}{27} = 0.593 = 59.3\% \] (4.26)

This is commonly referred to as the "Betz limit" [14]. This is the maximum achievable power coefficient a run of river turbine can achieve. In practice, commercially available cross-flow turbines typically have power coefficients, \( C_P \), in the 0.25-0.4 range and cut-in speeds from 0.5 to 1 m/s. Using Figure 4.4 one can determine that a representative turbine rotor within these ranges
with a coefficient of power of 0.35 and a cut in speed of 0.7 m/s would produce approximately 1.13 MWh every thirty days in this tidal energy resource. This estimate is slightly optimistic because it assumes a constant power coefficient. With the goal of producing at least 1 MWh of energy per month with existing turbine designs a 6 m² (3 m diameter, 2 m depth) rotor was shown to be sufficient. The average New Hampshire residential electric user consumes 0.621 MWh per month [66], thus this turbine will produce almost the amount of energy needed to power two average New Hampshire homes.

4.5 Energy Production Estimate

A more accurate estimate of annual energy production (AEP) was calculated based on a theoretical, representative power curve for a cross-flow turbine and the probability distribution of the tidal current speeds at the HG-14 survey site show in Figure 3.10. The power curve for the representative cross-flow turbine for a turbine with 6 m² flow-facing area (3 m diameter x 2 m height) is shown in Figure 4.6. The rotor is specified to have a maximum power coefficient, $C_P$, of 0.35 and a cut-in speed of 0.7 m/s.

Figure 4.6 shows the (representative) turbine rotor efficiency for its operational range of tidal current speeds. Turbine efficiency ramps up above cut-in speed until it reaches its peak value of 0.35 at 1.2 m/s, above which it remains constant. No power is converted at tidal current speeds below the cut-in speed of 0.7 m/s. At relatively low speeds, but faster than cut-in (0.7-1.2 m/s), little power is converted as the rotor efficiency begins to ramp up. As tidal current velocities continue to increase (1.2-3.0 m/s) the amount of power converted increases with the cube of velocity (since the turbine efficiency is constant in this range). Eventually the cut-out speed is reached at 3 m/s, which is also the speed at which this turbine would reach its rated (maximum) power. Above the cut-out speed, efficiency goes to zero as the turbine shuts down to prevent damage in high speed flows. Where available, actual turbine power curves based on performance measurements should be used to calculate AEP. Note that using a constant power coefficient $C_P$, as was done with the initial turbine sizing tool (cf. Figure 4.4), would likely lead to an overestimate.
Figure 4.6: Power curve for a representative cross-flow tidal turbine. Turbine rotor efficiency is shown in red, and power produce [kW] is show in blue.

of AEP, since turbine power conversion efficiency typically varies somewhat with tidal current velocity. Thus AEP was estimated [1] using:

\[
AEP = H \sum_{i=1}^{N_H} P_i(V_i) \cdot f_i(U_i) \tag{4.27}
\]

where for each velocity bin, \(i\), in the histogram the number of hours, \(H\), in a year is multiplied by the sum of the product of the power generated, \(P_i(U_i)\), at the mean tidal current velocity, \(U_i\), of each histogram bin by the frequency of that speed’s occurrence, \(f_i(U_i)\). Using the HG-14 resource in Figure 3.10 and the representative power curve in Figure 4.6, one can expect to convert 10,249 kWh per year into electrical energy. For the selected turbine (Figure 4.6) this yields a capacity factor of 0.12, which is low, but not unexpected due to strong mean kinetic power asymmetry.
4.5.1 Envirogen 025 Series Tidal Turbine Description

New Energy Corporation supplied an Envirogen 025 Series (EVG-025H) turbine to the project. The EVG-025H turbine is a four bladed vertical axis cross flow turbine rated to produce 25kW in 3m/s water currents. Two support arms support attach each blade to the drive shaft. The drive-shaft is used to spin a direct drive permanent magnet generator. A rendering of the EVG-025H is shown in Figure 4.7.

Figure 4.7: The EVG-025H, a four bladed cross flow vertical axis 25kW (at 3m/s current speeds) hydrokinetic turbine with a direct drive permanate magnet generator.

New Energy Corporation has produced one other EVG-025H series turbine before the one produced for the Living Bridge Project. In the spring of 2016 New Energy Corporation tested their
first EVG-025H turbine in Sicamous Lake in Sicamous, BC. Testing was performed by towing the EVG-025H turbine behind a tug boat on New Energy Corporation’s standard turbine boat. The tests were considered to be successful and it was declared that the turbine passed all requirements and exceeded expectations.

For the Living Bridge Project the turbine was slightly modified. The Living Bridge Project TDP had already been constructed with the intent of deploying the Instream Energy Systems turbine when UNH began working with NECI to supply a turbine. To accommodate the smaller moon pool on the TDP the EVG-025H rotor was reduced in size from 1.7 \( m \) tall and 3.4 \( m \) in diameter to 1.7 \( m \) tall and 3.2 \( m \) in diameter. The Living Bridge Project turbine deployment would also be the first time NECI had ever deployed one of their turbines for a long period of time in a saltwater marine environment. NECI hired a consultant and spent a great deal of effort themselves to marinize their turbine for the saltwater marine environment. The methods they used to marinize their turbine are considered proprietary and thus will not be discussed in this thesis, though UNH is working with NECI to assess the effectiveness of their marinization plan.

NECI also provided UNH with the power electronics necessary to control the turbine and condition the power generated by the turbine. Power comes off the permanent magnet generator as high voltage (variable based on generator speed, but on the order of hundreds of volts) wild AC current. This current enters an electrical panel called the Turbine Interface Panel (TIP).

The turbine interface panel allows the turbine operators as well as other power electronics to interface with the turbine. This panel was custom designed by NECI and has been certified to be UL508A compliant meaning that the panel is a safely designed industrial control panel. The TIP has controls for stopping the turbine, starting the turbine, switching the generator to be connected/disconnected from the rectifier, switching the generator to be connected/disconnected to the utility grid, and a switch to change from on-grid operating mode to off-grid test mode. Inside the TIP a contactor shorts out the generator to stop the rotor upon operator’s request. An electric heater provides heat during cold temperature testing. This heater also provides heat to the rectifier via a duct. A small inverter in the TIP converts 480V AC power from the bridge into 120V AC.
power. This 120V AC power outlet is used to run a battery charger (housed outside of the TIP) as well as anything else plugged into a standard 120V AC power outlet in the cabinet. Note that this 120V outlet is only a 10A outlet, so it should not be used to run high powered loads. Three 24V 35Ah batteries are housed within the TIP and are used to hold the braking contactor closed to short the generator to brake the turbine rotor. When the batteries are fully charged they can hold the brake on for 147 hours during a grid outage, and can provide braking power for up to 40 hours during off-grid testing. It is recommended that for off-grid testing a portable generator be used provide 120V AC power the 120V AC circuit in the TIP such that the battery charger can keep the batteries fully charged.

The TIP feeds power to a passive rectifier manufactured by a company called Voltsys. This rectifier converts the wild AC power produced by the generator to DC power. In off grid mode, this DC power is dissipated in a 25kW resistor bank. This 25 kW resistor bank could get warm during testing so it is recommended to keep personnel clear of the resistor during testing. The rectifier also controls the turbine and attempts to extract the maximum amount of power off the generator as possible. The rectifier is an Arduino based system and it’s control parameters can be modified via a Voltsys software and a USB cable housed inside the rectifier.

As of the publishing date of this thesis no power factor correction system has been provided by NECI. An active rectification system is necessary to increase the energy production of the system. When present a capacitor bank could be used for power factor correction. This capacitor bank would be attached to the rectifier. NECI has committed to the development of an active rectifier, but do not currently have one. If an active rectifier is developed it would take the place of the passive rectifier and no capacitor bank would be needed.

When operating in on-grid mode the DC power converted at the rectifier is transmitted to the inverter to be converted from DC to 480V AC grid phase matched power. This power is then transmitted via the droop cable up onto the bridge pier and onto the bridge grid.
5.1 Energy Management Configurations

It was known that the amount of power generated by the turbine would be highly variable due to the variable speed of the tidal currents. The amount of power needed to power the instrumentation was assumed to be more or less constant. Thus there would be times when the turbine would produce more power than the instrumentation would consume, and there would be times when the instrumentation would consume more power than the turbine was producing. Various energy management configurations were considered to determine which would be most appropriate to meet the project’s goals. Three systems were considered which included off-grid, energy storage system, and net metered. Each of these systems have advantages and disadvantages both in terms of their complexity and technological availability as well as in terms of how much they will utilize the power generated by the turbine to do useful work.

5.1.1 Off-grid

Possibly the simplest, but least efficient energy management configuration was a completely off grid system. This system would connect the turbine directly to the load (bridge and estuarine instrumentation) and a load bank. When the turbine produced enough energy it could run the load. When the turbine produced excess energy, that energy could be dissipated by a load bank. When not enough energy was produced the instrumentation would have to be shut down. This system is a very simple design because the power does not need to be conditioned for the grid and no grid connection permitting is required, but it is very inefficient because none of the power generated is utilized to do useful work. A diagram of this type of system is shown below in Figure 5.1.
This system’s advantage is its simplicity in that it only requires one to supply the turbine, electrical connections, power conditioning equipment, and a load bank. The complex part of implementing a system like this would be determining how to safely and reliably turn off all instrumentation without damaging it during the times when more power is being demanded by the instrumentation than is being produced by the turbine. One would also have to determine how to regulate the load bank such that it only dissipated the amount of power in excess of the instrumentation’s demand. This system also has the advantage that it does not require any permitting or inspection from the local utility regarding putting power onto the grid.

This system was not investigated in detail as it would not provide an efficient use of the power generated by the turbine and it would be technically difficult to devise a system where the instrumentation could safely and reliably be turned on and off when not enough power was being supplied. The system would also not allow measurements to ever be taken at slack tides or during slow currents.

NECI did include setting on their power electronics to allow the turbine to produce power in a mode similar to this. When the turbine is operated in the off-grid test mode all power produced by the turbine is dissipated in a resistor bank. The amount of power produced can be measured and less permitting is required. This enables the turbine deployment system to some day be used at the General Sullivan Bridge, UNH’s other permitted tidal energy test site where there is no grid.
connection currently available. This off-grid test mode has also enabled the Living Bridge Project team to gain confidence operating the turbine before connecting to the grid.

5.1.2 Off-grid with Storage

Another energy management system would be an off grid system that incorporates some energy storage. This system would use the power generated by the turbine to run the instrumentation. When the turbine was producing more power than the instrumentation was demanding a battery would be charged. If the battery became full, a load bank could be used to dissipate excess power. When the turbine was not producing enough power the instrumentation could run off the battery. If the battery became empty, the instrumentation would have to be shut down. A diagram of this type of system is shown below in Figure 5.2.

![Figure 5.2: A diagram of the off-grid with storage energy management configuration.](image)

This system builds slightly upon the off-grid without storage system in that it utilizes some of the energy that is produced during periods of excess. It exhibits the same complexities and drawbacks as the off-grid without storage system. It also would not require special permitting and inspection as it is off-grid.

This system was also not investigated in detail because an excessively large battery would be required in order to continuously provide power to the instrumentation. This battery was expected to be out of the budget of the project.
5.1.3 Automated Transfer Switch

North East Integration, an electrical integration company contracted on the Living Bridge Project, suggested the potential use of an automated transfer switch. Automated transfer switches are commonly used in residential applications to automatically switch houses off the utility grid and onto backup generator power. The way the system would work is the turbine would be connected to a battery and a load bank. The battery would be connected to an automated transfer switch. This automated transfer switch would be able to switch the load from the battery to backup utility grid power in order to provide continuous power to the instrumentation, but it aims to use as much energy as possibly be provided by the turbine. When the battery is full a load bank enables the energy management system to dissipate excess power.

For the Living Bridge Project this configuration was initially compelling because it would allow the turbine to provide the majority of the power for the instrumentation while still allowing the instrumentation to be run continuously on backup utility grid power when needed. It would also allow the turbine to operate off-grid as no power from the turbine would ever be supplied to the grid. It was hypothesized that this would enable the project to proceed with less permitting effort.

Figure 5.3: A diagram of the automated transfer switch energy management configuration.
To assess the feasibility of an energy storage system that would enable the bridge and estuarine instrumentation to continuously run independently of grid power an energy management model was created. The model can be used to study how an energy storage system can balance the temporal variations between a power load and source.

This model requires the user to input an instantaneous power production time series, an instantaneous power consumption time series, and a battery capacity. Within the model the user can adjust the time step over which each instantaneous power is ensemble averaged. The program then uses that time step to create three vectors that represent the amount of energy produced, the amount of energy consumed, and a time vector.

Within the model the user can prescribe at what percentage of the total capacity (in Wh) to initialize the battery. This analysis initialized the battery at half capacity. At each time step, the model takes the battery’s capacity from the previous time step and adds the difference between the amount of energy produced and the amount of energy consumed over that times step. When the battery exceeds its capacity the model keeps track of the amount of energy that is produced, but could not be used locally, and when the battery is empty the model keeps track of the amount of energy consumed.

Figure 5.4: Energy management system model flow chart.
energy that must come from another source to supply the load. At the end of the simulation the program determines the percent of the total energy generated that had to be exported to another source and the percent of the total energy generated that had to be imported from another source.

Temporal variations in tidal currents and a need for a constant power supply give rise to the requirement of a physical energy management system. This energy management system has the ability to store excess energy produced, pull energy from the external grid, and manage turbine efficiency based off battery charge level. The simulation of this system seen in Figure 5.5 showed that even with a relatively large battery bank (10kWh), the system would still produce excess energy during spring tides and insufficient energy during neap tides.

A selection tool, Figure 5.6, was created that showed the total micro-grid energy utilization factor for various rotor areas and battery bank sizes. The energy utilization factor \( k_u \) is defined as

\[
k_u = \frac{E_c}{E_c + E_d + E_g} \times 100\%
\]  

(5.1)

where \( E_c \) is the total amount of energy consumed to do useful work, \( E_d \) is the total amount of energy dissipated when the battery is full, \( E_g \) is the total amount of energy drawn from the grid when the battery is empty. The tool showed that for larger battery banks the energy utilization factor should increase. This is expected as a larger battery will be able to store more energy during periods of high energy tides. This has two advantages. The battery can store more energy before it becomes full and needs to shed power to a load bank as well as the battery can discharge more energy before it becomes empty and needs to draw power from the external grid. For large batteries the energy utilization factor exhibited a maximum at a specific rotor area. If the rotor area is greater than these optimal areas the amount of energy over produced with respect to the batteries capacity becomes too large and the system loses overall efficiency. For rotor areas smaller than the optimal areas the amount of energy converted is not always sufficient and more power needs to be drawn from the external grid which decreases the overall system efficiency.
Figure 5.5: Energy management system model results. Top: power production (blue) for a representative ($6m^2$) turbine rotor with a constant $C_p$ of 0.35 and cut-in speed of $0.7m/s$ and consumption (red) profiles with times and amounts of power over produced (magenta) and under produced (black lines). Bottom: battery charge level. The bottom smaller inset figures show typical examples of (bottom left) energy underproduction (switch to backup power source) and (bottom right) overproduction (dissipation of energy).
Figure 5.6: Energy utilization factor for a range of rotor sizes and battery banks.

The simulation showed that when the battery bank size was held constant and the turbine rotor area was increased the amount of energy over-produced increased, and the amount of energy under-produced decreased. When the turbine rotor area was held constant and the battery bank size was increased the amount of energy over-produced decreased and the amount of energy under- and over-produced decreased. Within the model the initial charge state of the battery can be described in terms of percentage of the total capacity (in Wh). It should be noted that for the given tidal energy resource, the model results were found to be relatively insensitive to the battery’s initial charge state for small batteries, and somewhat more sensitive to the battery’s initial charge state for increasing battery size. The initial charge state for the results presented here was 50%. Note that the batteries were modeled as ideal energy storage devices, with full charge/discharge capacity, 100% charge/discharge efficiency and no performance degradation with charge/discharge cycles. It is clearly beneficial to use an energy storage system with this energy resource, and to size it appropriately for the energy conversion system installed. For example, the maximum energy utilization factor using a 1 kWh battery is only 33%, but by using a 10 kWh battery it increases to 75%.
The increases in energy utilization factors become smaller as battery sizes are increased further, as can be seen comparing, for example, moderately sized battery bank (10 kWh) and a large battery bank (100 kWh). For comparison, the typical capacity for a 12 V car starter battery (the kind used with internal combustion engines) is about 0.6 kWh. The capacity of the Tesla Powerwall is 10 kWh [77], and the capacity of the SonnenBatterie is 4-16 kWh, in 2 kWh steps [72] - both are used for residential applications. The capacity for the Tesla Powerpack for industrial or utility applications is scalable, of course, but a base unit with 100 kWh capacity is offered [76]. Overall, the simulation suggests that a turbine with a 6 m² rotor coupled with a battery bank in the range of 10-20 kWh would be well suited for the resource and power demand at the Memorial Bridge. This analysis does not take into account technical, economic, and political factors that may suggest a different energy management strategy. The predictability of tides could be used to improve an energy management system, for example by varying the electrical load or turbine operating point. A smart energy management system could take advantage of periods of more powerful tides to increase sampling rates of instruments on the Living Bridge Project and take higher resolution measurements. Prior to periods of predicted over-production (maximum ebb tides) the power conversion system could be operated away from its point of peak efficiency (i.e. a non-optimal tip speed ratio for tidal turbines) or power could be dumped to a load bank to avoid over charging the battery bank. During periods of predicted under-production (slack and neap tides) non-essential loads could be shut off or reduced by a smart energy management system. On the Living Bridge Project, non-essential sensors could be shut off or their sampling rates could be decreased to eliminate or reduce their power draw. These strategies could be used during slack tides and or neap tides which can be accurately forecast. This simulation highlights the need for advanced energy management system research. Even with a highly predictable renewable power source such as tidal energy, there will still be periods of excess and insufficient power conversion. These periods of non-optimal power conversion can be mitigated through various strategies, but to provide continuous power, energy must either be stored or supplied from an external source. Decreasing power draw prior to a period of predicted low power conversion and increasing power consumption or
decreasing power production prior to periods of predicted high power conversion, could decrease energy storage requirements. A smart energy management system with the ability to predict energy production potential and vary energy production and consumption based on this information could decrease the cost of energy conversion systems that must provide continuous power, at either stand-alone or remote installations. These technologies are not yet readily available for application during the Living Bridge Project. Grid-connectivity with a net-metering scheme is still the easiest way to supply continuous power to the instrumentation at the Memorial Bridge, while (mostly) using a locally available renewable energy source.

5.1.4 Net Metered

Net metering is an energy management scheme commonly used in residential photo-voltaic installations. In these situations a bidirectional meter is installed with the photo-voltaic system. This bidirectional meter allows excess power to be sold back to the utility grid when production exceeds demand. It also allows the home owner to continue to purchase power from the grid when demand exceeds production. A diagram of how this type of configuration could be implemented is shown in Figure 5.7.

![Figure 5.7: A diagram of the automated transfer switch energy management configuration.](image)

In this configuration all of the energy produced is ultimately used to do useful work either at the source of its production or in another location on the grid \(K_u = 1\). This configuration
also requires that all equipment be UL1741 [80] certified such that the power produced at these
distributed generation sources is compliant with the power available on the utility grid. UL1741
certified inverters are readily available off the shelf.

A net metered system was selected for implementation because it will enable all of the energy
produced to be utilize and the technology to implement this system is readily available. The sys-
tem is also able to operate in an off-grid mode for testing. In the off-grid energy management
configuration the turbine will shed all of the power produced into a 25 kW resistor. The current
through and voltage across that resistor can then be measured to determine power production. This
configuration will not run any of the instrumentation although it will allow for turbine testing at
any location including the General Sullivan Bridge test site where no grid connection is currently
established.
TURBINE DEPLOYMENT SYSTEM DESIGN

6.0.1 Turbine Deployment Platform Alternatives Analysis

An alternatives analysis was performed to determine the configuration and materials for the turbine deployment platform (TDP). Three main TDP configurations were considered and the material with which they would be composed of were analyzed.

The UNH TDP V1.0 was built using an aluminum pontoon boat kit with the sole intent of enabling short term testing at the General Sullivan Bridge test site. This platform was then later reconfigured into UNH TDP V1.1 for additional short term testing at the General Sullivan Bridge and open ocean testing at the Muskeget channel [67]. An aluminum boat kit had been show to perform well for turbine testing, though it was thought to not be durable enough for long term testing and was thought to possibly be costly at the size needed for this deployment. TDP V1.0 was only 35 ft long and thus was too small for this deployment.

A configuration that used steel pontoons was considered. This configuration would enable the pontoons to act as a structural component while providing buoyancy. The ability to procure these pontoons was of concern as most large steel fabrication facilities in the local area are not near the water or have boat launching capabilities. Corrosion was also of concern.

Some would consider high density polyethylene (HDPE) to be an emerging marine material. It does not corrode in seawater, has good UV resistance, has good resistance to being punctured, and it is inexpensive. The main drawbacks to its use are that it has a relatively low strength to density ratio, meaning that lots of material (by mass) has to be used to ensure the component has sufficient strength.

A decision matrix was created to assess each material. The matrix first calculates each material’s strength to weight ratio and then places a value (from 1 to 10) upon the material’s expected
resistance to damage, fatigue, biofouling, corrosion, and cost. These factors were all considered relatively quantitative since they are based off the material’s properties, test results, and material and fabrication cost estimates. When all of these factors were coupled together one could calculate a material "M number" which acted as a quantitative indicator of the materials applicability. Qualitative weightings (from 1 to 10) were then added to these categories used to determine the "M number." The new qualitative categories, supplier/manufacturer relation, supplier/manufacturer location, ease of repair, and ease of assembly were introduced. These categories along with the "M number were then given weightings and a weighted score for each material which took into account both the quantitative factors and qualitative factors was calculated.

A summary of the results from this decision matrix is show in Table 6.1.
Table 6.1: "M number" determination

<table>
<thead>
<tr>
<th>Pontoon Material comparison</th>
<th>strength/density ratio [Mpa/ (g/cc)]</th>
<th>Source</th>
<th>Properties</th>
<th>Resistance to (10=high, 1=low)</th>
<th>cost</th>
<th>&quot;M number&quot;</th>
<th>Rank(5=Best, 1=Worst)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighting (10=Important, 1=Unimportant)</td>
<td>7</td>
<td>5</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Aluminum 6061-T6; 6061-T651</td>
<td>102</td>
<td>Matweb</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Aluminum 5052-H32</td>
<td>72</td>
<td>Matweb</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>ASTM A572 Steel, grade 50</td>
<td>44</td>
<td>Matweb</td>
<td>9</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>HDPE (High Density Polyethylene)</td>
<td>31</td>
<td>Plastics Intl.</td>
<td>8</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>HDPE (High Density Polyethylene)</td>
<td>27</td>
<td>Marley Pipes</td>
<td>8</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

(*)depends on coating
The decision matrix showed that HDPE, is a compelling material based on its material properties. When non quantitative factors are taken into account HDPE became a clear choice for pontoon material. This necessitated a rigid frame to join the pontoons and provide structural stability. It was decided to build the frame out of steel I-beam members to take advantage of the team’s structural steel design experience.

6.1 Load Determination

The following numbers represent the numbers that were used while designing each individual component.

The forces and moments on the turbine deployment system - vertical guides (VGPs), TDP, and marine hydro-kinetic (MHK) turbine - will be resisted by the mooring system attached to the Memorial Bridge’s Pier 2 and by the TDP. These forces and moments are due to gravitational effects, tidal currents (drag), wave action on submerged components, and wind drag on components above the surface of the water. The following subsections explain how these loads were calculated. For reasons previously discussed the first turbine to be deployed on the TDP is expected to be a cross flow (vertical axis) turbine. The load calculations were carried out for a 3 m x 3 m (9.8 ft x 9.8 ft) turbine, except where noted otherwise, as a conservative measure and to enable larger turbine testing in the future.

6.1.1 Gravitational Loading

Gravitational forces act vertically downward towards the center of the Earth and are a function of the TDP mass. The buoyant force of the TDP’s pontoons, which is the integral of the hydrostatic pressure distributed over the submerged surface, and equal to the weight of the water displaced, will act vertically upward and counteract the gravitational force. To size the pontoons the weight of the TDP as well as the weight of all objects on and attached to the TDP was estimated. The total volume of water that must be displaced to provide an adequate amount of buoyancy force was calculated and compared to the proposed volume of two 42 in (1.07 m) diameter and 49 ft (15 m) long pontoons. It was found that when the TDP is fully loaded (dead loads plus live loads)
the pontoons will be approximately half submerged, leaving reserve buoyancy. Throughout this report a pontoon length of 42 ft (13 m) is often used as a conservative estimate of the pontoon’s length due to the loss in volume caused by the raked front and back ends. The total length of the pontoons is 49 ft (15 m). The pontoon length used in the buoyancy calculation is 42 ft (13 m). The pontoons will be filled with cut closed cell solid foam cylinders to prevent catastrophic failure in the unlikely event that the pontoons leak. The pontoon configuration is inherently stable, and additional ballast is not needed. Table 6.2 shows the inputs used for the buoyancy determination.

Table 6.2: Buoyancy calculations

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>Weight</th>
<th>Imp</th>
<th>Weight</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>TURBINE TOTAL (INCL PWR ELEC)</td>
<td>5200</td>
<td>lb</td>
<td>2359</td>
<td>kg</td>
</tr>
<tr>
<td>Rotor</td>
<td>2600</td>
<td>lb</td>
<td>1200</td>
<td>kg</td>
</tr>
<tr>
<td>MOTOR BRAKE GEARBOX</td>
<td>1,500</td>
<td>lb</td>
<td>680</td>
<td>kg</td>
</tr>
<tr>
<td>STEEL MOUNTING FRAME</td>
<td>1,100</td>
<td>lb</td>
<td>499</td>
<td>kg</td>
</tr>
<tr>
<td>TURBINE DEPLOYMENT MECH</td>
<td>1681</td>
<td>lb</td>
<td>763</td>
<td>kg</td>
</tr>
<tr>
<td>PLATFORM</td>
<td>18780</td>
<td>lb</td>
<td>8519</td>
<td>kg</td>
</tr>
<tr>
<td>10 PEOPLE</td>
<td>2000</td>
<td>lb</td>
<td>907</td>
<td>kg</td>
</tr>
<tr>
<td>TOOLS</td>
<td>400</td>
<td>lb</td>
<td>181</td>
<td>kg</td>
</tr>
<tr>
<td>INSTRUMENTATION</td>
<td>300</td>
<td>lb</td>
<td>136</td>
<td>kg</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>28361</td>
<td>lb</td>
<td>12865</td>
<td>kg</td>
</tr>
<tr>
<td>RHO_WA TER</td>
<td>64</td>
<td>lb/ft³</td>
<td>1025</td>
<td>kg/m³</td>
</tr>
<tr>
<td>VOL DISPLACED BY WEIGHT</td>
<td>443</td>
<td>ft³</td>
<td>13</td>
<td>m³</td>
</tr>
<tr>
<td>PONTOON LENGTH</td>
<td>42</td>
<td>ft</td>
<td>13</td>
<td>m</td>
</tr>
<tr>
<td>PONTOON DIAM</td>
<td>3.5</td>
<td>ft</td>
<td>1.1</td>
<td>m</td>
</tr>
<tr>
<td>PONTOON VOLUME</td>
<td>808</td>
<td>ft³</td>
<td>23</td>
<td>m³</td>
</tr>
<tr>
<td>AVAILABLE BUOYANCY FORCE</td>
<td>51000</td>
<td>lb</td>
<td>230000</td>
<td>N</td>
</tr>
<tr>
<td>RESERVE BOUYANCY</td>
<td>45.2</td>
<td>%</td>
<td>45.2</td>
<td>%</td>
</tr>
</tbody>
</table>
6.1.2 Tidal Current Drag

Over the course of a four-month ADCP deployment performed near the deployment location in 2013-14, the maximum tidal current velocity measured by the ADCP was 2.06 m/s (4.1 kt) [42]. Based on the data gathered from the ADCP survey, bridge energy demands, and present turbine designs and performance specifications, The UNH research team decided that the cross-flow turbine for this site would have a 3 m (9.8 ft) diameter and a rotor depth of no longer than 3 m (9.8 ft) or a rotor swept area no larger than 9 m² (96 ft²).

Continuing from the derivation of turbine operating parameters in Chapter 4, it can be shown that from Equations 4.11, 4.13, 4.18, and 4.19 that

\[ F_{thrust,x} = \frac{1}{2} \rho A_{rotor} (V_1^2 - V_2^2) = \frac{1}{2} \rho A_{rotor} V_1^2 4a(1 - a) \]  \(6.1\)

Similarly to the power coefficient, a rotor thrust coefficient can be defined as

\[ C_T = \frac{C_{T,thrust}}{\frac{1}{2} \rho A_{rotor} V_1^2} = 4a(1 - a). \]  \(6.2\)

Typically when designing structures one is interested in the maximum possible value of \(C_T\).

To find the maximum value

\[ \frac{dC_T}{da} = -8a - 4 = 0. \]  \(6.3\)

Solving leads to \(a = \frac{1}{2}\). Therefore

\[ C_{T,\text{max}} = 4 \left( \frac{1}{2} \right) \left( 1 - \frac{1}{2} \right) = 1 \]  \(6.4\)

In practice this value can be slightly higher due to viscous affects and induction of wake rotation, which the theory neglects. Numerical modeling as well as physical testing of hydrokinetic cross flow turbines has shown maximum coefficients of turbine thrust (drag) to be approximately not more than 1.2 [12] [56] [26]. The equation to calculate the drag force is
\[ D = C_T \frac{1}{2} A \rho V^2 \]  

(6.5)

Table 6.3: Drag load calculations

<table>
<thead>
<tr>
<th>Current on Turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Diameter</td>
</tr>
<tr>
<td>9.84</td>
</tr>
<tr>
<td>Turbine Length</td>
</tr>
<tr>
<td>9.84</td>
</tr>
<tr>
<td>Turbine Area</td>
</tr>
<tr>
<td>96.9</td>
</tr>
<tr>
<td>Turbine CD</td>
</tr>
<tr>
<td>1.2</td>
</tr>
<tr>
<td>Turbine Drag</td>
</tr>
<tr>
<td>5230</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current on Pontoons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pontoon Diameter</td>
</tr>
<tr>
<td>3.5</td>
</tr>
<tr>
<td>Pontoon Length</td>
</tr>
<tr>
<td>49</td>
</tr>
<tr>
<td>Pontoon Frontal Area</td>
</tr>
<tr>
<td>9.62</td>
</tr>
<tr>
<td>Platform Pontoon CD</td>
</tr>
<tr>
<td>0.82</td>
</tr>
<tr>
<td>Number of Pontoons</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>Pontoon Drag</td>
</tr>
<tr>
<td>710</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current on Guide Posts</th>
</tr>
</thead>
<tbody>
<tr>
<td>VGP Diameter</td>
</tr>
<tr>
<td>1.3</td>
</tr>
<tr>
<td>VGP Length</td>
</tr>
<tr>
<td>21</td>
</tr>
<tr>
<td>VGP Area</td>
</tr>
<tr>
<td>49.5</td>
</tr>
<tr>
<td>VGP CD</td>
</tr>
<tr>
<td>1.17</td>
</tr>
<tr>
<td>VGP Drag</td>
</tr>
<tr>
<td>2230</td>
</tr>
<tr>
<td>Load Due to Current Drag</td>
</tr>
<tr>
<td>8200</td>
</tr>
</tbody>
</table>

where the \( D \) is the drag force, \( \rho \) is the density of sea water (approximately 1025 kg/m²), \( V \) is the tidal current velocity, and \( A \) is the rotor swept area. A turbine thrust force of 23.3 kN (5.2 kip) is calculated for the tidal current drag on the turbine. The drag forces on the pontoons and VGPs were also calculated using this same method with their respective \( C'_T \)s. In these calculations, the UNH research team conservatively assumed that these components were fully submerged. For the
determination of current drag on the pontoons, the pontoons were considered as fully submerged unstreamlined cylinders with their flat face facing into the flow. The coefficient of drag for a cylinder with an $L/D$ ratio equal to 14, a Reynolds number based on a diameter of 42 in ($1.06 \text{ m}$) of 1,500,000 and its flat face pointed into the flow was determined to be 0.82 [3], and the coefficient of drag for a cylinder with its length perpendicular to the flow and a Reynolds number of 600,000 was determined to be 1.17 [63]. These calculations are detailed in Table 6.3.

Based on these calculations, the total load due to current drag used for design was 36 $kN$ (8.2 kip). This force was applied parallel to the pier face in the direction of the currents. The drag load duration is limited each day, drag loading is directly proportional to the current speed squared, and is reversing with a significantly lower magnitude on the flood tide current.

### 6.1.3 Stability

<table>
<thead>
<tr>
<th>3MX3M TURBINE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PONTOON LENGTH[FT]</td>
<td>BOW DOWN[DEG.]</td>
</tr>
<tr>
<td>40</td>
<td>1.5</td>
</tr>
<tr>
<td>42</td>
<td>1.3</td>
</tr>
<tr>
<td>49</td>
<td>0.9</td>
</tr>
<tr>
<td>50</td>
<td>0.5</td>
</tr>
</tbody>
</table>

An calculation was performed to determine the bow-down (pitching) angle due to the moment caused by the drag force of the turbine and an uneven mass distribution on the deck of the TDP. The uneven mass distribution accounts for the weight of personnel on the platform, tools, and instrumentation all placed at the far edge of the platform to act with the moment created by the drag on the turbine. Figure 6.1 illustrates this loading.

To determine the pitching or "bow down" angle the TDP would operate at under tidal current forcing one must understand the relationship between the pitching moment created by the drag
force on the tidal turbine, and the righting moment created by the uneven distribution of buoyancy shown in the following equation

\[
\theta = \frac{M}{g_mW} \tag{6.6}
\]

where \( \theta \) is the pitching or "bow down" angle, \( M \) is the pitching moment, \( W \) is the weight of the structure, and \( g_m \) is the metacentric height. The metacentric height is the distance between the center of gravity of the structure (also known as the center of mass) and the metacenter (a point that occurs in a location where a line draw between the undisturbed center of gravity and center of buoyancy intersects a line drawn through the disturbed center of gravity and center of buoyancy).

The following equation can be used to analytically determine the metacentric height

\[
g_m = \frac{I}{V} - \overline{bg} \tag{6.7}
\]

where \( I \) is the moment of inertia of the structure, \( V \) is the displaced volume of the structure, and \( \overline{bg} \) is the distance between the center of buoyancy and the center of gravity. One should note that in scenario’s when \( b \) is above \( g \) the distance from the center of buoyancy to the center of gravity is added to the equation rather than subtracted.

With pontoons longer than 42 ft (12.8 m) the TDP will not pitch more than 1.3 degrees which is equivalent to a 5.7 in (0.15 m) elevation change over the length of the 42 ft (12.8 m) pontoons. This movement is acceptable for the stability of this platform. Note that in this calculation a shorter pontoon length (42 ft) was used to compensate for the loss in volume due to streamlining the ends. The bow down angle is related to drag load and its duration is limited each day.

6.1.4 Wave Loading on Turbine

To determine wave loading on the turbine, empirical wave estimations of the significant wave height (\( H_{\frac{3}{2}} \)) were performed. The selected design wave considered operational weather conditions and was based on a steady wind speed of 17.9 m/s (40 mph, 34.8 kt), equivalent to a fastest mile wind gust of 21 m/s (47 mph, 40.8 kt) over the longest fetch. Using the Hasselman method
modified for wind wave generation in shallow and transitional water [83] the significant wave height at the bridge location is 0.46 m (1.5 ft) and the significant wave period \( T_{\frac{1}{3}} \) at the Memorial Bridge location is 1.9 s. The largest 1% of waves \( (H_1) \) were used as a design wave.

\[
H_1 = 1.67H_{\frac{1}{3}} = 0.76m(2.5')
\]  

(6.8)

The wave length was calculated to be 5.64 m (18.5 ft) using

\[
L = \frac{gT_{\frac{1}{3}}^2}{2\pi}.
\]  

(6.9)

This design wave exceeds expectations set forth in a marine structures design guide [23] where it is suggested to use a 2 ft wave as a design wave for small craft harbors. There are numerous small craft harbors surrounding the Memorial Bridge site, and beneath the Memorial Bridge is a "headway speed" zone.

The wave loading on the turbine was performed as per Gaythwaite’s second edition of Design of Marine Facilities [39] and by simplifying the turbine rotor as a solid cylinder. When the ratio between a structure’s diameter and the wave lengths it is immersed in exceeds 0.2, diffraction forces due to the scattering of the incident wave by the structure are the dominant forces. These forces can be calculated using

\[
F = \frac{\pi}{8}\rho HD^2 \tanh\left(\frac{2\pi d}{L} C_m \cos(\omega t - \theta)\right)
\]  

(6.10)

where \( F \) is the force exerted by the waves on the turbine, \( \rho \) is the density (or "unit weight") of the fluid \( (\rho_{\text{seawater}} \approx 1025 \text{ kg/m}^3 \text{ (64 lb/ft}^3) \), \( H \) is the height of the design wave, \( D \) is the swept diameter of the turbine rotor, \( d \) is the water depth (18.28 m (60 ft)) at the Memorial Bridge location), \( C_m \) is the inertial coefficient (typically between 1.3 and 2, a conservative value of 2 was selected), \( \omega \) is the wave angular frequency, \( t \) is time, and \( \theta \) is the wave phase angle. Since the force is oscillatory the \( \cos(\omega t - \theta) \) term is set to its maximum value of 1 and the rest of the equation is evaluated to get a wave force of 53.4 kN (12.0 kip) on the turbine. This force value is considered conservative as it uses the full swept area projection of a running turbine and an infrequent 1%
design wave. The wave force is expected to be significantly lower when the turbine is not running as the rotor’s $C_T$ is much lower when it is not operating.

### 6.1.5 Wave Loading on Platform

To determine the wave loading from the TDP onto the VGPs mooring structure the Coastal Structures Handbook Series Docks, Piers and Wharves: A Design Guide [23] suggests a method that relies on experimentally determined added mass coefficients and Froude-Kriloff theory for determining the wave loading of a structure on its mooring [19]. The forces a floating structure will impart on its mooring that depend upon the dimensions of the floating structure, the floating structure’s displacement, a design wave height, and a design wave length. The method requires the designer to first determine the wave force per displacement of the structure using the characteristics of the design wave using Figure 6.2.

After determining the wave force per displacement the designer must determine a body length adjustment factor. This body length adjustment factor accounts for the fact that the force that the TDP imparts upon the mooring structure will vary as the ratio between wave lengths and structure length varies, as shown in Figure 6.3.

After determining the proper wave force per displacement and body length adjustment factor the wave load can be determined using the following equation

$$F = D \times W \times B$$

(6.11)

Where $F$ is the wave force imparted on the guide post mooring structure in lb, $D$ is the displacement of the TDP in $ft^3$, $W$ is the wave force per displacement found from Figure 6.2 in $lb/ft^3$ and $B$ is the body length adjustment factor found from Figure 6.3.

Upon examination of Figures 6.2 and 6.3, one can see that these two figures have counteracting behaviors. As wavelength decreases in Figure 6.2 the force on the mooring structure will increase while in Figure 6.3 the force on the mooring structure will decrease as relative body length goes below 0.5. Due to the uncertainty in expected wavelengths an iterative approach was taken where
Figure 6.2: Horizontal Wave Force on a Floating Object. Figure reproduced from [19], plotted with results from [23].
Figure 6.3: Wave force adjustment for relative body length. Figure reproduced [19], plotted with results from [23].

Figure 6.4: Wave forces for a range of wave lengths.
a range of wavelengths were analyzed using these charts. This process was repeated for waves progressing parallel to the pier where a body length of 49 ft (14.9 m) was used and for waves progressing perpendicular to the pier where a body length of 5.5 m (18 ft) was used. The highest force and the wave length that it would occur at were calculated. For the parallel to the pier case a highest load of 17 kN (3.5 kip) will occur when a 23.2 m (76.2 ft) wave impacts the TDP. For the perpendicular to the pier case a highest load of 37 kN (7.8 kip) will occur when an 8.9 m (29 ft) wave impacts the TDP. It should be noted that the perpendicular wave loading case cannot occur from wind-drive waves due to insufficient fetch, however, waves can be generated by passing boats which is the case considered here. The Coastal Structures Handbook Series Docks, Piers and Wharves: A Design Guide [23] suggested that when wave loads are analyzed in two directions 90 degrees opposed from each other this is sufficient to design for waves progressing in all other directions. Thus the VGP mooring structure was analyzed in two different configurations, (1) a parallel load case with the 53 kN (12 kip) wave load from the turbine added to the 13 kN (3.0 kip) wave force from the TDP when waves progress parallel to the pier and (2) a perpendicular load case with the 53 kN (12 kip) wave load from the turbine added to the 28 kN (6.2 kip) wave force from the TDP when waves progress perpendicular to the pier. The TDP’s frame was analyzed to resist wave loading. Depending on the direction of a group of waves propagation with respect to the TDP the waves may cause the TDP’s pontoons to "rack" in opposing directions from each other. Racking is where waves force one pontoon to pitch forward while the opposing pontoon simultaneously pitches backwards. This racking phenomenon is three dimensional and difficult to analyze using first principles thus Det Norske Veritas - Germanischer Lloyd’s (DNV GL) standards [28] and [29] were used to prescribe loads on the frame. FEA simulations were performed to assess the feasibility of a platform frame design. The FEA study showed that a frame could be designed to meet the project specifications and its results are included in this report.
6.1.6 Wind Loading on Above Water Structure

To calculate wind loading a 20 m/s (45 mph, 40 kt) wind was used based on operational expectations. In order to control potential TDP damage, it was decided that the TDP will be moved to a more sheltered location in the event of a storm with greater than 20 m/s wind conditions. Regular drills should be performed to ensure that this can be performed in a timely manner with transient graduate student management of the TDP. A coefficient of drag of 1 was used for the above sea-surface area of the TDP. Its area was roughly calculated to be 1.5 m x 5.5 m (5 ft x 18 ft) or 8.4 m$^2$ (90 ft$^2$). Using Equation 6.5 a drag force due to wind was calculated to be 2.3 kN (0.5 kip). This calculation should be revised if additional structures are added on the TDP.

6.1.7 Turbine Torque Loading

When the turbine operates it will impart a torque onto the platform at its mounting location. This torque, $T$ is a function of the amount of power, $P$ that the turbine is producing and the rotational speed the turbine is rotating at, $\omega$.

$$T = P\omega \quad (6.12)$$

It was previously shown the amount of available power a turbine can convert from a flow is determined using the following equation

$$P = \frac{1}{2} \rho A V^3 \quad (6.13)$$

Using this equation for seawater with a density of 1025 kg/m$^3$ (64 lb/ft$^3$), a coefficient of power of 0.42 [56] a turbine with a front facing area of 9 m$^2$ (96 ft$^2$), and current velocity of 2.05 m/s (6.73 ft/s) one can determine the maximum power available in the flow is 39 kW (53.3 hp). The angular velocity that the turbine will operate at from tip speed ratio, $\lambda$ at maximum $C_p$, which is around 2.25 [12] can be calculated using
\[ \omega = \frac{\lambda V}{R} \]  

(6.14)

Where \( R = \frac{D}{2} \) is the rotor radius. For a 3 \( m \) (9.8 \( ft \)) rotor diameter an angular velocity of 3.075 \( rad/s \) is determined. This means that turbine will rotate at 29.4 revolutions per minute. Using Equation 6.12, a turbine torque of 5.4 \( kNm \) (4000 \( ft-lb \)) can be calculated for a 3 \( m \) x 3 \( m \) turbine producing 17 \( kW \) (22 \( hp \)).

### 6.1.8 Load Summary

Table 6.4 displays all of the load categories with magnitude and direction used in the design of the TDP.

### 6.1.9 Additional Loadings

The loadings analyzed in this report represent the expected loads during normal TDP operation. Scenarios do exist where loadings will be different. For example when a work boat is moored to the TDP. Loads may also slightly increase with the addition of biofouling to the structure. Therefore, the mooring structure will be instrumented with strain gauges to ensure that the capacity of the anchorage will not be exceeded. Before operating in any condition not covered in the initial design, the structural response of the mooring structure will be monitored and analyzed to determine allowable operating conditions and to aid in the refinement of a maintenance plan.

### 6.2 Pontoon Racking FEA Study

The TDP will use two pontoons for buoyancy, as shown in Figure 6.5, to float at the water’s surface while submerging the turbine’s rotor below its deck into the currents.

Racking is a phenomenon which can occur on twin hulled (pontooned) structures in waves. When racking occurs waves impinge on the pontoon structure with a heading between 45 and 60 degrees with respect to the length of the pontoons and a wave length of approximately the diagonal distance between the pontoon ends. This causes a situation where the bow end of the starboard pontoon to pitch up while the bow end of the port pontoon pitches down and the opposite
### Table 6.4: Loading assumptions and calculations

<table>
<thead>
<tr>
<th>Component</th>
<th>p</th>
<th>q</th>
<th>x</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mooring Loads</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Velocity</td>
<td>6.73</td>
<td>ft/s</td>
<td>0.06</td>
<td>m/s</td>
</tr>
<tr>
<td>Wind Velocity</td>
<td>6.73</td>
<td>ft/s</td>
<td>2.13</td>
<td>m/s</td>
</tr>
<tr>
<td>Hs</td>
<td>0</td>
<td>ft</td>
<td>0.46</td>
<td>m</td>
</tr>
<tr>
<td>Turbine Diameter</td>
<td>9.44</td>
<td>ft</td>
<td>1.2</td>
<td>m</td>
</tr>
<tr>
<td>Turbine Length</td>
<td>9.44</td>
<td>ft</td>
<td>0.3</td>
<td>m</td>
</tr>
<tr>
<td>Turbine Area</td>
<td>96.88</td>
<td>ft</td>
<td>0.3</td>
<td>m²</td>
</tr>
<tr>
<td>Turbine CD</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Turbine Drag</strong></td>
<td>5229</td>
<td>lb</td>
<td>23261</td>
<td>N</td>
</tr>
<tr>
<td>Pontoon Diameter</td>
<td>1</td>
<td>1</td>
<td>0.6</td>
<td>m</td>
</tr>
<tr>
<td>Pontoon Length</td>
<td>1</td>
<td>1</td>
<td>0.3</td>
<td>m</td>
</tr>
<tr>
<td>Pontoon Frontal Area</td>
<td>0.02</td>
<td>ft</td>
<td>0.06</td>
<td>m²</td>
</tr>
<tr>
<td>Platform Pontoon CD</td>
<td>0.82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Pontos</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pontoon Drag</strong></td>
<td>719</td>
<td>lb</td>
<td>3157</td>
<td>N</td>
</tr>
<tr>
<td>VGP Diameter</td>
<td>1</td>
<td>1</td>
<td>0.46</td>
<td>m</td>
</tr>
<tr>
<td>VGP Length</td>
<td>1</td>
<td>1</td>
<td>0.6</td>
<td>m</td>
</tr>
<tr>
<td>VGP Area</td>
<td>49.48</td>
<td>ft</td>
<td>0.6</td>
<td>m²</td>
</tr>
<tr>
<td>VGP CD</td>
<td>1</td>
<td>1</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td><strong>VGP Drag</strong></td>
<td>2226</td>
<td>lb</td>
<td>9901</td>
<td>N</td>
</tr>
<tr>
<td>Above water width</td>
<td>18</td>
<td>ft</td>
<td>5.49</td>
<td>m</td>
</tr>
<tr>
<td>Above water height</td>
<td>5</td>
<td>ft</td>
<td>1.52</td>
<td>m</td>
</tr>
<tr>
<td>Above Water Area</td>
<td>90</td>
<td>ft</td>
<td>8.36</td>
<td>m²</td>
</tr>
<tr>
<td>Above Water CD</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wind Drag</strong></td>
<td>509</td>
<td>lb</td>
<td>2265</td>
<td>N</td>
</tr>
<tr>
<td>H1</td>
<td>1</td>
<td>1</td>
<td>0.76</td>
<td>m</td>
</tr>
<tr>
<td>Ts</td>
<td>1.55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>18.5</td>
<td>ft</td>
<td>5.64</td>
<td>m</td>
</tr>
<tr>
<td>Turbine Diameter</td>
<td>9.44</td>
<td>ft</td>
<td>1.2</td>
<td>m</td>
</tr>
<tr>
<td>Turbine Height</td>
<td>9.44</td>
<td>ft</td>
<td>0.3</td>
<td>m</td>
</tr>
<tr>
<td>Inertial Coefficient</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth</td>
<td>60</td>
<td>ft</td>
<td>18.29</td>
<td>m</td>
</tr>
<tr>
<td><strong>Wave Load on Turbine</strong></td>
<td>12179</td>
<td>lb</td>
<td>54269</td>
<td>N</td>
</tr>
<tr>
<td>Wave Load on Platform (Parallel to Pier Face)</td>
<td>1</td>
<td>1</td>
<td>0.76</td>
<td>m</td>
</tr>
<tr>
<td>Wave Height</td>
<td>2.51</td>
<td>ft</td>
<td>0.76</td>
<td>m</td>
</tr>
<tr>
<td>Wave Length</td>
<td>76.2</td>
<td>ft</td>
<td>23.2</td>
<td>m</td>
</tr>
<tr>
<td>Draft</td>
<td>6</td>
<td>ft</td>
<td>0.86</td>
<td>m</td>
</tr>
<tr>
<td>( F_w ) from Chart</td>
<td>8.06</td>
<td>lb/ft</td>
<td>142</td>
<td>kg/m</td>
</tr>
<tr>
<td>Platform Mass</td>
<td>23.61</td>
<td>lb</td>
<td>12864</td>
<td>kg</td>
</tr>
<tr>
<td>Displacement</td>
<td>443</td>
<td>ft³</td>
<td>12.6</td>
<td>m³</td>
</tr>
<tr>
<td>BodyLength</td>
<td>49</td>
<td>ft</td>
<td>14.9</td>
<td>m</td>
</tr>
<tr>
<td>RelativeBodyLength</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BodyLengthAdjFactor</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WaveForceParallel</strong></td>
<td>35.38</td>
<td>lb</td>
<td>15726</td>
<td>N</td>
</tr>
<tr>
<td>Wave Load on Platform (Perpendicular to Pier Face)</td>
<td>1</td>
<td>1</td>
<td>0.76</td>
<td>m</td>
</tr>
<tr>
<td>Wave Height</td>
<td>2.51</td>
<td>ft</td>
<td>0.76</td>
<td>m</td>
</tr>
<tr>
<td>Wave Length</td>
<td>29</td>
<td>ft</td>
<td>8.84</td>
<td>m</td>
</tr>
<tr>
<td>Draft</td>
<td>12</td>
<td>ft</td>
<td>0.48</td>
<td>m</td>
</tr>
<tr>
<td>( F_w ) from Chart</td>
<td>17.1</td>
<td>lb/ft</td>
<td>30.57</td>
<td>kg/m</td>
</tr>
<tr>
<td>Platform Mass</td>
<td>227.29</td>
<td>lb</td>
<td>10390</td>
<td>kg</td>
</tr>
<tr>
<td>Displacement</td>
<td>443</td>
<td>ft³</td>
<td>12.6</td>
<td>m³</td>
</tr>
<tr>
<td>BodyLength</td>
<td>18</td>
<td>ft</td>
<td>5.49</td>
<td>m</td>
</tr>
<tr>
<td>RelativeBodyLength</td>
<td>0.62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BodyLengthAdjFactor</td>
<td>0.92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WaveForcePerpendicular</strong></td>
<td>77.52</td>
<td>lb</td>
<td>34492</td>
<td>N</td>
</tr>
<tr>
<td>Turbine Torque</td>
<td>1</td>
<td>1</td>
<td>1.2</td>
<td>x</td>
</tr>
<tr>
<td>Power available</td>
<td>53.28</td>
<td>hp</td>
<td>39737</td>
<td>w</td>
</tr>
<tr>
<td>C_p</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torque on Turbine, ( P )</td>
<td>22.35</td>
<td>hp</td>
<td>16698.7</td>
<td>w</td>
</tr>
<tr>
<td>TSR at ( c_{p,max} )</td>
<td>2.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \omega )</td>
<td>3.08</td>
<td>rad/s</td>
<td>3.08</td>
<td>rad/s</td>
</tr>
<tr>
<td>RPM</td>
<td>28.35</td>
<td>RPM</td>
<td>28.35</td>
<td>RPM</td>
</tr>
<tr>
<td><strong>Torque = ( P )*( \omega )</strong></td>
<td>4803</td>
<td>lb-ft</td>
<td>5,428</td>
<td>Nm</td>
</tr>
</tbody>
</table>
occurs at the stern ends of the pontoons. This phenomenon torques the frame of the structure that holds the pontoons together. Due to its three dimensional nature as shown in Figure 6.6, it is difficult to accurately calculate the loads exerted on the frame when racking occurs with simple hand calculations derived from first principles.

Marine classifications societies have realized that racking is often of concern and its effects are difficult to calculate when designing twin hulled structures and have created standards to determine design loads. DNV GL, the world’s largest international certification body and classification society specializes in technical assessment, advisory, and risk management of maritime vessels, oil and gas, and marine renewable energy structures.
DNV GL specifies three loads that apply to racking, vertical bending moment and shear force $M_s$, pitch connecting moment $M_p$, and twin hull torsional moment $M_t$ [28] and [29]. The calculations to determine these design loads are empirically derived from results of experimental tests. After calculating the loads FEA and structural analysis studies were performed in Solidworks FEA Simulation and SAP2000 to determine the stresses and moments the platform frame would experience from waves at the deployment location. The SAP2000 simulations were performed by Maryam Mashayekhizadeh and Tim Nash. Solidworks simulations produced similar results. The results of these calculations as well as the SAP studies are presented here. The structure was designed based off the results of the SAP simulations.

6.2.1 Pontoon Racking Analysis

6.2.1.1 Structure Classification

Before calculating the expected loading of the structure the structure must first be classified according to standards set forth by DNV GL. To do this DNV GL uses what is called a service area restriction notation where the maximum distance the vessel is expected to go from the nearest harbor or safe anchorage are given in DNV GL’s Rules for Classification of High Speed, Light Craft and Naval Surface Craft Part 1 Chapter 1: General Regulations Table B1 on page 12, shown here in Figure 6.7.

The term nearest harbor or safe anchorage is not precise as technically this structure will always operate within an area that many ships would consider to be a harbor. Agreements have been made with the NH Port Authority (on a flood tide) and The NH commercial fishing pier (on an ebb tide).
that in the event of an emergency the platform will be allowed to moor at one of these locations. Under normal conditions the platform will be brought to the UNH Pier. The UNH pier will also serve as the location where the structure will be serviced. The New Hampshire Port Authority is less than 0.6 nautical miles upstream the Piscataqua from the deployment location at the Memorial Bridge. The NH commercial fishing pier is less than 0.25 nautical miles from the Memorial Bridge Deployment site. The UNH Pier is less than 2 nautical miles from the deployment location at the Memorial Bridge, and shown in Figure 6.8. The platform will be operated all four seasons of the year yielding a classification of Inland (R5) as the maximum distance to safe anchorage is less than 1 nautical mile from its deployment location. It should also be noted that there are similar structures that are moored only a few hundred feet from the deployment location year round, but the structure will not be moored there due to logistical restrictions.

Figure 6.8: Map of the Lower Piscataqua River with the distance to the UNH Pier marked.

In DNV GL’s Rules for Classification of High Speed, Light Craft and Naval Surface Craft Part 3 Chapter 1: Design Principles, Design Loads [29] DNV GL specifies that an acceleration coefficient at the craft’s center of gravity \( a_{cg} \) must be calculated. To calculate \( a_{cg} \) one must know the velocity of the craft. During most of the craft’s operation it will be stationary and have a 0
During transportation, the craft will be towed and the maximum towing velocity is unknown. The maximum current velocity 2.05 m/s (3.98 kt) was used as an estimate for the craft's maximum velocity. This yields a $\frac{V}{\sqrt{L}}$ ratio of 0.529 where $V$ is the craft’s speed in knots and $L$ is the craft’s length in m 15 m (49 ft). According to section B 205 of DNV GL’s Rules for Classification of High Speed, Light Craft and Naval Surface Craft Part 3 Chapter 1 when $\frac{V}{\sqrt{L}} < 3$

$$a_c g = 6 \frac{H_S}{L} \left(0.85 + 0.35 \frac{V}{\sqrt{L}} \right) g_0 \left(\frac{m}{s^2}\right)$$

(6.15)

where $H_S$ is the significant wave height in m (0.76 m). This yields an $a_c g = 4.02 m/s^2$. DNV GL specifies a minimum $a_c g = 0.5 * g_0$ for service restrictions R5-R6. Therefore

$$a_c g = 4.91 \frac{m}{s^2}$$

(6.16)

### 6.2.1.2 $M_S$ Load Case

Load Calculation as per DNV GL:

![Figure 6.9: Loading for $M_S$ as per DNV GL.](image)

$$M_S = \frac{\delta a_c g b}{s} (kN m)$$

(6.17)

where $\delta$ is the fully loaded displacement in metric tons in salt water (density 1.025 $t/m^3$)($\delta = 13t$), $b$ is the transverse distance between the center-lines of the two hulls ($b = 4.47 m$), and $s$ is a
factor specified by DNV GL to be 8 for service restrictions R4-R6. This yields a value of 35.67 kN\(\cdot\)m (20.3 kip\(\cdot\)ft). For the purpose of running an FEA simulation this moment was converted into a force by dividing it by the width of the framing structure (5.49 m) to get a force of 6.49 kN (1459 lb). To perform the SAP2000 structural analysis of the Ms load scenario, the joints on one side of the frame were fixed (green squares) while the 6.49 kN (1.459 kip) load was applied along the outermost beam of the frame (black arrows), as shown in Figure 6.9. Maximum moments, shown in the red fill diagram, at the support are equal to 35.0 N\(\cdot\)m (25.8 kip\(\cdot\)ft), as shown in Figure 6.9. Maximum shear and stress were found to be 7.56 kN (1.70 kips) and 278.7 MPa (10.42 ksi) respectively.

![Figure 6.9: Ms Loading condition and moment diagram from SAP2000.](image)

6.2.1.3 \(M_P\) Load Case

Load Calculation as per DNV GL:

\[
M_P = \frac{\delta a_{cg} L}{8}(\text{kN}m)
\]

\(M_P\) was calculated to be 97.1 kN\(m\). To simulate this load, structural analysis in SAP2000 was performed where the joints on one side beam were fixed (green squares) and a force couple was applied to the opposing beam (black arrows). The magnitude of the forces used to create this
couple were calculated to be 7.96kN (1.789 kips) by dividing the Mp torque by the length of the frame equal to 12.2 m (40 ft) as shown in Figure 6.11. Maximum moments, shown by the red and blue fill diagram above, were found to be 39.3 N − M (29.0 kip − ft), as shown in Figure 6.11. Max shear and stress were calculated as 6.9 kN (1.56 kips) and 63.8 MPa (9.25 ksi) respectively.

6.2.1.4 $M_T$ Load Case

Load Calculation as per DNV GL:

$$M_t = \frac{\delta a_c b}{4} (kN m)$$  \hspace{1cm} (6.19)
Figure 6.13: Loading for $M_T$ as per DNV GL.

$M_T$ was calculated to be 71.18 kNm. To simulate this load a SAP2000 analysis was performed where the joints on one end beam were fixed (green squares) and a force couple was applied to the opposing beam (black arrows). The magnitude of the forces used to create this couple were calculated to be 12.97 kN (2.916 kips) by dividing the $M_T$ torque by the width of the frame equal to 5.49 m, as shown in Figure 6.13. The maximum moment, shown above, was found to be 66.0 kNm (48.7 kip − ft), as shown in Figure 6.13. The max shear and stress respectively were equal to 9.39 kN (2.11 kips) and 123.5 MPa (17.91 ksi).

Figure 6.14: $M_T$ Loading condition and moment diagram from SAP2000.
6.3 Design Considerations

6.3.1 Guide Post Elevation Determination

The two vertical guide posts (VGPs) were designed to serve as mooring points to attach the TDP to the bridge pier. Drawings provided by HNTB Corporation, see Figure 6.15, for the design of the reconstructed bridge were used to determine water levels in reference to the bridge.

Figure 6.15: Excerpt from HNTB "PIER 2 - RETROFIT PLAN AND ELEVATIONS."
The Living Bridge design team determined that the TDP must be able to rise to at least the 100 year flood elevation at EL 9.00 ft plus 2.5 ft (0.76 m) for platform free board allowances. The 100 year flood elevation is determined by the Federal Emergency Management Agency (FEMA) and includes the combined influence of still water flood elevations, and wave effects. This provision puts the top of the travel-able section of the VGPs at a minimum elevation of EL. 11.50 ft. The 100 year flood elevation corresponds with FEMA’s Base Flood Elevation [35] which includes waves at high water, thus no additional wave action was included at the top. Note that these elevations are with reference to the surface elevation datum NGVD29. The TDP must be able to recede down to the lowest water level it will experience. NOAA publishes 1% tidal high and low water exceedances. These exceedances are shown in Figure 6.16 for the nearby Seavey Island, ME [61].

The research team found no published figure for low water elevation that includes wave action. To determine the lowest level that the TDP must be able to travel on the guide posts NOAA’s 1% low water exceedance level was used. This water level does not include wave action. Throughout this report, a 2.5 ft (0.76 m) wave height has been used as the design wave. Thus a 1.25 ft (0.38 m) elevation, corresponding to the wave amplitude, decrease is possible from a wave. A 2.5 ft (0.76 m) wave height is conservative because after converting from NA VD88 to NGVD29 one can determine that the difference between NOAA’s 1% high tide exceedance (the no wave number high water elevation) and FEMA’s Base Flood Elevation (the high water waves included number) is 0.13 ft (0.04 m). This means that at the highest high water there is typically only 0.13 ft (0.04 m) of wave action. However, the platform will have 2.5 ft (0.76 m) of free board where the mooring connection will be made. Thus the bottom of the VGPs should be placed at the level of the 1% low water exceedance plus the difference between the free board height and the wave height. When a conversion is made from NAVD88 to NGVD29 this puts the bottom of the VGPs at the minimum elevation of EL -5.78 ft.
6.3.2 Pile Guide Design

The TDP was designed to be moored to the VGPs using chain type marine pile guides. This design is often used for docks moored to piles and commercial pile guides of this type are available such as Merco Marine’s Chain Pile Guide, shown in Figure 6.18.

These pile guides allow the TDP to rise and fall along the VGPs with the changing water elevations due to tides. The chain type design was selected over a solid hoop type pile guide to allow for quicker connection and disconnection to the VGPs. Additionally, any slack in the chain type pile guides will allow for a decrease in the required travel length on the vertical guide posts.

Figure 6.16: NOAA high and low water exceedances in meters with reference to NAVD88. These water levels do not include wave action [61].
These pile guides will create a connection that was assumed to load one VGP in shear with 100% of the load.

A commercially available chain type pile guide with a specified load rating could not be found. Custom designed pile guides were made using load rated parts. This pile guide is shown in Figure 6.19.

A significant amount of time was spent deciding if in the event of an unexpected load being applied to the TDP should the TDP break free from the VGPs with a weak link or should the TDP attempt to remain attached to the VGPs. It was decided that a weak link that would release the platform in an unexpected event was a bad idea as the platform could cause significant damage to property up and down the river if let loose. The idea of the platform never letting loose from the VGPs was also not favorable as ripping the VGP anchorage out of the bridge pier would cause
damage to the bridge pier which the NH-DOT (a project sponsor) is responsible for as well as cause damage to critical transportation infrastructure that travelers through Portsmouth and Kittery rely upon, especially with the closure of the Sara Mildred Long bridge for reconstruction during a portion of this project.

The pile guides were designed such that they would have a breaking strength that would be similar to the the VGP anchorage’s breaking strength.

The pile guides used \( \frac{7}{8} \) in Crosby hoist rings (HR-1000CT Stock No. 6608139) which have a working load limit (WLL) of 6200 lb and have been proof tested to 2 times this WLL so their breaking strength (BS) must be significantly greater than 12400 lb most likely somewhere around 24000lb. The hoist rings connect to \( \frac{5}{8} \) in Crosby shackles (G-2130 Stock No. 1019490) which have...
a WLL of $3 \frac{1}{4}$ tons (6500 lb) and a minimum design factor of 5 in accordance with ASME B30.26 [8] so they should have a minimum BS of 32500 lb. The shackles connect to a West Marine Grade 43 $\frac{1}{2}$ in chain (Model # 10616225) with a maximum working load (MWL) of 9200 lb and a BS 27600 lb. This chain wraps around the VGPs and is covered with small sections of PVC pipe to allow it to smoothly roll up and down the VGPS. The hoist rings thread into a 1 in thick steel plate that is welded to the TDP frame. The threads on this plate were first tapped, then the plate was welded to the frame and the frame was galvanized. After the frame was galvanized, the tapped holes where then re-tapped to remove the galvanizing material from the threads. A nickle based
marine grade anti seize was applied inside the holes to prevent the hoist rings from seizing to the frame. The hoist rings were installed with a torque wrench to the specified torque.

Note: these pile guides were not a successful design and more information regarding their redesign is included in the employment chapter.

6.3.3 Vertical Guide Post Vortex Induced Vibrations

Flow induced vibrations (or vortex induced vibrations(VIV)) are caused by oscillating vortices shedding off bodies in cross flow. The VGPs are one such scenario where VIV could potentially occur. When designing to avoid VIV one should avoid a scenario where the natural frequency of one’s structure is close to the vortex shedding frequency. The period at which vortices shed from a cylinder can be determined by the non-dimensional Strouhal number \(S_n\) given by

\[
S_n = \frac{f_{vs} D}{V}
\]  

(6.20)

where \(f_{vs}\) is the vortex shedding frequency, \(D\) is the diameter of the cylinder, and \(V\) is the velocity of the flow. For a 0.41 m (16 in) cylinder in sea water with a kinematic viscosity of \(1.38 \times 10^{-6} \text{ m}^2/\text{s}\) \((1.48 \times 10^{-5} \text{ ft}^2/\text{s})\) and in currents of 2.05 m/s \((4.59 \text{ mph})\) its Reynolds number is 611000.

Achenbach and Heinecke defined smooth cylinders to have a \(k/d\) of less than \(10^{-5}\) where \(k\) is the height of the surface roughness and \(d\) is the diameter of the cylinder. Their roughest cylinders had a \(k/d\) of \(300 \times 10^{-4}\). Steel commercial pipe has a \(k\) of 0.000045m. This gives a \(k/d\) of \(1.09 \times 10^{-4}\). Although the guide posts are not as smooth as Achenbach and Heinecke’s they cannot be considered rough in their installed condition. As the vertical guide posts wear and foul their roughness is expected to increase lowering their Strouhal number and vortex shedding frequency. As a worst case scenario smooth surfaced cylinders are considered for the Reynolds number calculated where the Strouhal number is 0.38. Using Equation 1 the vortex shedding frequency can be calculated to be 1.9 Hz. This is the frequency at which a vortex will shed off one side of the cylinder and create forces in the cross flow direction. A force will be created at twice that frequency \((3.8 \text{ Hz})\) in
the parallel to flow direction. A modal analysis was performed in SAP. In this analysis the lowest natural frequency of the vertical guide post structure with the turbine deployment platform frame linked to it was calculated. This calculation was performed with a lumped mass of 4600 lb for the tidal turbine placed at the center of the turbine deployment platform frame. The simulation was run with the turbine deployment platform at 1/3 and 2/3 of the total travelable length from the bottom of the guide posts. Placing the turbine deployment platform lower on the vertical guide posts resulted in a lower natural frequency. The stiffness of the chain type pile guide connection between the turbine deployment platform and the vertical guideposts is difficult to estimate. A range of stiffnesses were simulated for this connection from 1 in/lbf to $1 \times 10^{11}$ in/lbf. The analysis showed that for a mooring stiffness of 1000 in/lbf the first mode of vibration occurred at 2.265
This analysis was purely a structural analysis and did not account for hydrodynamic effects such as added mass and viscous damping.

Figure 6.21: Natural frequency adjustment factors for partially submerged cylinders in crossflow. 

\( \frac{d}{H_s} \) is the ratio between the submerged depth of the cylinder to the total length of the cylinder. 

\( \frac{H_s}{D} \) is the ratio between the total length of the cylinder and the diameter of the cylinder. 

\( \frac{\omega_{wet}}{\wet_{dry}} \) is the ratio between the wet natural frequency of the submerged cylinder to the dry natural frequency of the cylinder. This chart was taken from Lozzo et al 2012 [50].

Figure 6.21 can be used to correct the SAP model natural frequencies to account for hydrodynamic affects such as added mass and viscous damping.

A cylinder in crossflow can be modeled analytically as a first order mass spring damper system.
To write the equations of motion for this system one can begin with Newton’s Second Law of Motion

\[ \sum F = m \cdot a \quad (6.21) \]

One can then substitute in the equations that show the amount of force the spring and damper put onto the mass

\[ -kx \pm b\dot{x} = m\ddot{x} \quad (6.22) \]

The mass of the system must include the true mass of the structure as well as the added mass of the system due to the dynamic motions in water. The damping of the system must include
the internal damping that exists in the structure itself as well as the viscous damping due to the structure being immersed in water.

\[-kx + -(b_{int} + b_v)\ddot{x} = (m + m_a)\ddot{x}\] (6.23)

Moving all terms to one side and separating displacement yields

\[\frac{m + m_a}{k}\ddot{x} + \frac{b_{int} + b_v}{k} \dot{x} + x = 0\] (6.24)

The standard form of a second order differential equation is

\[\frac{1}{\omega_n^2} \dddot{x} + \frac{2\zeta}{\omega_n} \ddot{x} + x = 0\] (6.25)

By comparing Equations 6.24 and 6.25 one can see that the natural frequency of the system is

\[\omega_n = \sqrt{\frac{k}{m + m_a}}\] (6.26)

and the damping ratio is

\[\zeta = \frac{b_{int} + b_v}{2\sqrt{k(m + m_a)}}\] (6.27)

The modes of vibration for the structure were determined using a system model similar to Equation 6.23 where added mass and viscous damping were not accounted for. The modal analysis did not account for added mass or viscous damping, but the equations governing the system can be used to qualitatively determine the effects of added mass and viscous damping. Added mass will decrease the natural frequency of the system. This is bad because the vortex shedding frequency was less than the modal frequencies. An increase in damping will increase the value of the damping ratio, although this is not important to the design goal of having the natural frequency far from the vortex shedding frequency. An increase in damping will decrease the amplitude of oscillations, therefore an added mass correction must be used. A casing could be placed on the vertical guide posts to increase their diameter. This will decrease the vortex shedding frequency.
slightly. Roughening the surface of the vertical guide posts will decrease the vortex shedding frequency significantly although it may cause issues with allowing the turbine deployment platform’s vertical travel on the vertical guide posts and with their ability to shed ice.

6.3.4 Frame Transportation, Corrosion, and Assembly

The steel frame was designed with transportation, corrosion protection, and assembly in mind. It was known that the frame would have to be transported on roads. The surface Transportation Assistance Act (STAA) of 1982 established the maximum allowable width for commercial trucks to be 102 inches.

Various forms of corrosion protection were considered. Both coal tar epoxy and galvanization were recommended as appropriate solutions by Duncan Mellor of Tighe and Bond. Galvanization was selected for its superiority over coal tar epoxy. This left the restriction that the frame had to be dipped into Duncan Galvanizing’s zinc bath which is 40 ft. by 5 ft. by 7 ft.

The requirement to fit on public roads without an over-sized load permit and fit into Duncan Galvanizing’s zinc bath necessitated the use of field connections. Field connections are a connection of a frame which are completed after the frame leaves the fabrication shop. Field connections can add significant cost to a structure as they require additional fabrication to ease assembly or additional work to be performed during assembly. Bolted connections were designed which enabled the frame to be broken into two main halves and three cross beam connectors. These bolted connections most likely added cost to the fabrication, though the number of connections was kept small by fabricating the large two main halves completely in the fabrication shop. The two main halves would fit on a flatbed truck and could be transported on public roads along with the cross beam connectors.

6.3.4.1 Pontoon/Frame Connection

The connection between the steel frame and HDPE pontoons was designed to accommodate several differences in material that exist between HDPE and steel. Variations in temperature will cause both steel and HDPE to expand and contract in a relationship that is given by
Figure 6.24: Frame connections used to enable transportation and galvanization.

\[
\frac{\delta L}{L_0} = \alpha \delta T
\]  

(6.28)

where \(\delta L\) is the change in length, \(L_0\) is the original length, \(\alpha\) is the coefficient of thermal expansion (CTE) for a given material, and \(\delta T\) is the change in temperature. The highest reported values for the CTE of low carbon steel is \(9.22 \frac{\mu m}{m^\circ C}\) [53] while the highest reported values of the CTE of HDPE is \(120 \frac{\mu in}{m^\circ F}\) [9]. The ratio the CTE of HDPE to the CTE of HDPE is 13. This means that for any increase in temperature any given length of HDPE will expand 13 times more than the same length of steel. A solution to this issue was necessary to ensure that the steel frame and HDPE pontoons could be joined in a reasonable range of temperatures even if they had been fabricated in similar temperatures.

The HDPE pontoons were fabricated in October of 2016 in Louisville, KY in a temperature controlled shop with the thermostat set at 73\(^\circ\)F. At the completion of their construction they were left outside. The steel frame was fabricated in February of 2017 in Merrimack, NH in a temperature
controlled shop where the temperature was unknown but estimated to be around 60°F. After the steel frame was fabricated it was trucked to Everett, MA to be hot dip galvanized. After the frame was galvanized it was trucked to the NH Port Authority Pier in Portsmouth, NH and assembled outside in the second half of March 2017.

To design for the varying range of temperatures and CTEs of the two materials expansion joints were designed to connect the pontoons to the steel frame. The joints consist of extended length bolts inserted through the HDPE pontoon saddles and the pontoon mounting plates in the steel frame. Figure 6.25 shows a view of two pontoon joints.

Figure 6.25: A view of the rigid stern joint and the first expansion joint. The stern joint is fixed rigid to the frame. Expansion joint 1 allows expansion and contraction of the pontoons. The expansion and contraction allowed increases with joint number and increasing distance from the rigid stern joint. Note: the decking and decking joists have been removed from this view to improve clarity.

The view in Figure 6.25 shows the pontoons in a state where they are at a temperature of 73°F. If the temperature of the pontoons were to drop to their minimum allowable temperature of 32°F they would contract and the extended length bolts would have less available travel as can be seen in 6.26.

Extended length bolts were used to allow the frame to be joined to the pontoons in temperatures ranging from 32 to 100°F. The expansion joints were also designed to allow for a \( \pm \frac{1}{8} \) in tolerance along the 40 ft. length of the steel frame as the fabricator specified. In the design of the expansion joints the steel was assumed to be rigid throughout all temperatures. The connection point at
the stern (or seaward) end of the pontoons was designed to be fixed to the frame and allow no translation.

After the deployment of the system the pontoon saddle spacings were visually inspected at both hot and cold temperatures. It is believed that the heating from the sun, and cooling (or heating) from the water keep the pontoons at a relatively stable temperature, and thus they do not expand or contract as much as originally expected. For future use of similar pontoon saddles joined to a steel frame, the expansion joints are not expected to be necessary.

6.3.5 Ice Loading

Ice impact forces are believed to not be of concern for the tidal energy conversion system. Ice in the Great Bay/Piscataqua River Estuary is only able to form in the upper shallow slow current regions of the estuary. Ice formation at the Memorial Bridge is extremely rare due to the salinity of the water, fast currents at the site, and proximity to the warmer waters of the Atlantic. Less ice typically forms in the shallow regions of the estuary than in a freshwater system in a similar climate because of the decreased freezing temperature of the salt water. Ice that does form in the shallow regions of the estuary is typically very weak as the frequent changes in tidal elevation mix
large amounts of air and salt into the ice which significantly decrease its strength. The connection between the turbine deployment platform and the vertical guide posts is compliant. This compliance will decrease the amount of impulse imparted upon the vertical guide posts from the turbine deployment platform due to a collision with ice. To calculate an estimated ice impact force one must first determine the thickness of ice that will impact the structure. If no measurements of ice thickness are available (which is common) ice thickness can be estimated using meteorological data. The US Army Corp of Engineers Cold Regions Research and Engineering Laboratory (USACE ERDC CRREL) suggests a method [24] the first calculates the accumulated freezing degree days (AFDD) and then uses a modified Stefan equation to determine maximum ice thickness on rivers. Various methods for predictions of sea ice thickness do exist, but the turbine deployment platform will be deployed in a river, not on the open seas and the growth rate of ice will be slower in a river. In a cold winter the Great Bay achieved 898 FDD (based off a 32 °F (0 °C) freezing temperature of water). Because the Piscataqua River is a salt water river a freezing temperature of 28.4°F (-2°C), the freezing temperature of seawater, was used to recalculate the AFFD and 623 AFDD were calculated with a 28.4°F freezing temperature.

The USACE CRREL report suggests a C value of 0.12-0.15\( \frac{in}{\sqrt{\text{Fdays}}} \) for average rivers with snow. At the Memorial Bridge the Piscataqua River has very fast currents and no snow typically accumulates on the surface of the river. These C values are believed to be very high for the Memorial Bridge deployment site. The modified Stefan equation is

\[
t_i = C(AFDD)^{0.5}
\]

\[
t_i = 0.12(623)^{0.5} = 2.995\text{in}
\]

USACE recommends using a AASHTO(1994) codes for bridge pier design for estimating the dynamic force of moving ice on bridge piers. For

\[
F = F_i \cdot f_i \cdot \frac{D}{t_i} > 6
\]
Figure 6.27: AFDD plotted for the Great Bay Reserve with a freezing temperature of 28.4°F

where \( F \) is the static equivalent force, \( F_C \) is the crushing force of the ice, and \( D \) is the width of the structure. The turbine deployment platform is 18 ft (5.5 m, 216 in) wide.

\[
\frac{216}{2.995} = 72 > 6 \quad (6.32)
\]

\[
F_C = C_a p D t_i \quad (6.33)
\]

where \( C_a \) is parameter used to account for the aspect ratio between the thickness of the ice and the width of the structure and can be found using

\[
C_a = \left( \frac{5t_i}{D} + 1 \right)^{0.5} \quad (6.34)
\]
\[ C_a = \left( \frac{5 \times 2.995}{216} + 1 \right)^{0.5} = 1.03 \] (6.35)

\( p \) is the effective ice crushing pressure. Discussions with experts in the field of ice engineering suggest that the maximum ice crushing pressure achievable by the aerated and salty ice in the Great Bay/Piscataqua River Estuary is no more than 30 psi.

\[ F_C = 1.03 \times 30 \times 216 \times 3.39 = 20,000 lb \] (6.36)

The total load from wind waves and currents expected on the platform is approximately 28,000 lb. Although the turbine deployment platform and vertical guide posts were not designed to withstand loads of this magnitude this load in addition to typical operating loads is within factors of safety of the design. The TDP will be monitored in ice impact conditions and an assessment will be made to determine if the system can be operated during times of expected ice melt.

### 6.3.6 Instrumentation

The TDP was designed to accommodate instrumentation meant to characterize the environment in which the turbine is deployed in. A large number of instruments can be deployed off the TDP. The TDP was first equipped with the following instrumentation

- 2 LinkQuest FlowQuest 1000 Acoustic Doppler Current Profilers
- 2 LUXUS underwater cameras
- 1 Airmar 200WX Weather Station
- 1 Valeport Midas CTD+ with chlorophyll and turbidity sensors

A more detailed explanation of this instrumentation can be found in [30] and will be expanded upon in Kaelin Chancey’s thesis.

The TDP is also equipped with an experimental wildlife deterrent system designed by Lite Enterprises. This system is designed to sense fish in the underwater cameras. If a fish is detected a set of underwater UV lights flash to attempt to scare the fish away from the turbine.
A webcam has also been installed at Harbour Place One to monitor the TDP. This webcam is saving images on its local drive as well as uploading a live feed to the project website.

### 6.4 Instrumentation Mounts

![Figure 6.28: The CTD mounted in the deployed position over the side of the TDP.](image)

A need existed to mount the estuarine instrumentation to the TDP. It was discovered that very few, if any, off the shelf eustuarine instrumentation mounts existed. A solution was devised with two undergraduate researchers (Kaelin Chancey, and Paul Gessel) and a senior design team [25] that consisted of using off the shelf structural pipe fittings (a leading commercial brand is called Kee Klamp) to join sections of pipe and mount the instruments to the TDP frame with very few custom components. The system is adaptable enough to allow for mounting of various different instruments. Mounting brackets for these systems were placed in various locations around the TDP. The mounts were designed to withstand the expected wave and tidal current loads the the
Memorial Bridge site. An example of the mounting system is shown in 6.28 where it is being used to mount the CTD.

6.5 Turbine Pitching Mechanism Design

A turbine pitching mechanism (TPM) was needed to allow for the deployment of turbines through the moon pool of the TDP. At the onset of the design of this mechanism a requirements list was developed.

6.5.1 Requirements

It was decided that the TPM must be able to:

• Support a turbine with a $9 \, m^2$ cross sectional area in up to $2.05 \, m/s$ currents and $2.5 \, ft$ waves

• Pitch a non-rotating $9 \, m^2$ turbine out of the water during both ebb ($2.05 \, m/s$) and flood ($1.35 \, m/s$) tides at the Memorial Bridge

• Must fit on the existing TDP and under the Memorial Bridge

• Must be able to survive the marine environment for 20 years

• Must be adaptable to mount and deploy a range of turbines

• Must be able to remove and deploy the turbine once per day without significant maintenance

• Must allow the turbine to remain in the deployed or removed position for one continuous month without becoming bound

• Must be powered by 120 V AC which will be available on the TDP

6.5.2 Alternatives Analysis

UNH-CORE has designed various configurations of turbine deployment mechanisms for previous deployments. Some of the first tidal turbine tests on the TDP V1.0 in 2009 used a crossflow
vertical axis turbine similar to the IES turbine [22] [37]. To deploy this turbine the group lifted
the turbine vertically through a steel cage. The cage would oftentimes become bound, thus the
rotor could only be removed and deployed during slack tides. This device also placed the center
of gravity of the platform at a high location when the turbine was out of the water which made the
platform less stable.

In 2012 TDP V1.0 was refurbished to create TDP V1.1 in preparation for testing of an axial
flow turbine [67]. To do this a new deck which included a much larger moon pool was installed and
a new turbine pitching mechanism was developed. This new turbine pitching mechanism pitched
(or rotated) the turbine in and out of a much larger moon pool instead of vertically lifting the
turbine out of a smaller opening in the deck.

This pitching mechanism design worked for short term (single tidal cycles) tests in the Pisc-
cataqua River and on the open ocean at the Muskeget Channel.

6.5.2.1 Spanning Beam

The first requirement stated that the TPM must support a turbine in the currents and waves
expected at the Memorial Bridge site. The requirements also stated that the TPM must allow the
turbine to be pitched in and out of the TDP moon pool on both ebb and flood tides.
In previous CORE tidal turbine tests the method of pitching a turbine in and out of the moon pool proved to be much more successful than lifting the turbine vertically out of the moon pool, and thus it was decided that the turbine deployment mechanism for this TDP would use a pitching mechanism. The fact that other commercial turbine developers with similar turbine configurations also pivoted, or pitched their turbine in and out of the water was another reason for a pitched deployment. Thus a TPM similar to those developed by commercial turbine developers deploying turbines similar to the one we planned to deploy was designed.

The beam which spanned the moon pool and pivoted about its axis, the spanning beam, needed to be sized. It was determined that the spanning beam needed to transfer the load of the weight of the turbine as well as the tidal currents and waves on the turbine rotor to the TDP. AISC design codes were used to determine an adequate spanning beam size. To do this the demands of the spanning beam were compared to the capacity of an HSS 16x0.5 and are shown in Table 6.5.

This yields a factor of safety of 2.6 for the spanning beam. Localized stresses due to small connection areas were also investigated to determine if a smaller wall thickness 16 inch HSS section could be used to save weight. To do this an FEA study was run in Abuqus which showed that a 16 inch HSS section with a smaller wall thickness could not be used as localized stresses at the connections were too large large. The use of a smaller wall thickness 16 inch HSS sec-
tion with the use of reinforcement plates at the connections was also considered. It was observed that the weight of the reinforcement plates required when using a smaller wall thickness 16 inch HSS section was greater than the reduction of weight due to decreasing the wall thickness. Small reinforcement plates (called half circles) were shown to reduce stresses in the connections at the interface brackets to an acceptable level and thus were included in the interface brackets.

### 6.5.2.2 Spanning Beam Supports

Supports for the spanning beam on each end were required to transmit the load from the spanning beam into the TDP frame. These supports also had to allow the spanning beam to pivot, and had prevent the spanning beam from pivoting while the turbine rotor was in operation or while it was being stored out of the water. The TDP had been designed prior to the completion of the design of the TPM, but it was designed to accommodate the loads of the turbine by adding stiff-
Table 6.5: Capacities and demands as per AISC

<table>
<thead>
<tr>
<th></th>
<th>Capacity Equation</th>
<th>Capacity</th>
<th>Demand</th>
<th>Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Tension</td>
<td></td>
<td>898000 lb</td>
<td>12000 lb</td>
<td>0.02</td>
</tr>
<tr>
<td>Shear</td>
<td>(0.58 \times YS \times A)</td>
<td>521000 lb</td>
<td>19000 lb</td>
<td>0.02</td>
</tr>
<tr>
<td>Bending</td>
<td>(\frac{YS \times I}{D/2})</td>
<td>284000 ft-lb</td>
<td>70000 ft-lb</td>
<td>0.3</td>
</tr>
<tr>
<td>Torsional</td>
<td>(\frac{YS \times 0.58 \times J}{D/2})</td>
<td>329000 ft-lb</td>
<td>15000 ft-lb</td>
<td>0.05</td>
</tr>
<tr>
<td>Combined</td>
<td>(\frac{\sum \text{Capacities}}{\sum \text{Demands}})</td>
<td></td>
<td></td>
<td>0.39</td>
</tr>
</tbody>
</table>

eners and mounting holes in expected mounting locations. These supports were designed to act as the interface between the TDP and the TPM. These supports also had to be able to survive in the marine environment for 20 years and had to be able to remove and deploy the turbine once per day without needing maintenance. The supports also had to allow the turbine rotor remain in either the deployed or removed position for at least one month without becoming bound. Although the idea of connecting smaller rods to the ends of the spanning beam to allow the use of commercially available bearings as a pivot point for the spanning beam and to allow the beam to sit closer to the water was considered, it was decided that this connection would have too high of localized stresses and a pivot for a 16 inch diameter beam would be developed. This was a unique design challenge as a connection had to be developed that would allow a 16 inch shaft to pivot. It is not difficult to find off the shelf bushings or bearings that would withstand the loads these connections were expected to see, or that would be able to survive the marine environment, but it was very difficult to find off the shelf bushings or bearings with a 16 inch bore. Four alternatives were considered.

1. Custom Delrin bushings could be fabricated
2. A very loose Delrin cradle could be made
3. Thordon bushings could be ordered
4. Rollers could be used to create a bearing surface
Polyoxymethylene also known as acetal or Delrin (when it is sold by DuPont) is a thermoplastic known for its high strength and low friction. It is commonly used in marine applications as a bearing surface and also as a material which has a low rate of corrosion. DuPont has published manual titled General Design Principles for Bearings to aid designers in the design of Delrin bushings. This manual provided design insight as the proper amount of diametric oversizing of the bushings, and the addition of debris relief slots. This design guide also warned of using bushings that are too long as large edge loads on longer bushings can cause their shaft to bind and not pivot. The idea of using a very loose Delrin cradle was also considered. This cradle would be much larger than the 16 inch outside diameter of the spanning beam and thus would not over grip the pipe and prevent binding. This design would me looser and would allow the spanning beam to vibrate as the turbine operates. It would have also used much more expensive Delrin than the bushings. A third option was offered by IES to use bushings made by Thordon Bearings Inc. Thordon made the bearings used in IES’s spanning beam pivot. Thordon makes water-lubricated propeller shaft bushings for boat propellers and other marine applications. The use of Thordon bearings offered a few benefits over the use of Delrin. Some forms of Delrin are prone to stress relaxation and thus some Delrin bushings do not hold their shape over time while under very high stresses. The Thordon bushing material also has a lower coefficient of thermal expansion, less water swell, and a lower coefficient of friction meaning that it holds its shape better and will slide better. Also being an ordered component, experienced Thordon engineers would help us design these bushings and stand behind their work if the bushings did not perform as they we specified to. The downside of these bushings was that although they were nearly guaranteed to work, IES noted that it was not an extremely low friction bearing at their Roza canal installation. Thordon also required the bearing surface of the spanning beam to be a precision component, which would be difficult to do with the rest of the spanning beam being galvanized. Discussions were had with Thordon where they suggested welding on a stainless steel ring to the spanning beam and then getting that ring ground to have a 16-32 μinch finish on it. This ring would also need an H7 tolerance. Ace, welding estimated that this work could put the cost of the turbine pitching mechanism at over $100,000 as it was not
something that they could do in house. Our marine contractor Pepperrell Cove Marine Services suggested looking into the use of rollers to support the spanning beam. A company called Sunray Inc. was found. Sunray specializes in the production of custom built rollers. They were able to provide 6 inch long polyurethane rollers with a 2.5 inch OD and 0.75 inch bore with stainless steel ball bearings rated at 3,500 lbs. These rollers could be used to create a large custom roller bearing for the spanning beam that would withstand the load and be able to accommodate a 16 inch shaft. On each side of the spanning beam the beam is supported by 8 of these rollers. The rollers are supported within a housing called the beam cradle. The beam cradle supports the rollers and transfers loads from the spanning beam to the rollers into large base plates into the TDP. The components of the beam cradle which support the rollers are bolted such that in the event of a roller failure, an air powered lifting bag can be inserted under the spanning beam to lift the spanning beam and the roller can be un-bolted and replaced. During the design of the TDP the I-beams around the moon pool were reinforced with stiffeners and holes were drilled in multiple locations along the edges of the moon pool to allow for the mounting of the turbine and the device which would pivot the turbine rotor out of the moon pool in multiple possible locations. It was decided that the turbine should be mounted as close to the center of the TDP as possible to keep the center of gravity of the TDS close to the center of the TDP.

6.5.2.3 Actuation

To pivot or pitch the turbine out of the water three different mechanisms were considered. This mechanism had to be able to survive in the marine environment and enable the turbine to be removed during both ebb and flood tides at the Memorial Bridge.

Pistons: The first mechanism to be considered, and the mechanism which the TDP was originally designed to accommodate was a set of electric actuators. These electric actuators would be attached to the TDP frame on one end, and arms welded to the spanning beam on the other end. By adjusting the length of the actuators, one could adjust the angular orientation of the turbine rotor. The use of electric actuators would enable precise control of the position of the turbine rotor as...
it was pitched in or out of the moon pool. This mechanism could be remotely controlled or even automated as there would be no need to reconfigure the mechanism when changing from pitching the turbine rotor in or out of the moon pool. It was difficult to find off the shelf actuators that would run on 120V AC power which were also suitable for the marine environment, and could provide enough travel and force to pivot the turbine rotor out of the water. The actuators would also have to potentially always be on, or needed to have a locking mode to hold the turbine rotor in place while it was operating.

Figure 6.32: An early concept of the TPM that used electric actuators to pitch the turbine rotor out of the moon pool.

Motor, Chain, and Sprocket: Another mechanism that could also enable precise control of the position of the rotor and allow for remote or automated pitching of the turbine rotor into or out of the moon pool was a motor which drove a chain attached to a sprocket on the spanning beam. Additional holes would have to have been drilled in the TDP frame for the motor mount. In order to automate the pitching of the turbine rotor with a chain and sprocket, a locking motor would have been needed with a very tight chain that did not allow much backlash because the motor would
have been used to lock the turbine rotor in place. It was also difficult to find a motor that could run on 120V AC or 12V DC power that could supply enough torque to meet the requirement of being able to winch the rotor out of the water during flood and ebb tides. At the onset of the design of the turbine pitching mechanism the need for remote or automated removal of the turbine rotor was considered. It was determined that it was not a requirement of the design as the drag loads on a crossflow rotor can be reduced drastically by just stopping the rotor.

In the event of an emergency where the loads on the TDP must be rapidly reduced the turbine rotor would be stopped. This would significantly reduce loads due to tidal currents and waves on the turbine rotor. Thus a system which would require an operator to be present to pitch the turbine rotor in or out of the water would satisfy all design requirements.

Winch: The use of a winch was considered. Winches are commonly available in pull strengths reaching nearly 20,000 lb. The winch would have to pull on some extension of the spanning beam to create a torque on the spanning beam which would overcome the torque generated by tidal current drag and wave forces on the turbine rotor. Like the electric actuators and chain and sprocket solution the winch would also have to be able to survive the marine environment and be powered off locally available 120 V AC power. Three winches were considered and compared.

The Smittybilt X20 Comp Gen 2 Wireless 12,000 lb. winch was selected as the best choice. To use this winch a battery would be required. This acts as an added safety feature where in an emergency if the TDP were to lose connection from the grid the battery could still supply power to operate the winch. If the winch is not functioning, a come along can be used in place of the winch to remove the turbine. The Smittybilt winch has an IP68 rating. This means that the winch is certified that it has complete protection to prevent the ingress of dust (first digit), and can be continuously operated while being immersed in water beyond 1m deep (second digit). The winch was selected for its Dyneema synthetic rope. Dyneema is a material commonly used in the marine environment. Compared to a traditional steel rope the Dyneema rope is lighter, gives less stretch to prevent damage or injuries if a rope breaks, is not prone to galvanic corrosion and is non-conductive to maintain electrical isolation between the TDP frame and the water. The Dyneema rope is specially
treated to be UV stable, although Dyneema itself is UV sensitive so a cover is included with the winch to cover the rope with. The winch will also be under the bridge deck sheltered from the sun most of the time. The winch rope has been trimmed to reduce the likelihood of it becoming tangled on the spool. Operators should note that the winch’s operators manual specifies that a minimum of 10 wraps of rope must remain on the spool at all times to ensure the rope stays attached to the spool.

**Strongback:**

The strongback serves to allow the winch to create a torque on the spanning beam. A W8x20 I-beam was selected for the strong back. HSS 1.5x1.5x1/8 rungs are welded to the strong back to create a ladder, such that emergency maintenance can be performed at the top of the strongback.
Originally the winch was positioned on the tope of the strongback. This was done to enable one winch to be used to winch the turbine in and out of the moon pool. After installing the TPM and testing it with the winch on the strongback it was decided that the winch would be better placed on the deck of the TDP where it could more easily be maintained and a second hand winch would be installed on the deck at the aft end of the TDP to assist in winching the turbine into the moonpool. The top of the strong back was fitted with two hoists ring bolted to it as a pick points for the winches. A hoist rings is bolted to the TDP frame in near the bow winch on the deck of the platform. The purpose of this hoist ring is to enable to turbine rotor to be removed in an emergency using a come-along. The hoist rings are oversized for these tasks as they are re-purposed from the chain type pile guides that did not function as intended. The three limiting factors which determined the appropriate height of the strong back were: it needed to be long enough to provide enough torque to overcome the moment generated by a spring flood tide, it needed to be short enough to fit under the bridge deck at the highest expected water level, and it needed to extend to the approximate location of the pick point on the deck of the TDP. To determine the amount of clearance available under the bridge deck at the highest expected water level the Memorial Bridge as built drawings were compared with the vertical guide post drawings and the TDP model. From HNTB Memorial Bridge As Built Structural Drawings Sheet B9 [78]:

![Figure 6.34: Memorial Bridge elevation drawing taken from [78].](image)
It was determined that 25.02 ft existed between MSL and the bridge deck clearance line. The VGP’s were designed for FEMA’s 100YR base flood elevation (wave’s are included in 100YR flood) and 1.5 ft of TDP freeboard. This gives 16.02 ft of clearance from the highest expected waterline to the bottom of the bridge or 14.52 ft of clearance from the TDP deck to the bottom of the bridge deck.

The Solidworks model roughly confirms these dimensions, and also shows that an 11 ft strong back will stay clear of the bridge deck. The winch, which is placed at the top of the strong back will have a minimum clearance of 1 ft 8 in under the bridge with an 11 ft long strong back. The image above shows the highest point of travel for the TDP. At this point the still water level is slightly below the 100 year flood mark because the FEMA’s base flood elevation (100 year flood) includes wave setup. It was determined that 1 ft 8 in of clearance under the bridge deck was an acceptable amount of clearance, thus an 11 ft strong back was selected. This strong back would place the winch approximately over the pick point on the deck of the TDP when the turbine rotor was in the removed position. When determining the amount of moment needed to pitch the turbine rotor out of the water it was assumed that the turbine was balanced about the spanning beam pivot, the bearings in the beam cradles were frictionless, and the rotor would always be stopped when pivoting it in or out of the water. The NECI turbine is equipped with normally open contactor that
will close if the turbine loses power. This will short the generator and bring the rotor to a stop. This will significantly reduce the drag force on the rotor. To hold the normally open contactor closed a battery bank was placed in the turbine interface panel. These batteries, if fully charged, should have enough energy in them to hold the contactor closed for a maximum of 147 hours. If the turbine interface panel is connected to the grid, these batteries will be constantly charging and remain topped up. If this braking method does not work when needed for some reason the operators will wait until slack tide where the rotor will come to a stop. Once the rotor is stopped they will pitch the turbine rotor out of the water. The rotor should also not be removed when waves are present as the oscillating loads on the turbine rotor could cause slamming loads on the winch cable which could potentially break the rope. If needed the turbine rotor is sufficiently strong enough to also be removed while spinning, and this is something that NECI has done multiple times.
6.5.2.4 Winch Power

Smittybilt specified a battery with a minimum of 650 cold cranking amps (CCA) be used to power the winch. Various battery types are available which meet this specification. Also of concern was placing this battery in the marine environment where there is an unlikely, but potential possibility of battery material entering the water. A battery with low environmental impact was desirable. Also of desire was a lightweight battery that held enough energy to winch the turbine rotor out of the water and then back into the water all within one day. The first type of battery investigated was a sealed lead acid battery. Most car starter batteries are sealed lead acid batteries.

<table>
<thead>
<tr>
<th>Model</th>
<th>Backup 1250750</th>
<th>ValuePower VP-65</th>
<th>K2 Energy K2B12VG27-2</th>
<th>Dohon 27-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>Picture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCA</td>
<td>750</td>
<td>650</td>
<td>NA</td>
<td>1150</td>
</tr>
<tr>
<td>CA</td>
<td>NA</td>
<td>NA</td>
<td>400 (two wired in parallel for 800)</td>
<td>NA</td>
</tr>
<tr>
<td>Weight</td>
<td>15lb</td>
<td>47.2lb</td>
<td>19lb</td>
<td>16lb</td>
</tr>
<tr>
<td>Chemical Make-up</td>
<td>LifePo4</td>
<td>Lead Acid</td>
<td>LifePo4</td>
<td>LifePo4</td>
</tr>
<tr>
<td>Price</td>
<td>$499.97</td>
<td>$49.88</td>
<td>$1230 ($615 each)</td>
<td>$426.99</td>
</tr>
<tr>
<td>Ah</td>
<td>50</td>
<td>NA</td>
<td>48</td>
<td>65</td>
</tr>
</tbody>
</table>

Figure 6.37: A comparison of four different battery models considered.

6.5.3 Analysis

6.5.3.1 Winch Sizing

The moment expected from a stopped turbine rotor on the fastest flood tide (1.35 m/s) was 4012 ft · lb. To overcome this moment and winch the turbine rotor out of the water an equal
moment would have to be generated by the winch on the strong back. Simple statics can show that the winch will have to supply 503 lb. of tension to create a moment equal to the moment created by the drag on the rotor due to a flood tide. The moment expected from a stopped turbine rotor on the fastest ebb tide (2.05 m/s) was 9264 ft-lb. It can be shown that the winch will have to supply 993 lb of tension to overcome the moment expected from a stopped turbine rotor on an ebb tide and winch the rotor into the water. The 12,000 lb winch was deemed adequate.

6.5.3.2 Interface Bracket

The interface bracket was initially designed by engineers at IES as the way they would like to attach their turbine to the pitching mechanism. UNH suggested that the design be made in English units for fabrication in the US, but bolt hole layout be made in metric for universality. A diagram of the bolt hole layout is shown as a part of the engineering drawings of the TPM in the appendix. This drawing should serve as a mechanical interface between the TPM and future turbines that could be tested on this system. This drawings utility has already been proven in the design of an adapter bracket to adapt the NECI turbine to the TPM.

6.5.3.3 Adapter Bracket Design

The work in the following subsection was performed at New Energy Corporation as a part of an NSF INTERN non-academic experience.

The Envirogen 025 turbine typically mounts in a through beam configuration on both the floating support and fixed support configurations where its bearing housing bolts to two flanges at the center of the spanning beam.

The UNH TPM was designed to mount a turbine in a "beside beam" configuration, thus an adapter bracket had to be designed to mount the Envirogen 025 turbine to the UNH TPM. The bearing housing typically mounts to the spanning beam using sixteen $\frac{3}{4}$-10 bolts passed through a pipe flange and threaded into an eight bolt 11.75 in diameter evenly spaced circular bolt pattern on each side of the bearing housing. The width of the bearing housing at the bolt patterns intended for mounting is 7.75.
Figure 6.38: The two commercially available turbine mounting configurations offered by New Energy Corporation. Image courtesy of New Energy Corporation.

An adapter bracket was designed to mount the Envirogen 025 turbine to the UNH TPM. This bracket uses the existing bolt interfaces of the UNH TPM and the Envirogen 025 turbine to join the two without the need for redesign of any existing components.

Figure 6.39: The adapter bracket with components labeled.
The adapter bracket consists of a 5/8 in thick back plate that is bolted to the interface brackets on the UNH TPM. The back plate has the UNH interface bracket bolt pattern on it as well as four holes cut out of it to reduce weight. Two side brackets are welded to the back plate using slot and fillet welds. These side brackets have the bolt pattern for the Envirogen 025 mounting side flanges, as well as lettering welded onto the material that reads "ENVG 025 ONLY." Bottom and top gussets as well as a cross bar are incorporated to provide lateral stability to the side brackets. The cross bar is positioned to allow 0.72 in of clearance to the vertical pipe of the bearing housing. The adapter bracket should allow the Envirogen 025 to be mounted on the UNH TDP with the top of its rotor approximately level with the bottom of the TDP pontoons. It ensures that the generator will not interfere with the TDP decking. In the removed position this adapter bracket lifts the rotor high enough such that no part of the rotor is in the water.

The adapter bracket is made up of G40.21 44W galvanized steel plate with a Young’s modulus of 290,000 ksi, a mass density of 0.284 lb/in$^3$, and a yield strength of 44 ksi.

A static FEA simulation was performed in SolidWorks on the adapter bracket to check that the predicted stress in the part did not exceed the yield strength of the material. The mesh used for the final simulation is shown in Figure 6.40. It is composed of 41186 three dimensional tetrahedral elements.

In this simulation the bearing housing is used as a means of accurately transferring the loads of the rotor to the adapter bracket. The bearing housing has already undergone a separate structural analysis [58] and has been shown to perform as designed in multiple field tests. To simplify the model and improve computational speed a simplified bearing housing mock-up is used which allows the forces to be applied at the same locations and transmitted into the adapter bracket in the same way. The bearing housing’s elements are set to be rigid. This assumption is reasonable as the forces are applied far away from the interface between the bearing housing and the adapter bracket.

All loads are transmitted into the adapter bracket through the bearing housing. At the top of the bearing housing on the generator flange two loads are applied. [58] specifies that the designed
weight of the rotor is 2900 lb and the design weight of the generator is 1600 lb. The combination of these two loads are applied as an evenly distributed force along the top of the generator flange in the direction normal to the flange surface. When the bracket is tested in the removed position the
rotor load is applied in the bottom flange of the bearing housing and the generator load is applied to the top of the bearing housing. Both loads are applied in a direction through the thickness of the back plate. [58] specifies that the designed rotor torque is 67200 \text{ in} - \text{lb}. This torque is applied evenly distributed and parallel to the top surface of the generator flange and axially around the bearing housing vertical pipe in a clockwise (looking down from above) direction. [58] specifies an 7975 \text{ lb} design drag load of the rotor. This drag load is applied as an evenly distributed force on the bearing mounting surface at the bottom of the bearing housing in the direction represented by the thickness of the back plate in the ebb direction. Various other drag load directions are tested. The inside surface of the eight bolt holes are fixed radially and axially with a cylindrical surfaces fixture to represent the bolts holding the adapter to UNH’s interface brackets. These fixtures are a conservative representation of the true fixture that the bolts will provide as the bolts will be used with washers to distribute the forces of the load onto the surface of the back plate. A global bonded contact is set which bonds all parts that are up to 0.3 \text{ in} apart. The surfaces used to represent the welds used to join the vertical pipe to the side flanges had to be suppressed in the model. The bearing housing gussets were set to be numerically fixed to the vertical pipe since the welds were suppressed out. The simulation was run on the author’s personal laptop with an Intel CORE i7-3517U CPU 1.90GHz, with two cores and 8 GB of RAM. The simulation took approximately 10 minutes to solve.

A convergence study was performed to ensure the validity of the results. Figure 6.41 shows that as the number of elements in the mesh increased the maximum von Mises stress decreased. This can be explained by the location where the maximum stress is occurring. In all simulations (including the one shown in Figure 6.42) the maximum von Mises stress occurred at the tip of one of the bottom gussets. This is a location where the material comes to a point and is likely to form a singularity, causing inaccurately high stresses due to large element sizes. In the final mesh used a mesh control was implemented that refined the mesh to a smaller element size on the bottom gussets and the back plate. One can see in the convergence study that as the total number of elements was increase (and the size of elements was decreased) the maximum stress decreased
as this singularity began to be more accurately resolved. The study showed that approximately 30,000 elements must be used to accurately resolve the stress in the part, thus a mesh with 30481 elements was selected for all simulations.

The maximum displacement of the material is 0.008 in. It was important to ensure that the bearing housing would not interfere with the cross bar once loaded. The unloaded distance between the cross bar and the bearing housing is 0.72 in. A factor of safety of 90 was calculated for displacement. It should also be noted that the maximum displacement occurs at the bottom of the bearing housing, far away from the cross bar. A plot of the displacement throughout the part is shown in Figure 6.43.

A series of simulations were performed where the direction of the drag force load was applied in every 45 deg. increment from the 0 deg. (ebb flow direction) to deg. direction to simulate a range of side loadings of the rotor as well as a flood tide loading. The results from these simulations are presented in Table 6.6.
Figure 6.42: von Mises stress plot for the adapter bracket.

Figure 6.43: Displacement plot for the adapter bracket.
Table 6.6: Directional loading scenarios

<table>
<thead>
<tr>
<th>Direction [deg.]</th>
<th>Max Stress [kips]</th>
<th>Max Displacement [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebb</td>
<td>0</td>
<td>10.64</td>
</tr>
<tr>
<td>Side</td>
<td>45</td>
<td>12.46</td>
</tr>
<tr>
<td>Side</td>
<td>90</td>
<td>7.19</td>
</tr>
<tr>
<td>Side</td>
<td>135</td>
<td>11.53</td>
</tr>
<tr>
<td>Flood</td>
<td>180</td>
<td>10.28</td>
</tr>
<tr>
<td>Side</td>
<td>225</td>
<td>12.1</td>
</tr>
<tr>
<td>Side</td>
<td>270</td>
<td>7.28</td>
</tr>
<tr>
<td>Side</td>
<td>315</td>
<td>12.37</td>
</tr>
</tbody>
</table>

A simulation was also performed which examined the stresses in the adapter bracket when the turbine rotor was in the horizontal removed position. It predicted a maximum stress of 6.569 kips and a maximum displacement of 0.003 in.

Out of all simulations the maximum von Mises stress calculated was 12.46 kips when the drag load is applied at 45 deg. from the ebb direction. Out of all simulations the maximum displacement calculated was 0.008 in. 12.46 kips is below the yield strength of the material and gives a factor of safety against yielding of 3.53. 0.008 in is less than the unloaded distance from the bearing housing to the cross bar, thus indicating that interference will not occur. A factor of safety against displacement of 90 is calculated. The adapter bracket is estimated to weigh 297 lb. It will be galvanized to protect against corrosion. To account for the bonded connections the "puzzled" weld studs must be completely filled and a weld bead must be made all around all interfaces that is at least half the thickness of the material wide.

This analysis allowed the bracket to be reduced in weight from approximately 500 lb in its original conceptual design to 297 lb while achieving a factor of safety of 3.53. The highest stress in the material is expected at the location where the bottom gusset comes to a point and is welded.
to the back plate. This design was selected because it was expected to be easily fabricated and installed on the TPM.

It should be noted that during the initial deployment of the EVG-025H larger than expected deformation of the adapter bracket was observed, possibly due to an underestimation of loads during design calculations. A new bracket was designed which will also allow the deployment of larger turbines in the future. As of the writing of this thesis the new adapter bracket is being fabricated. Drawings for the new bracket can be found in the appendix.
CHAPTER 7
FABRICATION AND DEPLOYMENT

7.1 TDP Assembly, Installation, and Commissioning

On February 24th, 2017 the TDP frame was galvanized at Duncan Galvanizing in Everett, MA. Before galvanization of a component its surface has to be prepared to ensure proper adherence of the zinc. To do this components are first bathed in hot alkaline cleaner bath (most likely consisting of a 9% sulfuric acid bath) to remove any greases, or dirt on the surface of the steel. The components are then dipped in another acid bath to remove mill scale and any oxides. This bath is typically filled with room temperature hydrochloric acid. Components are then dipped in a flux bath that consists of a zinc ammonium chloride solution which also removes oxides and prevents oxidation before the component enters the molten zinc bath. After the surface is prepared the component is then dipped into an 830 °F molten zinc bath that typically consists of around 98% pure zinc and 2% aluminum, bismuth, and nickle additives.

In the design of components for galvanizing care must be taken to design parts to ensure that they can be hung off cranes in the galvanizing plant, fit into the zinc bath, and allow the zinc to flow throughout the part. Small holes had to be drilled into some of the instrument mount pipes to give a place where they could be hung by the cranes. Holes also had to be drilled in the vertical guide posts to allow the zinc to flow through the piles. These holes were then later sealed before the vertical guide posts were installed on the bridge. The frame and the vertical guide posts were built in sections small enough to allow them to fit in the zinc bath. The galvanization process is also known to deform thin sections of components due to the high temperatures.

The pontoons were fabricated by ISCO Industries in Louisville, KY. Sewer pipes were cut to 45° angles on the ends. The pipes were then filled with a closed cell rigid expanded polystyrene
foam called InsulFoam I which has a density of 1.0 pound per cubic foot and a water absorption percentage of <4.0% of its volume. ISCO recommended this foam stating that although it would not fill the pontoons as completely as poured foam mixture, it would be much cheaper. A process called fusion welding, where the ends of the pipe are heated on a plate and then pressed up against the surface they are mating against was used to attach end plates onto the 45° cuts at the ends of the pipes. A process called extrusion welding was used to fix the saddles to the pipes. The advantage of fusion welding over extrusion welding is that fusion welds are guaranteed to be watertight and are stronger than the material they are bonding. The pontoons were delivered fully fabricated to the New Hampshire Port Authority in Portsmouth, NH on 1 March 2017.

![Figure 7.1: A picture of the pontoons at the NH Port Authority. Note: the pontoons are upside down in this picture.](image)

After spending time to cure at Duncan Galvanizing the frame was delivered to the NH Port Authority on 17 March 2017. The next week, on 21 March assembly of the TDP began. Pepperrell Cove Marine Services (PCM) used their boom truck to lift one main half of the frame onto one pontoon. Then the other frame half was lifted onto the other pontoon and the two halves of the TDP were joined by the the three cross beam connectors.

The pressure treated joists were added to the steel frame and the McNICHOLS pultruded fiber-glass grating was fixed to the joists using McNICHOLS grating fasteners. The railing posts and
cables were added. Bare steel railing cables were accidentally provided. To attempt to remedy this the cable ends were painted with cold galvanizing compound and antiseize was added to the threads.

7.2 TDP Deployment

Moores Crane was hired by PCM to lift the TDP from the NH Port Authority Pier into the water. On the morning of 31 March the TDP was lifted into the water and hip towed to the Memorial bridge by PCM and their 90 HP work skiff at slack tide. PCM attached the TDP to the vertical guide posts using the chain type pile guides.

At approximately noon on 31 March it was noticed that the chain type pile guides were not letting the TDP rise with the incoming tides. The combination of the horizontal tidal current drag force and upward buoyancy force of the pontoons were causing the pile guides to bind on the vertical guide posts. PCM was called and they were able to use a boat hook to unbind the pile.
guides. An attempt was made to loosen the chains on the pile guides, but they still bound. The TDP was monitored for the rest of the flood tide and then towed back to the UNH Pier on the next slack tide.

![Figure 7.3: Bound pile guides. Platform shown listing due to the bound pile guides not allowing the TDP to rise with the flooding tides. Inset: close up of bound pile guides.](image)

After a survey of many of the docks around the NH seacoast new pile guides were designed and fabricated. These new pile guides used HSS 10x3 rectangular box beams to form a rigid box around the vertical guide posts. Inside of this box 8 rollers purchased from Henderson Marine (Item NO. 06-01 (HD), 06-01 SD (SD)) allow the pile guides to translate up and down the vertical guide posts with minimal friction. UHMWPE rub pads provide a backup rub surface just behind
the rollers if two rollers were to fail. The back beam of the box can be hinged open for attachment and removal from the vertical guide posts. The box is fixed to a plate of steel which is bolted to the existing holes on the TDP frame that were designed for the chain type pile guides. Like the chain type pile guides these pile guides are sized to fail at a similar load as the VGPs. In the event of an emergency removal the bolt heads mounting the pile guides to the TDP can be cut or torched off for rapid removal.

Figure 7.4: New pile guides. Left: a rendering of the new pile guides shown wrapped around the vertical guide posts. Right: a picture of the new pile guides shown attached to the TDP with the TDP moored at the UNH Pier.

After redesigning the pile guides and attaching the instrumentation to the TDP the TDP was re-installed on the Memorial Bridge on 22 June 2017. The turbine deployment platform remained at the Memorial Bridge until 8 November 2017 when it was removed from the Memorial Bridge in preparation for the installation of the turbine pitching mechanism.

The CTD, and ADCPs were run for the majority of the summer. One ADCP had its cable connector broken off by an assumed passing piece of debris. The connector was replaced and the ADCP was redeployed.

7.3 TPM Fabrication and Assembly

In October and November of 2017 fabrication of the turbine pitching mechanism (TPM) took place at Ace Welding.
In December 2018 the majority of the components for the turbine pitching mechanism were delivered to the UNH pier and assembly began. The beam cradles were assembled including the installation of the rollers in the parking lot. The TDP was brought alongside the floating dock. Pepperrell Cove Marine Services parked their boom truck on the pier and individually lowered each beam cradle onto the TDP deck. The slots in the beam cradles allowed for plenty of play to account for any error in the fabrication of the TDP frame. The spanning beam was then lowered into the beam cradles. The strongback was finally lifted down onto the TDP and bolted to the spanning beam.

![Image of assembly process](image1)

Figure 7.5: Assembly of the TPM. Top left: beam cradle installation. Top right: spanning beam lift. Bottom left: pitching mechanism nearly complete, note: winch mounted on strongback which was later moved to be on the TDP deck. Bottom right: completed TPM.

Initially, the winch was located on the strongback as this would allow the pitching mechanism to be pitched in and out using one winch. After testing the winch at the pier it was decided that it would be better to have the winch on the deck and a second hand operated winch could be mounted on the stern of the TDP to supply the small amount of force needed to pitch the turbine.
into the water. A Dutton Lianson WG2000 HEX winch was purchased and installed to pitch the
turbine into ebb currents. It should also be noted that without a turbine mounted on the TPM, it
is cumbersome to pitch as the system is not balanced and gravity pulls the TPM into the removed
position.

7.4 Additional Buoyancy Section

As the delivery of the turbine approached a check of all calculations was performed and concerns
were voiced that the bow down angle of the TDP while the turbine would be operating was of
concern. This was caused by adding significant additional weight to the system since its original
design. The turbine pitching mechanism, power electronics, and the turbine itself all turned out to
weigh more than originally assumed in the early stages of the design process. To ensure that bow
down would not be an issue and to allow for the testing of high weight turbines additional buoyancy
modular pontoon sections were added to the bow and stern of the TDP. These additional buoyancy
modular pontoon sections are rotomolded HDPE pontoons made of closed cell foam filled floats
fixed together and to the TDP using pressure treated lumber. The two buoyancy members (one
at the bow and one at the stern) add a total additional buoyancy force of 3920 lb to the TDP.
The modular pontoon sections were purchased from a company called Nautilus Floats, and extra
modular pontoon sections were purchased for potential future work.

Figure 7.6: Additional buoyancy modular pontoon sections added to the bow and stern of the TDP.
7.5 Electronics Shelter Assembly

An electronics shelter was designed while participating in the NSF INTERN Program at NECI in Calgary. The purpose of this shelter was to provide a mounting location for majority of the turbine power electronics on the TDP. The EVG-025H requires the use of an inverter, a rectifier, and a control cabinet. These three panels have sheltering and spacing requirements for ingress prevention and heat dissipation. The panels are arranged in the electronics shelter to satisfy these requirements as well as to allow space for cable routing in between the panels.

The electronics shelter is constructed primarily of galvanized steel unistrut members. The unistrut members were sized to enable the shelter to survive expected wind speeds as per ASCE 7-10 [7] 100 year mean recurrence interval at both the Memorial Bridge and at the UNH pier as per ASCE 7-05 [71]. The electronics shelter is shown in Figure 7.7.

![Figure 7.7: Left: a rendering of the electronics shelter design. Right: a photo of the assembled and deployed electronics shelter with associated power electronics.](image)

7.6 Turbine Assembly

NECI shipped the turbine from Alberta on 29 May 2018 in three crates shown in Figure 7.8. The turbine arrived at the UNH Pier on 4 June 2018 where the pier support facility forklift was used to offload the crates.
Unpackaging and assembly of the turbine was performed on the UNH Pier on the morning of Thursday 7 June 2018. By mid day the turbine had been lifted off the pier and bolted to the pitching mechanism by Pepperrell Cove Marine Services using their boom truck. Loctite 243 was applied to all bolts and all hardware was torqued as specified by NECI. Torque and retorque values for all bolts on the EVG-025 turbine are given in the appendix.

On that same afternoon the UNH and NECI team mounted the electronics shelter and resistor bank on the TDP. They also added the T-111 wall panels to the electronics shelter. Wires in flexible conduit were run from the electronics shelter to the resistor bank, and an outdoor rated wire bundle was run from the generator to the TIP. The nitrogen purge system was also hooked up to the generator. Work was completed late at night finishing just before sunset.

The next morning on 8 June 2018 Pepperrell Cove Marine Services towed the TDP with the turbine to the Memorial Bridge and attached the TDP to the vertical guide posts during the morning slack tide.
Figure 7.9: Upper Left: turbine drive train as packaged for shipping with crate walls removed. Lower Left: Martin torquing bolts to attach the blade supports to the hubs. Upper Right: clearance check after everything was mounted. Lower Right: turbine lift from the pier down onto the TDP.

Figure 7.10: TDP enroute to memorial bridge. A hip tow was used. Note it is important to keep the boat attached far enough aft on the TDP in order to ensure good control during towing. A bridled tow has also been used for towing operations once in open water.
In the afternoon of Friday 8 June 2018 as the currents were ramping down the UNH and NECI team was able to run the turbine for the first time in off-grid mode. Testing continued throughout that weekend with the NECI team.

As of the writing of this thesis the turbine has only been operated in off-grid mode where all power generated by the turbine is dissipated in a resistor bank shown in 7.11. This resistor bank was sized to be 25kW in order to be able to dissipate the rated power output of the turbine. For on-grid testing a droop cable shown in Figure 7.12 has been installed to connect the turbine to the grid. Along with transmitting power to and from the grid this cable also transmits data from the instrumentation on board the TDP to the Living Bridge server housed in the Memorial Bridge.

Figure 7.11: The 25kW resistor bank which is used to dissipate all power generated by the turbine during off-grid testing.

Figure 7.12: The droop cable. This cable bundle serves as the data and power connection between the bridge and the TDP.
Figure 7.13: A photo of the installed system including the EVG-025H turbine in the removed position.
8.1 Conclusions

A turbine deployment system was developed at the Memorial Bridge. In doing this it was demonstrated that there are advantages to deploying hydrokinetic turbines at bridges.

- The tidal currents at the Memorial Bridge were characterized and the Memorial Bridge test site exhibits good currents for a "nursery" scale hydrokinetic test site.

- A vertical guide post based system was designed constructed and installed which enabled the turbine deployment platform to use the existing bridge pier as its mooring point.

- The Living Bridge Project turbine deployment system was deployed as an auxilary component of the Memorial Bridge and therefore it was determined that the tidal turbine deployment fell under the bridges National Environmental Protection Act (NEPA) Categorical Exclusion.

- A droop cable was installed which enables power to be transmitted from the turbine to the grid via the bridge grid without installing a subsea cable.

The project also successfully developed a site and infrastructure which could be used for future hydrokinetic turbine testing. New hydrokinetic turbine developers can now come to the Memorial Bridge test site and test their turbine in a real tidal environment on the actual grid with less infrastructure development and permitting effort than if they were to develop their own test site.
8.2 Future Work

This project will not produce power at a price that is commercially competitive with existing energy generation technologies, but as with any demonstration project, the goal is to demonstrate an emerging technology with the hopes that one day it ultimately become commercially viable. This work lead to many discoveries which could bring tidal energy closer to becoming a commercially viable energy generation technology. To make tidal energy generation at bridges commercially viable installing and operating a turbine must become cheaper. To do this the following work would be reasonable areas to investigate.

8.2.1 Turbine Wave Forcing

A better understanding of the wave forcing on the turbine and turbine deployment structure is needed to commercialize a floating design. Due to the high level of uncertainty in the wave loading of the structure very conservative design decisions were made when designing against wave loads. The size of the TPM, TDP frame, and the VGP’s could all potentially be reduced if the wave loads on the structure were better understood. This would result in a large reduction in cost of the system, bringing it closer to commercialization.

I suggest an instrument be deployed to measure the waves at the turbine deployment site. This would aid in confirming that a proper design wave was used. Wave measurements could also be compared to strain measurements on the strain gauges on the VGPs as well as the TPM load cells to determine how much force the TDP and the turbine have imparted upon them due to waves.

8.2.2 Turbine Performance

The performance of the EVG-025H turbine should be investigated. After nearly a decade of turbine development there are still many aspects of the EVG-025’s performance that could be better understood and the Living Bridge Project and the Memorial Bridge test site represent a perfect opportunity to further investigate these parameters.
The cut in speed of the turbine should be more specifically determined. To produce accurate AEP estimates the a precise cut in speed is needed. NECI’s primary use of the EVG-025H turbine has been in freshwater riverine applications where current speeds are relatively constant. Some turbine tow testing has been performed in lakes behind a tug boat, but the boat’s minimum speed was limited. At the Memorial Bridge test site the tidally driven currents are constantly varying. This will produce multiple data points for the cut in speed of the rotor.

The constantly varying current speeds will also produce data sets with many different tidal current speeds and turbine power outputs. This will enable the creation of high fidelity power curves for the turbine. Higher fidelity power curves are essential for accurate AEP estimations.

8.2.2.1 Fender Wake

One feature of the Memorial Bridge test site is the fender wake that develops especially on the ebb tide. The effect of this fender wake on turbine performance is not known. Further work is suggested to investigate if this fender wake improves or decreases the power production of the turbine.

This fender wake is also inducing turbulence into the oncoming flow which could also accelerate turbine wear rates causing premature blade or bearing failure. The turbulence intensity of the oncoming flow should be characterized.

There will most likely be some difference between the power curves produced at the Memorial Bridge Test site and power curves produced at a site that receives clean oncoming flow. The difference between these two curves should be investigated such that a power curve corrected for the fender wake can be created for turbines that will typically be sited in clean oncoming flows.

8.2.3 Full Scale System Feasibility and Design

This project has demonstrated that bridges are an advantageous location to deploy hydrokinetic turbines. At a commercial scale developers would want to build a much more powerful system to produce a meaningful amount of energy.
Various concepts for deploying tidal turbines at bridges could be explored. Examples of these potential concepts are shown in Figure 8.1 [86]. All of these designs would require bridge designers and a hydrokinetic energy device developer to work together from the beginning of a project. These designs are not suggested as retrofits to existing bridges but significant projects that would require the turbine to be considered from the start of the bridge design process. In doing this there are potential benefits that the bridge project provides to the tidal turbine deployment and vice versa.

The turbine could potentially help to sway public support for a controversial bridge project in energy progressive municipalities. The turbine could be used to increase the resilience of powered bridge operations thereby increasing the resilience of the transportation infrastructure by creating a local source of power generation.

A single turbine could be deployed on a bridge pier where it is positioned to take advantage of accelerated flow coming off of the bridge pier. The bridge pier fenders could be designed such...
that they not only defend the bridge from loose ships, but also serve to further accelerate the flow and create a one sided contraction. The turbine could then strategically be placed in this one sided contraction to increase performance.

Multiple turbines could be deployed across a bridge span section that boat traffic does not use. The two piers on each end of this bridge section would act as a two sided contraction for all of the turbines. Multiple large turbines could also be deployed between bridge piers. Crossflow turbines rectangular flow intercepting area allows them to efficiently use the space between two bridge piers compared to an axial flow device.

A large turbine could be built into a bridge pier and the bridge pier could be designed to act as a two sided contraction. This scenario enables the turbine to be sheltered from large debris, and also heavily relies upon the structural rigidity of the bridge pier.

These scenarios would all require further investigation. With larger turbines intercepting a higher percentage of the total tidal flow increased impact on the environment and existing use of the waterways can be expected. The environmental, societal, and economic effects of these devices are areas of research with numerous unanswered questions.
BIBLIOGRAPHY


[59] NOAA. Tides and Currents.


[72] Sonnen Inc. The Sonnen Batterie.


[76] Tesla Inc. Tesla Commercial - Powerpack.

[77] Tesla Inc. Tesla Powerwall.


[81] University of New Hampshire. The Living Bridge Project.


APPENDIX A
SUGGESTED MAINTENANCE

This is an initial maintenance list developed based on the recommendations of manufacturers and expected wear. As more experience is gained in operating the system this maintenance list should be updated.

A.1 Yearly in August

• Check bolts between steel frame and Pontoons for wear
• Check pontoon bolt holes for expansion
• Check frame/pontoon mounting plates for hole expansion
• Check pontoon saddles for wear

A.2 Monthly

• Inflate fenders as needed
• Check turbine bolt torques
• Clean navigation lights as needed (see below)

The Sealite navigation light manual suggests cleaning the solar panels warm soapy water and rinsing with fresh water every month. They suggest changing the battery every 3 years to ensure the lights continue to function as designed.

Every 1000 hours (41 days) the bolts in the load cells should be replaced or at least checked for excessive corrosion. If the bolts show signs of corrosion they should be replaced with M10-1.5x50mm class 12.9 zinc finish socket caps screws as per the LCM Systems specifications. Marine grade anti-seize should be used on all threads. The bolts should be torqued to 70Nm as per the LCM Systems specifications. The load cells should be re-calibrated every time the bolts are replaced.
APPENDIX B

SAFETY PROCEDURE

These procedures were adapted after reviewing the safety procedures for open water testing developed by Matt Rowell [67]. They have been adapted for the Living Bridge Project and it is encouraged that these procedures be reviewed and adapted as personnel and equipment on the project are changed. The goal of these safety procedures is to ensure the safety of first the people working on the water for this project, and second for the equipment used on this project.

B.1 Boat Transit Protocol

Before leaving the dock, the boat operator should lead a brief safety meeting with the entire crew of the boat. This safety meeting can vary in its depth based on the crew and their familiarity with work on the water and the system. In this meeting the team heading out onto the water should review the planned work for the day, any expected hazards that could occur due to that work, and what is going to be done to mitigate the risk of those hazards. It should be established that the boat operator is in charge of the boat and everyone else on the boat should assist the operator as requested. The boat operator should operate the boat in a manner that keeps the crew safe. Some, but not all, potential hazards and some, but not all, methods of mitigating hazards that can occur while operating the boat are listed in Table B.1.

B.2 Turbine Operating Safety Protocol

The TDP should be considered an industrial work environment. When the turbine is operating care should be taken to ensure the safety of the crew and the equipment. To do this a clear overseer of the equipment should be designated. Unless otherwise delegated by the overseer, this overseer should be operating the winch controller and running the turbine controls. The rest of the crew should assist the overseer as requested. Some, but not all, potential hazards and some, but not all, methods of mitigating these hazards when working on the TDP and operating the turbine are listed in Table B.2.

At any time everyone should always speak up about something they see that could pose a potential hazard and those in charge should encourage this type of responsible behavior. Actions should be taken to prevent or eliminate those hazards.
Table B.1: Boating transit safety

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Docking and undocking in fast currents</td>
<td>Listen to commands of boat driver and dock and undock how they prefer. Remove the stern dock lines first, then remove the bow dock lines. Always dock the boat at the TDP such that the bow is pointed into the currents. Ensure that the boat fenders are positioned on the correct side of the boat for docking.</td>
</tr>
<tr>
<td>Cuts, scrapes, tripping</td>
<td>Long pants and close toed shoes are required for working on the TDP.</td>
</tr>
<tr>
<td>Transiting</td>
<td>Evenly distribute weight in the boat (equipment and personnel). Personnel should not move excessively around the boat. The boat driver should use caution and stay alert in areas known to have rough water such as Henderson Point and in the wakes of other boats. The boat driver should stay within channel markers while in transit.</td>
</tr>
<tr>
<td>Environmental hazards</td>
<td>PFDs should be worn at all times when on the water. Proper clothing that suits the current weather conditions should be worn. Operations at night or in low visibility should be avoided, and if they must be performed proper lighting or visibility aids (radar reflectors) should be used.</td>
</tr>
</tbody>
</table>
### Table B.2: Turbine safety

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Man overboard situations</td>
<td>Close railing cables if they do not impede the work on the TDP. PFDs are required for work on the TDP. Be aware of procedures for using the life ring.</td>
</tr>
<tr>
<td>Electrical hazards</td>
<td>Personnel working inside the TIP should be familiar with its functions and should perform maintenance on the system when it is in a de-energized state. All personnel on the TDP should be aware of the locations of the emergency stop buttons and know that they will brake the turbine if pressed.</td>
</tr>
<tr>
<td>Turbine Winching</td>
<td>Personnel should stay clear of the potential snap area of the winch rope. A winch rope damper should be used. The winch rope should be inspected for excessive fraying, kinks, or any other damage. The winch cover should be used to prevent rope damage. While winching the turbine into the moon pool check that the strongback and locking arms will not hit anything such as railing cables, the load cell clevises, walkway, or other personnel.</td>
</tr>
<tr>
<td>Turbine Operation</td>
<td>No personnel should climb the strongback, be on the spanning beam, or on the movable platform over the moon pool when the rotor is spinning. Any work that can be done on the top of the strongback should be done when the rotor is in the removed position to avoid the need to climb the strongback.</td>
</tr>
<tr>
<td>Cuts, scrapes, injury</td>
<td>All personnel should be aware that there is a first aid kit on the TDP, in the emergency toolkit. The first aid kit should remain stocked with bandages and an emergency blanket.</td>
</tr>
</tbody>
</table>
APPENDIX C

TDP ENGINEERING DRAWINGS
MEMORIAL BRIDGE PIER 2 [EXISTING]

VERTICAL GUIDE POST (2X)

DECKING

RAILINGS

PILE GUIDES

STEEL FRAME

HDPE PONTOON (2X)

VERTICAL AXIS CROSS FLOW TIDAL TURBINE [NOT INCLUDED IN THE SCOPE OF THIS WORK]
TO KITTERY

STARBOARD

BOW

PORT

35.77x12.22x0.5 PLATES X12
SEE "FRAME - MOUNTING PLATE"
AND "FRAME - END MOUNTING PLATE"

W12X26 AT
LEAST 232
LINEAR FEET

SEE "FRAME - CONNECTIONS" FOR CONNECTION DETAILS
DETAILED ALL CONNECTIONS

TO PORTSMOUTH

FRAME - DIMENSIONS

TURBINE DEPLOYMENT PLATFORM

MILD STEEL
MIN YS = 50 KSI

QUANTITY: 1

UNLESS OTHERWISE SPECIFIED,
DIMENSIONS ARE IN INCHES.

MIN = A. SEE X
MAX = B. SEE X

I. GAGNON
7/12/16

SHEET 2 OF 22
NOTE: BLUE denotes moments and forces calculated by DNVGL.
2X Ø .81 THRU ALL

3.00

35.77

8.26

10.00

1.11

BOTTOM OF I-BEAM FLANGE INSTALLED HEIGHT

MATERIAL: MILD STEEL
MIN YS = 50KSI

QUANTITY: 10

DO NOT SCALE DRAWING.

TURBINE DEPLOYMENT PLATFORM

FRAME - MOUNTING PLATE

Sheet 1 of 22

University of New Hampshire
College of Engineering and Physical Sciences
BOTTOM OF I-BEAM FLANGE INSTALLED HEIGHT

FRAME - END MOUNTING PLATE
BOLT DECKING TO FRAME AS NECESSARY WITH 1/2-13 GALVANIZED BOLTS
BOLT RAILINGS THROUGH SILLS AND I-BEAM FLANGES IN NECESSARY LOCATIONS
WITH 3/8 HEX SCREWS

REMOVED SPECIFIC DECKING HOLES AND REQUIRED
RAILING HOLES THROUGH I-BEAM FLANGES
STIFFENER PLATE LOCATIONS HAVE BEEN MARKED WITH THE "Z" DATUM MARKERS IN THE CASE OF "Z"" ONE BRACKET SHOULD BE WELDED ON EACH SIDE OF THE HEAVY STIFFENERS SHOULD BE CENTERED BETWEEN THE MOUNTING HOLES THEY ARE LOCATED UNDER OR AS DIMENSIONED.
BRACKETS ARE WELDED 4.25 IN BELOW TOP I-BEAM FLANGE
SEE "FRAME - BRACKET MOUNTING"

MOUNTING BRACKET LOCATIONS HAVE BEEN MARKED WITH THE 1 AND 2 DATUM MARKERS
SEE "FRAME - BRACKET MOUNTING"
IN THE CASE OF 1 ONE BRACKET SHOULD BE WELDED TO THE SIDE OF THE I-BEAM MARKED BY THE DATUM
IN THE CASE OF 2 TWO BRACKETS SHOULD BE WELDED ON EACH SIDE OF THE I-BEAM WEB
THE FLAT MOUNTING FACE OF THE BRACKET SHOULD BE ALIGNED WITH THE DIMENSIONED LINES ABOVE
A TOTAL OF 62 BRACKETS ARE NEEDED

1 | 1 BRACKET AT THESE LOCATIONS
2 | 2 BRACKETS AT THESE LOCATIONS
JOISTS BOLT TO JOIST BRACKETS WITH GALVANIZED BOLTS
JOISTS SPACED EVERY 18" AS PER THRU-FLOW DECKING SPECS

TOP OF SILLS AND JOISTS SHOULD BE FLUSH

ROPE CLEATS
MCMASTER #33B057480 (8X) OR EQUIVALENT
BOLTED THROUGH SILLS
TRIM DECKING PANNELS AS NEEDED

MOVED CLEATS TO TOP OF FLANGE

SILLS BOLT TO TOP I-BEAM FLANGE

PRESSURE TREATED 2X6 FOR JOISTS AND SILLS
AT LEAST 754 LINEAL FEET
DECK PANELS ARE THRU-FLOW LIGHT GREY AQUA-DEK PANELS 36"X24" 
80 PANELS NEEDED @ $41.94 EACH
DECKING IS TO BE INSTALLED AS PER MANUFACTURER’S SPECIFICATIONS
DECKING CAN BE TRIMMED AWAY TO FIT RAILING FOOTINGS AND CLEATS
NEW SHACKLE SPEC

THE HOST RINGS CONNECT TO SHACKLES RATED TO 2000 LB WITH A 1.61 DESIGN FACTOR SUCH AS FASTENAL PART NO. (35U): (061) 244
THE SHACKLES CONNECT TO A CHAIN RATED TO A LEAST 74000 LB
THE CHAIN IS COVERED IN 2IN SECTIONS OF STEEL PIPE TO ACT AS ROLLERS ON THE VERTICAL GUIDE POSTS

MEASURE AS BUILT VGP DIMENSION BEFORE FABRICATION

86.88

= AS BUILT CENTER TO CENTER VGP DIMENSION

16.00 PILE

FENDER PLATE (2X)

UNHWPE

4X .53 THRU ALL

1/2-13 UNC THRU ALL

1/1-14 UNC THRU ALL

.42 THRU ALL

4X 1.13 X .74

1.18 X 90°, NEAR SIDE

1.50

5.00

4X .42 THRU ALL

1/2-13 UNC THRU ALL

2X 1.11 THRU ALL

1/1-14 UNC THRU ALL

.42 THRU ALL

4X 1.13 X .74

1.18 X 90°, NEAR SIDE

1.50

5.00

 LEAVE OPENING FOR WATER TO DRAIN

FENDER SPACER (2X) (BEHIND FENDER PLATES)

UNHWPE

4X .53 THRU ALL

1.50

5.00

PILE GUIDE PLATE (2X)

COLD ROLLED STEEL HDG

2.22

1.50

6.50

4X .42 THRU ALL

1/2-13 UNC THRU ALL

2X 1.11 THRU ALL

1/1-14 UNC THRU ALL

4X .53 THRU ALL

1.13 X .74

1.18 X 90°, NEAR SIDE

1.50

5.00
NOTE: THIS COMPONENT CAN BE MADE IN TWO SEPERATE PIECES DIVIDED ALONG THE LINE OF SYMMETRY
<table>
<thead>
<tr>
<th>REVISION</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>REMOVED BOLTED SPICE (FRAME - DIMENSIONS)</td>
</tr>
<tr>
<td>2</td>
<td>MOVED CLEAT MOUNT HOLES TO BEAM FLANGE (FRAME - DECKING AND POLE ROOM HOLES)</td>
</tr>
<tr>
<td>3</td>
<td>ADDED HOLE PATTERN FOR MOUNT MOUNT (FRAME - DECKING AND POLE ROOM HOLES)</td>
</tr>
<tr>
<td>4</td>
<td>CHANGED FROM 1/4 IN. TO 3/16 IN. CENTER (FRAME - INSTRUMENT MOUNT HOLES)</td>
</tr>
<tr>
<td>5</td>
<td>ADDED STIFFENERS (FRAME - STIFFENERS)</td>
</tr>
<tr>
<td>6</td>
<td>MOVED CLEATS TO TOP OF FLANGE (FRAME - WITH DOTS AND DOTS)</td>
</tr>
<tr>
<td>7</td>
<td>MODIFIED PILE GUIDE DESIGN (FRAME - PILE GUIDE)</td>
</tr>
<tr>
<td>8</td>
<td>REMOVED SPECIFIC DECKING HOLES</td>
</tr>
<tr>
<td>9</td>
<td>ADDED ADDITIONAL MOUNTING HOLES</td>
</tr>
<tr>
<td>10</td>
<td>SWITCHED FROM SINGLE TO DOUBLE HOLES MOUNT HOLES</td>
</tr>
<tr>
<td>11</td>
<td>SWITCHED FROM 2 EYE BOLTS TO 4 EYE BOLTS</td>
</tr>
<tr>
<td></td>
<td>SWITCHED FROM PIPE FLANGE TO PIPE POSTING</td>
</tr>
<tr>
<td></td>
<td>SWITCHED FROM TUBE TO PIPE TO CARABINERS</td>
</tr>
<tr>
<td></td>
<td>SWITCHED FROM PIPE TO ROD</td>
</tr>
<tr>
<td></td>
<td>ADDED KICKPLATE</td>
</tr>
<tr>
<td>12</td>
<td>ADJUSTED MOUNT HOLES IN MOON POOL</td>
</tr>
<tr>
<td>13</td>
<td>ADDED ADDITIONAL RAILING SPECs</td>
</tr>
<tr>
<td>14</td>
<td>SWITCHED TO HEX SCREWS</td>
</tr>
<tr>
<td>15</td>
<td>NEW SHACKLE SPEC</td>
</tr>
<tr>
<td>16</td>
<td>CREATED TWO SPICE LINES</td>
</tr>
<tr>
<td>17</td>
<td>ADJUSTED BRACKET DIMENSIONS TO MEET TIMBER DESIGN CODE</td>
</tr>
<tr>
<td>18</td>
<td>ADDED FRAME - MOMENT SPICE CONNECTION DRAWING</td>
</tr>
<tr>
<td>19</td>
<td>SWITCHED BACK TO ONE SPICE</td>
</tr>
<tr>
<td>20</td>
<td>INCLUDED ADDITIONAL CONNECTION DETAIL DRAWINGS</td>
</tr>
<tr>
<td>ZONE</td>
<td>REV.</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX D

TPM ENGINEERING DRAWINGS
5MWT YXILT X20 WOP GEN 2
WIRELESS 12,000LB WINCH
 PROVIDED BY UNH

INSTREAM ENERGY SYSTEMS (IES)
10KW TIDAL TURBINE
 PROVIDED BY IES

POWER MANAGEMENT
 CONTROLS CABINET (PMCC)
 PROVIDED BY IES.

TURBINE PITCHING
 MECHANISM (TPM)

RIGHT BEAM CRADLE

SPANNING BEAM ASSEMBLY

FABRICATOR SUPPLIES ALL HARDWARE UNLESS
NOTED OTHERWISE
USE GALVANIZED HARDWARE

TURBINE PITCHING
MECHANISM

<table>
<thead>
<tr>
<th>NAME</th>
<th>SIGNATURE</th>
<th>DATE</th>
<th>REVISION</th>
</tr>
</thead>
<tbody>
<tr>
<td>DARRIE J. GAGNON</td>
<td></td>
<td>08/19/17</td>
<td></td>
</tr>
<tr>
<td>DARRIE J. GAGNON</td>
<td></td>
<td>09/20/17</td>
<td></td>
</tr>
<tr>
<td>APPLYRA W. WISEN</td>
<td></td>
<td>09/20/17</td>
<td></td>
</tr>
</tbody>
</table>
THIS DRAWING IS THE PROPERTY OF THE UNIVERSITY OF NEW HAMPSHIRE AND ITS AUTHORS.
IT MUST NOT BE COPIED OR REPRODUCED IN WHOLE OR IN PART BY ANY MEANS WHATSOEVER
WITHOUT THE APPROVAL OF ITS AUTHORS.

See interface bolt pattern sheet 11 of 21
For detailed mounting schedule

1

Spanning Beam Assembly

Turbin Pitching Mechanism

Heads

1

A3
LOCKING PIN MUST PASS THROUGH LOCKING ARM AND CLEVIS WHICH IS MOUNTED TO THE LOAD CELLS MOUNTED ON BASE PLATES AFTER GALVANIZATION.
ALL WELDS MUST BE AT LEAST AS STRONG AS THE MATERIAL THAT THEY ARE BONDING. HALF RINGS SHOULD FIRST BE WELDED TO SPANNING BEAM, THEN OTHER COMPONENTS WELDED TO HALF RINGS AND SPANNING BEAM.
LEFT INTERFACE BRACKET MOUNTING FACE AFTER WELDED TO SPANNING BEAM

RIGHT INTERFACE BRACKET MOUNTING FACE AFTER WELDED TO SPANNING BEAM

8X Ø 1.10 28 THRU ALL

SUGGEST MAKING TEMPLATE ON CNC TO BE USED WHEN WELDING BRACKETS TO SPANNING BEAM.

USE 8 GALVANIZED 100MM CLASS 10.9 M24X3 BOLTS WITH HIGH STRENGTH EXTRA WIDE HEX NUTS AND OVERSIZED WASHERS JAM THE NUTS WITH JAM NUTS

CORRESPONDS TO SPANNING BEAM CENTER LINE
LEFT BEAM CRADLE (MAKE 1)

SUNRAY 3500# 2.5' OD ROLLER 0.75' SS SHAFT WITH SEALED BALL BEARINGS (SUPPLIED BY UNH)

UPPER RETAINER
THrust Bearing
BACKER PLATE
U-CRADLE
ROLLER SPACER
LEFT EXTERIOR BASE PLATE
USE JAM NUTS TO JAM BOTTOM NUTS ON
WELD U-CRADLE TO BASE PLATES ALL AROUND

RIGHT BEAM CRADLE (MAKE 1)

RIGHT EXTERIOR BASE PLATE
RIGHT INTERIOR BASE PLATE

MATERIAL: HDG
QUANTITY: 1
TURBINE PITCHING MECHANISM

DRAWN: L. GAUGHAN
DATE: 08/19/17
CHECKED: J.J.
APPROVED: A. WOJSNICK
DATE: 09/20/17

1
BEAM CRADLE

SWG NO. A3

SHEET 12 OF 21
WELD U-CRADLE TO BASE PLATES (SHEET 14)
AND RETAINER BRACKETS ALL AROUND (SHEET 15)
WELDS SHOULD BE AT LEAST AS STRONG AS MATERIAL THAT THEY ARE BONDING
PRESS UHMWPE BUSHING INTO THIS GROOVE

UHMWPE

STEEL

∅ 1.31 THRU W/ 45 DEG 0.1 IN CHAMFER

3x ∅ .56 THRU ALL

4.75

3x ∅ .56 THRU ALL

4.75

0.38

R3.5

1.98

1.50

1.50

1.50

1.50

∅ 1.31 THRU W/ 45 DEG 0.1 IN CHAMFER

4.00

1.25

0.20

0.20

M4 X 5.62 KSI 3/8" STEEL PLATE (LEFT)
UHMWPE (RIGHT)

1

UPPER RETAINER

TURBINE PITCHING MECHANISM

QUANTITY: 2

DO NOT SCALE, TRIM, OR CUT AND BROKE PART OFF

DRAWING SHEET 1 OF 31

A3

UNIVERSITY OF NEW HAMPSHIRE
College of Engineering and Physical Sciences

DRAWN: L. GARCIA
CHECK: L.E.
APPROVED: R. WODNICK

09/17

09/17

08/19/17
UNH WILL SUPPLY ADDITIONAL ROPE CLEAT
SPRAY HOLES WITH COLD GALV AFTER DRILLING,
LET DRY, THEN INSTALL BOLTS.

RECESS/CUT AWAY DECK GRATING IF NECESSARY
TO ACCOMMODATE NUT/BOLT HEADS

.DXF FILES AVAILABLE FOR NUMERIC CUTTING

THIS SIDE GOES ON THE EDGE OF THE PLATFORM

UNH WILL SUPPLY 3 CROSBY HR-1000CT 6608139
HOIST RINGS TO BE THREADED INTO THE 7/8-9 HOLES

.DXF FILES AVAILABLE FOR NUMERIC CUTTING

DRILL NEW HOLES [0.56"] IN EXISTING FRAME FOR:

<table>
<thead>
<tr>
<th>HOIST RING MOUNT PLATES</th>
<th>8</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEW CLEAT</td>
<td>2</td>
<td>B</td>
</tr>
<tr>
<td>PMCC MOUNT</td>
<td>4</td>
<td>C</td>
</tr>
<tr>
<td>LOAD CELL MOUNT PLATES</td>
<td>16</td>
<td>D</td>
</tr>
</tbody>
</table>

HOIST RING MOUNT PLATES (MAKE 3):
2 ON PLATFORM, 1 ON STRONGBACK

Φ .77 THRU
7/8-9 UNC. THRU

PMCC MOUNT BARS (MAKE 2)
SPRAY PAINT WITH HIGH VIS PAINT AFTER GALVANIZING

4X Ø .56 THRU
4X Ø .56 THRU ALL

4.50
14X Ø .56 THRU

6.00
2.00

42.50
39.00

62.37
4.00

21.00
4.50

3.25
2.25

3.25
2.25

6.50
1.00

6.50
6.50

1.00
1.00

1.00
1.00

2.00
3.00

4.50
4.50

2.00
2.00

1.00
1.00

1.00
1.00

1.00
1.00

1.00
1.00

1.00
1.00

1.00
1.00
TURBINE JUNCTION BOX TO PMCC - 646IN
CABLES SUPPLIED AND RUN BY IES

PMCC TO DROOP - 400IN
CABLES SUPPLIED AND RUN BY UNI I

- Run from end of spanning beam to PMCC via cable carrier (UNH supplies assemblies and mounts) then under decking clipped to joists using McMaster Part No. 7565K33 or similar.
- Run from junction box to spanning beam suggest IES adds clips to zip-tie cable to turbine mounting bracket.
- Holes may be cut through decking grating to pass cables through where needed.

PCM/Ace weld on 1/2" HDG steel rod to spanning beam to secure cables to. Leave >1/2" gap between rod and spanning beam surface to place zip-ties. Use standoff if necessary. No bending radii in rod smaller than 6". End rod near holes for cable carrier pointed towards platform bow. Ensure no interference with turbine. Contact UNH for additional information if needed.
APPENDIX E

TPM ENGINEERING DRAWINGS
203

SOLIDWORKS Educational Product. For Instructional Use Only

ITEM NO.  PART NAME  QTY.
1       BACK PLATE 1
2       TOPPER PLATE 2
3       SIDE ARM 2
4       UPPER GUSSET 2
5       LOWER GUSSET 2
6       BACK STIFFENER 1
7       CROSS BAR 1

FILLET WELDS SHOULD BE USED AROUND ALL JOINTS
NOTCHES SHOULD BE FILLED WITH WELD AND
OPEN ENDS SHOULD BE FILLED WITH WELD AND GROUND FLUSH

ESTIMATED ASSEMBLY WEIGHT: 697LB

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES:
   X =  ± .125
   Y =  ± .125
   Z =  ± .030
Weld: ASME A307

SHEET 1 OF 8
APPENDIX F

TURBINE TORQUE VALUES
NOTE: RE-TOURQUE VALUE IS LOWER BY 10% TO PREVENT DAMAGING THE THREADLOCKING COMPOUND.