Bodega Bay Hydropower Feasibility

By Marty Allgeier, Jon Martindill, and Alex Sloan

Acknowledgements

We would like to thank the following individuals for their generous time and assistance in helping us complete this project:

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Introduction

The Bodega Bay Marine Research Laboratory (BML) was founded in 1960 by the National Science Foundation and transferred to UC Davis in 1983 [1]. The Bodega Marine Reserve surrounds BML—this 362-acre stretch of protected habitat provides researchers and students with optimal conditions for conducting world-renowned research on coastal ecosystems. BML's interdisciplinary research includes assessing the impacts of climate change (e.g., sea level rise, increasing ocean temperatures) and anthropogenic damages (e.g., oil spills, invasive species) on marine habitats [1]. Driven by the nature of their research and the UC Carbon Neutrality Initiative, BML leadership is working to achieve an internal goal of becoming the first carbon-neutral marine research and education facility.

BML recognizes the value of energy efficiency, evidenced through several existing improvements made to facility systems including the installation of variable speed drives on major pumps, upgrading to a condensing boiler to save propane costs, and a sea water heat exchanger for space conditioning in one building. To reach carbon neutrality, they plan to continue making efficiency upgrades and also develop renewable energy generation.

Problem Description

The Bodega Marine Research lab facility uses a considerable amount of energy in its current configuration, averaging 150-180 MWh per month. This costs UC Davis about $260,000 per year, making it one of the most expensive operational expenses required to keep the facility running. Recognizing this challenge, BML seeks to find low carbon alternatives to reduce or offset this sizeable load. In particular, they are interested in the viability of using hydroturbines to harness the mechanical energy of seawater at the outflow of their facility depicted as "Potential Turbine Site" in Figure 1. This report serves as a feasibility assessment to address this potential renewable generation opportunity.
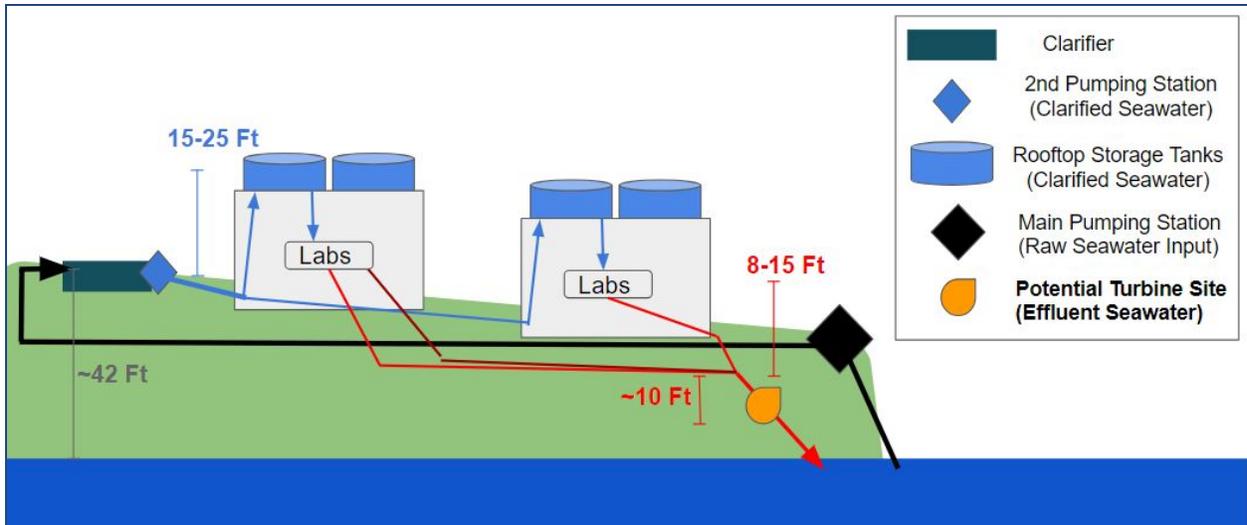
Figure 1: Diagram of BML's seawater distribution system

System Description

Figure 2 shows a diagram of BML's seawater distribution, while appendices A and B contain more detailed aerial views of the system. BML's seawater flow begins with two 15-horsepower pumps continuously pulling approximately 400 gallons per minute from Horseshoe Cove up a 50-foot incline. Once it reaches the building-level, seawater runs through a clarifier, followed by a second pumping station that delivers it to rooftop tanks for storage. From the tanks, seawater is gravity-fed to the labs and effluent flows freely via three separate pipes that run underground until they converge on the coast. At this point, the combined effluent runs back to the ocean. The location just down-flow from the convergence is assumed to be most practical installation location for a hydroturbine to maximize head.

Figure : Three pumps sending seawater to rooftop holding tanks at BML facility

Though the clarifier filters most of the influent initially, the effluent can contain plant and animal materials picked up from the laboratory. Buildup of these materials including sand, mud, kelp, and shells is a challenge for the facilities team and requires a subcontractor to perform occasional

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high-pressure pipe cleaning to clear blockages. Adequate 24/7 operation of the seawater distribution system is essential for the facility since some marine species in the facility require a consistent flow to stay alive. For example, if sea anemones do not receive adequate flow for more than five hours, they may die and subsequently release toxins that can then kill other species in the facility.

Literature Review

The first step in developing a recommendation for BML entailed research into the research into literature related to the proposed installation. Our findings were primarily related to biofouling and corrosion, performance of similar installations, and suitable types of hydroturbines.

Biofouling & Corrosion

Any surface exposed to seawater (especially raw seawater) are prone to biofouling. Organisms such as muscles, algae, and even crabs can grow on anything submerged in seawater. During a tour of the BML facility, the research team observed multiple organisms emerging from the influent before entering a separator shown in Figure 3.

Shrimp, crabs, seaweed, and other organisms either find their way through the pumps or are born inside the system. The growth of organisms on a proposed turbine will increase drag, thereby reducing efficiency and potentially causing a malfunction.

Figure : Primary separator for influent pouring into the clarifiers

Furthermore, many turbines are also sensitive to impure water and lose efficiency with increasing turbidity. Object collisions and biofouling can significantly reduce turbine life expectancy [2]. Several experimental methods of reducing biofouling on oceanic machinery exist.

Foul release coatings (FRCs) are non-toxic compounds that alter the microscopic texture of a surface. These coatings can create a low surface energy condition that inhibits the adhesion of macroscopic organisms such as algae and muscles [3]. However, these surfaces still allow the development of biofilm, which is a tenacious layer of bacteria. Being thin and flat, biofilms are subject to very little shear forces and therefore can cling on to even fast-moving turbine blades. Periodic power washing is a typical method for removing biofilms. However, ultrasonically activated streams (UASs) have proven to be three times more effective than traditional power washing. UAS can operate at low flow rates, cleaning without chemicals and without damaging the surface of the machinery [3].

Corrosion is a major concern with any seawater installation. The Yanbaru pumped hydroelectricity energy storage (PHES) system in Okinawa, Japan which was the only seawater-based PHES installation in the world until it closed in 2016 used a turbine constructed of austenitic stainless steel [4], though seals and biofouling still presented challenges [5]. In a

pumped hydro technical analysis, Katsaprakakis [6] et al. note that all parts of the Pelton turbines in their proposed design (runner, needles, nozzles, etc.) must be made from nickel chrome stainless steel (G-X5CrNi13.4Mo).

Turbine Selection

With estimated flow rates of under 0.05 m³/s and a vertical head somewhere between 3 and 10 meters,
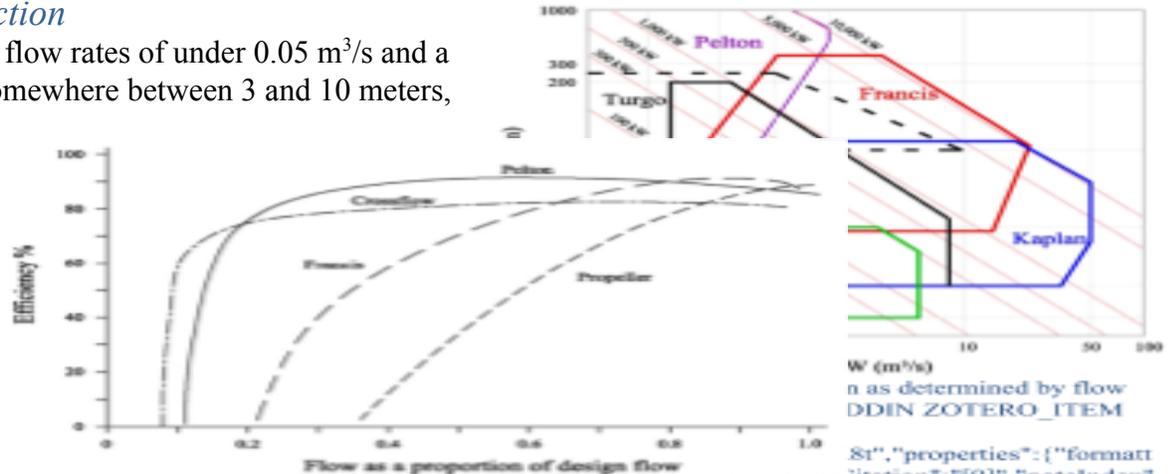
Figure : Turbine efficiency at portion of design flow

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this site requires a turbine designed for low flow and low head (**Error! Reference source not found.**). In addition, since the facility does not produce a consistent, controlled flow, the turbine must have the ability to work with a wide range of flows. Given these basic limitations, many types of turbines could be eliminated from consideration. According to an analysis of low-head "micro" hydropower turbines from Elbatran, *et al.* [7], Pelton, Turgo, and Francis turbines are only effective at heads greater than 10 meters. Propeller turbines, such as the Kaplan, require flow at or near their designed flow rate in order to be reasonably efficient (**Error! Reference source not found.**). Therefore, according to this study, the only two turbine types that are feasible for this site are the crossflow turbine and the Archimedes screw. In addition, other papers in the literature, such as Yaakob, *et al.* [8], identify the gravitational vortex turbine as a highly efficient low-flow turbine that can operate at high efficiency in a range of flow rates.

1. Cross-Flow Turbine

The cross-flow turbine is an impulse-type turbine that functions by pressurizing water at a nozzle and firing it at an optimal angle through a rotating drum (**Error! Reference source not found.**), allowing it to extract a great deal of energy from the water at lower vertical heads than Pelton turbines [9].

Figure : Diagram of cross-flow turbine

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2. Archimedes Screw Turbine

The Archimedes screw is a highly efficient turbine that operates extremely well with low amounts of head and can perform well at a wide range of flow rates [10]. A notable feature is that this unit is designed to allow fish and other debris to pass through unharmed, so any issues that could arise with debris outflow from the lab might be mitigated by selecting this turbine.

Figure 7: Overview of an Archimedes screw turbine [11]

3. Gravitational Vortex Turbine

The gravitational vortex turbine is a newer technology that uses a concrete structure to direct the flow of water in order to form a vortex. Like the Archimedes screw, it is designed to allow the safe passage of large objects and debris, including live fish [8]. It is also designed to function at high efficiencies in areas without significant pressure head, making it a potentially ideal turbine for this site.
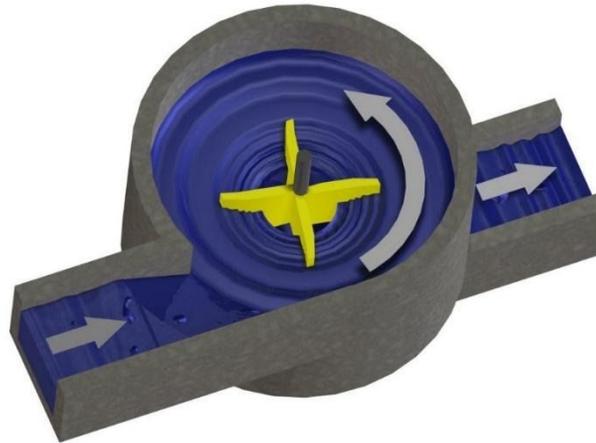
Figure 8: Gravitational vortex turbine [12]

Methodology

To complete the hydropower feasibility assessment for BML, the steps outlined in **Error! Reference source not found.**were followed. The first stage of information gathering started off with a kickoff call followed

by a site visit. These initial operations helped the research team understand BML's motivation for pursuing the project and helped develop an understanding of the barriers facing a proposed installation. After gaining this insight, literature review and collection of water flow, energy, and billing data took place.

After receiving the necessary data, the team performed various analyses to determine the energy generation potential of an installed turbine. As described in the section below, certain assumptions were made. Initial findings were then passed along to multiple turbine manufacturers to determine appropriate turbine selection and cost to install. In sequence with turbine manufacturer outreach, contact with UC Davis's Pacific Gas & Electric Company (PG&E) account manager and the UC Davis Director of Environmental Planning took place. PG&E discussions centered on available incentives and interconnection while discussions with the planning team focused on regulatory compliance.

Once all necessary information was gathered, a final economic analysis was completed, comparing estimated benefits from generated electricity with production and maintenance costs.

Analysis

Flow Analysis

In order to perform the necessary calculations to determine which turbine to use and how much electricity can be generated, a set of assumptions were made. Specifically, a detailed elevation profile of the facility's water flow (e.g., vertical distance between buildings and outflow) was not available. Additionally, the water pressure of the effluent pipes at the outflow was unknown. Consequently, characteristics of the system are assigned estimates based on the research team's site visit and available blueprints.

BML provided the chart shown in Figure 10. Typically, the flow through the effluent pipe of potential hydropower location fluctuates between 375-550 gpm, with an average value of 400 gpm. The system also experiences occasional peaks of up to 750 gpm that tend to last approximately 30 minutes. Consequently, calculations were performed on the premise that the system would receive an average of 400 gpm, but is also capable of receiving up to 1,000 gpm for short periods of time.

Figure 10: Chart of flow through effluent pipe on March 9th, 2015

Given that the BML piping system is largely underground, the characteristics of the pipe flow must be estimated. Manning's equation for partially-filled pipes (Appendix C) indicates that the point of interest has water flowing at approximately 14 m/s with a depth of 10 inches in the 12 inch pipe. This indicates that the effluent pipe is not hydraulically pressurized, therefore much of the pressure head energy is lost during the downhill flow. Instead of the potential 12-meter head for a pressurized system, the partially-filled pipes are estimated to have a 3-meter head.

Economic Analysis

In order to better understand how the variables of the hydraulic system will impact the economic performance of a turbine installation, a theoretical economic analysis was performed for the site. First, a physical equation was selected that would allow adjustments to the flow rate, head, and pump system efficiency (Equation 1). A range of potential values were tested with this equation to determine the potential range of power outputs from the turbine.

Equation : Theoretical pumping system power generation and estimates for parameters ADDIN
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To convert the power generation to economic benefits, a cost of $0.132 per kWh was assumed, as was a $12 reduction in monthly demand charges. These assumptions come from electricity

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cost data provided by the BML, as well as an investigation into the electricity tariff structure of the lab. In addition, this analysis uses a 3% discount rate and a 20 year target payback time.

Using these parameters, the relationship between flow rate and annual revenue from a turbine installation was estimated (Figure 11). The most efficient turbine at 700,000 gallons per day would generate about $1000 per year, and would generate around $700 at 500,000 gallons per day.
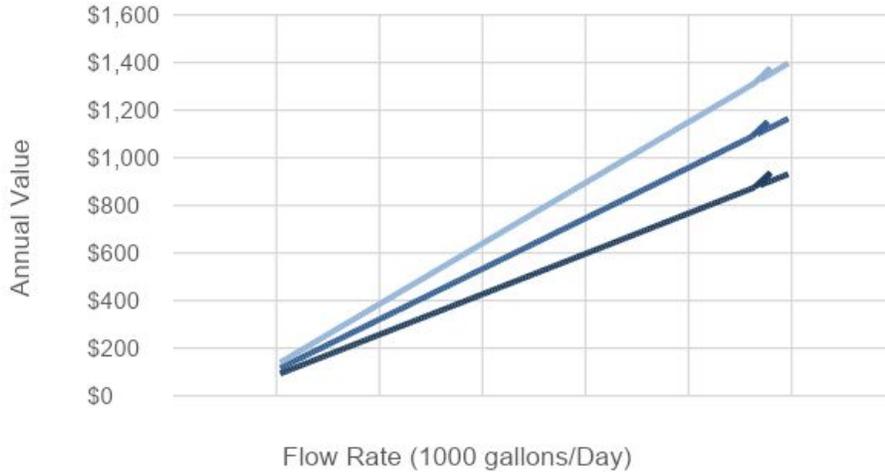
Figure 11: Annual value of a turbine vs. flow rate and efficiency, assuming 3 meters of head

In addition, the vertical head available makes a very large difference in the theoretical annual value. If the hydraulic system is able to capture the entire pressure head from water coming out of the labs, the annual value of a turbine could exceed $3,000. On the other hand, if the only vertical head available is the incline at the shoreline itself, the system would likely produce less than $1000 per year (Figure 12).
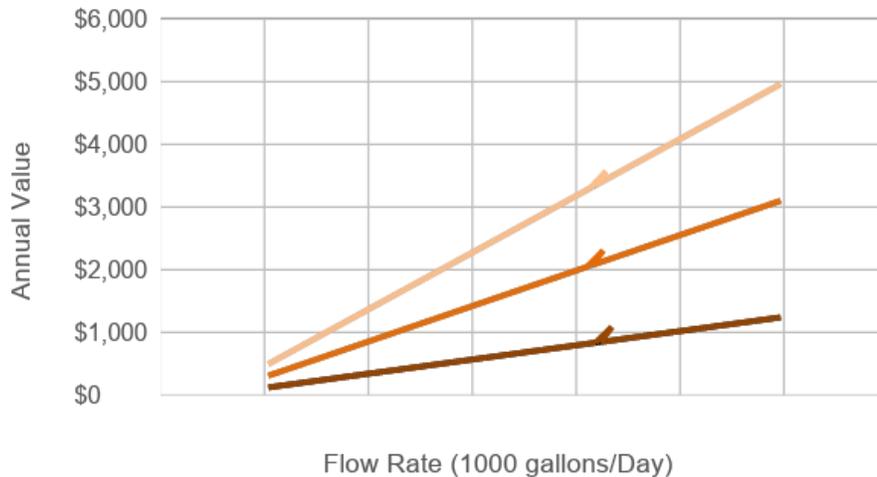
Figure 12: Annual value of a turbine vs. flow rate and head, assuming 75% efficiency

These changes to annual value have a major impact on the highest feasible turbine cost. Assuming a 20 year target payback at a 3% discount rate, the most that a project could cost in the

worst-case head scenario is under $10,000, while capturing the entire pressure head would allow for a project that costs four times as much (Figure 13)
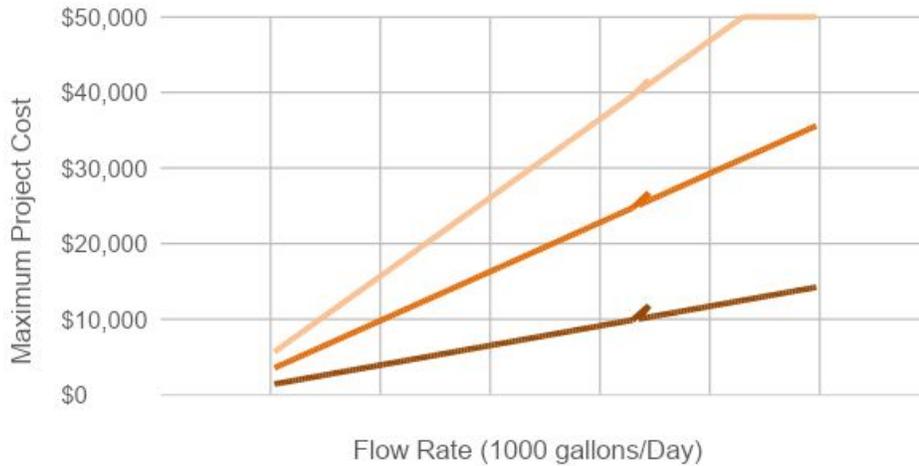

Figure 13: Maximum feasible project cost vs. flow rate and head, assuming 75% efficiency

The results of this theoretical analysis indicate that any project must have initial costs below $10,000 if it is not expected to capture any head before the shoreline outflow. Since the pipe is currently not full, any project that does attempt to capture the pressure head above the shoreline would require additional construction. However, given the significant economic benefit to increasing the available pressure head, such construction could be justified.

Turbine Selection

This report investigated the economic costs and performance specifications for three different turbine technologies from three different manufacturers. The three technologies were selected based on the literature review for their applicability to the site given its vertical head, average flow rate, and high degree of flow variance. Manufacturers for each turbine time were contacted in order to verify the technical feasibility of the installation given the parameters of the site as well as estimates of power generation and cost. While manufacturers of both cross-flow and vortex turbines were willing to provide this information, no manufacturer of the Archimedian screw turbine was willing to discuss costs and feasibility with the researchers. Fortunately, multiple feasibility studies on Archimedes turbine installations in England were available [13]–[15], and were used to estimate costs and benefits from installing a turbine at this location.

Results and Discussion

Cross-Flow Turbine – Scott Hydroelectric

Scott Hydroelectric [16] offers a 1500 watt cross-flow turbine for $3,900, with additional equipment and installation costs bringing the total upfront cost to around $12,000. The turbine itself is only 70 pounds, which means it could be installed without the use of heavy machinery. The turbine is most efficient at around 1,200,000 gallons per day of flow and at least 8 meters of head, though it can operate well with 5 meters of head. In order to achieve this level of head at the installation site, a new outflow pipe with a smaller diameter would have to be installed at the site. As seen in **Error! Reference source not found.**, this turbine operates at a high efficiency at a wide range of flow rates.

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The turbine is built to power off-grid homes near streams and is designed to operate with minimal maintenance and no specialized skills. As a result, it has an extremely low annual cost, estimated at $300. This turbine can handle small debris, but is not designed to handle larger debris such as rocks and living animals. As such, the installation of this turbine may require screens to prevent such debris from entering the system.

While this analysis assumes 5 meters of head, a larger upgrade to the system could allow for the ability to capture up to 12 meters of head, which could potentially allow the turbine to generate over 1 kW of electricity on average. However, assuming that a larger upgrade will not happen, it would produce an estimated 0.82 kW on average, saving the lab $1100 in electricity costs per year. Based on these estimates, this project has a net present value of -$2,750, assuming a 3% discount rate, and a payback period of 21 years (**Error! Reference source not found.**).

Gravitational Vortex Turbine – Barnard Hydro Solutions

Barnard Hydro Solutions, Inc. is a manufacturer and distributor for a specific type of gravitational vortex turbine called the Kouris Centri-Turbine (KCT) [17]. The KCT highly modular and scalable – instead of requiring a large concrete structure, the turbine is pre-built from steel or plastic and can be installed at any site within 12 hours. However, it would require concrete reinforcement at this given site due to the potential damage caused by ocean waves, and would require a large truck to transport the turbine itself.

A 1 kW turbine would cost about $20,000, and added equipment and installation costs are expected to lead to a final upfront cost of around $50,000. While the turbine should require minimal maintenance each year, $500 has been budgeted for annual costs of maintenance. It is a more complex and specialized machine than the crossflow turbine, but is significantly less complex than the Archimedian screw.

Since the turbine was designed to operate at high efficiency without a pressurized pipe, it would not be necessary or beneficial to make additional changes or upgrades to the system. Therefore, the costs and benefits from this installation carry a greater certainty than those presented for the crossflow turbine. Unfortunately, the high costs of the equipment and installation prevent this turbine from being economically feasible. With a net present value of -$40,400 and a payoff time greater than 100 years, this project is not a quality investment (**Error! Reference source not found.**).

Archimedian Screw Turbine

Given the available space, vertical head, and flow rate at the site, upfront costs of $210,000 were estimated, including construction costs and all equipment. The Archimedian screw turbine is larger than the gravitational vortex turbine, requires specialized skills to install its complicated gearbox, and demands highly precise and professional installation to ensure optimal orientation of the turbine itself. Further, despite general low maintenance needs, annual costs are estimated at around $600 per year due to the highly complicated nature of the turbine, which requires specialized skills to service.

While the Archimedian screw turbine has by far the greatest efficiency of the alternatives, its high installation and maintenance cost lead to it having a net present value of -$190,000, and a payback time far greater than the lifetime of the machine (**Error! Reference source not found.**).

Table 1: Economic analysis for three turbine alternatives

	Archimedian Screw	Gravitational Vortex	Crossflow
Upfront Costs	-$210,000	-$50,000	-$12,000
Annual Costs	-$600	-$450	-$300
Power (kW)	0.95	0.85	0.82
Annual Benefit	$1250	$1125	$1100
Annual Net	$650	$625	$800
NPV (20 year)	-$190,000	-$40,400	-$2,750
Payback Time	100+ Years	100+ Years	21 Years

The crossflow turbine has an estimated payback of 21 years, making it the only turbine alternative with a payback time within the lifetime of the machine. However, this calculation is based on the assumption that five vertical meters before the turbine can be pressurized, and that mitigating any medium to large debris in the outflow can be accomplished easily. Since the turbine would generate about 0.8 kW on average, it could generate over 7,000 kWh per year. Assuming 0.28 tonnes of CO_2 per MWh of electricity in California [18], this would mean an abatement of around 2 tonnes of CO_2 per year. The gravitational vortex turbine would abate a similar amount of CO_2, and would not require any adjustments to the system or removal of debris. While the high upfront cost makes the installation economically unfeasible, BML could still elect to build the turbine because it will have less of an impact on their current system, and would further their goal to achieve carbon neutrality.

In an effort to uncover ways to decrease costs, incentive options were reviewed, but appear to be limited for hydroturbine installations. According to PG&E, the proposed installation does not qualify for their self-generation incentive program, though there is a possibility to receive custom funding due to the demonstration novelty of the project. Additionally, the federal tax credit for hydropower no longer available (expired 12/31/2017). Although incentives are not available, hydroelectric generation is eligible for Net Energy Metering 2.0, meaning that if the hydroturbine is interconnected to the grid, BML is eligible to receive payment for any generation fed back into the grid to offset on-site energy use. Regardless of whether or not the system is interconnected, PG&E must be consulted as part of the development project to ensure the system is built safely for the distribution network.

The proposed installation of a hydroturbine near the effluent termination could require considerable regulatory costs not included in the economic analysis. Due to this location being on the coast, it must meet any requirements from the California Coastal Commission. As this is a brand-new installation that requires the use of some heavy equipment like trucks and cranes, it likely requires an initial screening to prepare an Opportunities and Constraints report. UC Davis

is its own land use authority, so this effort may take place internally with university resources. However, even with a best-case scenario of receiving an exemption, the requisite procedures and expert staff (e.g., biologist, environmental planner) can add around $20,000 to complete an initial review. Depending on the findings of the report, subsequent environmental compliance steps could reach up to $400,000 or more.

Recommendations and Conclusion

Installation of a hydroturbine at Bodega Marine Laboratory (BML) is technically feasible, but creates a marginal amount of energy generation at a high cost in the investigated configuration. Additionally, permitting costs and risks of biofouling and pipeline pressure issues raise concern. If BML's primary focus is on offsetting as much electric use as possible with renewable generation, hydropower alone is not practical. Hydroturbine technology is mature appears to be feasible at the BML facility, however other mature technologies such as photovoltaics may result in a quicker payback.

Despite having a low return on investment, this project may serve as a demonstration project that ties in well with BML's vision for carbon neutrality. When linked with other upgrades like a new ZNE building, it could result in good publicity and attract more visitors, which is also beneficial for meeting goals of the California Coastal Commission.

To improve the accuracy of this report's findings, a more detailed site assessment should be performed to fill in the gaps for assumptions made in this study. Suggested activities include creation of a full elevation profile to determine feasible head, recording pressure measurements in outflow pipes, identification of a possible interconnection points, and determining whether the outflow system can be all or partially pressurized by reducing pipe size.

If pursued, it is not recommended to execute this project independently, but rather to pair with other facility development projects. Two potential developments mentioned in the course of this project include system upgrades to protect against algal blooms and creation of a new Zero Net Energy building. Pursuing multiple developments in tandem can greatly reduce permitting costs by limiting the number of site visits, paperwork, and interaction with other agencies.

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Appendices

Appendix A: Bodega Marine Lab Piping Plan

MARINE LAB BUILDING FIRST FLOOR PIPING PLAN
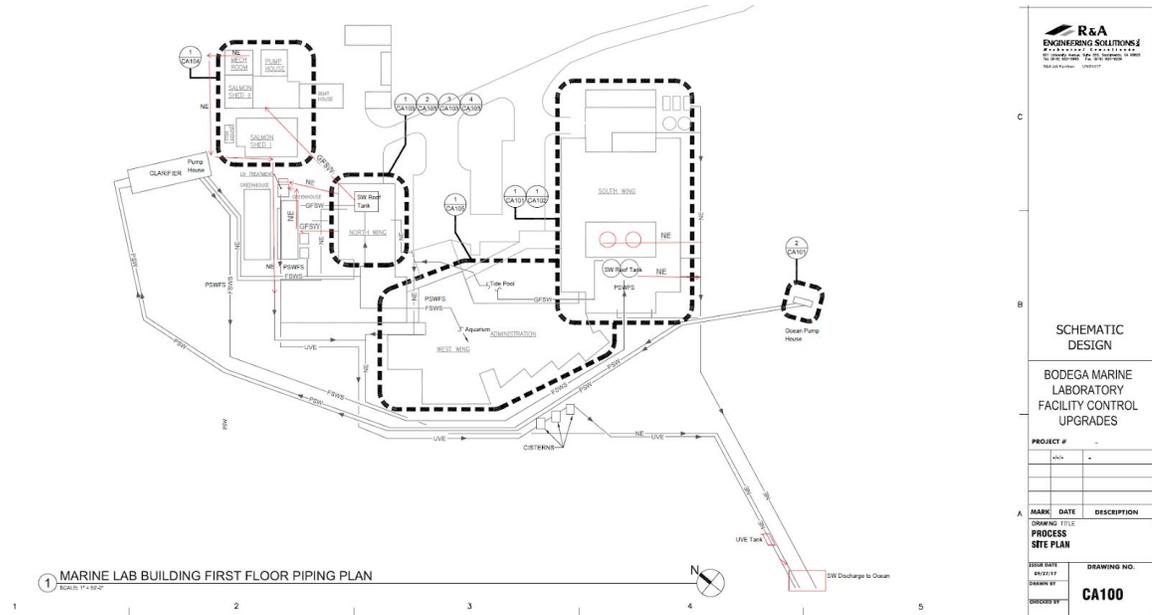
Appendix B: Bodega Marine Lab Water Systems
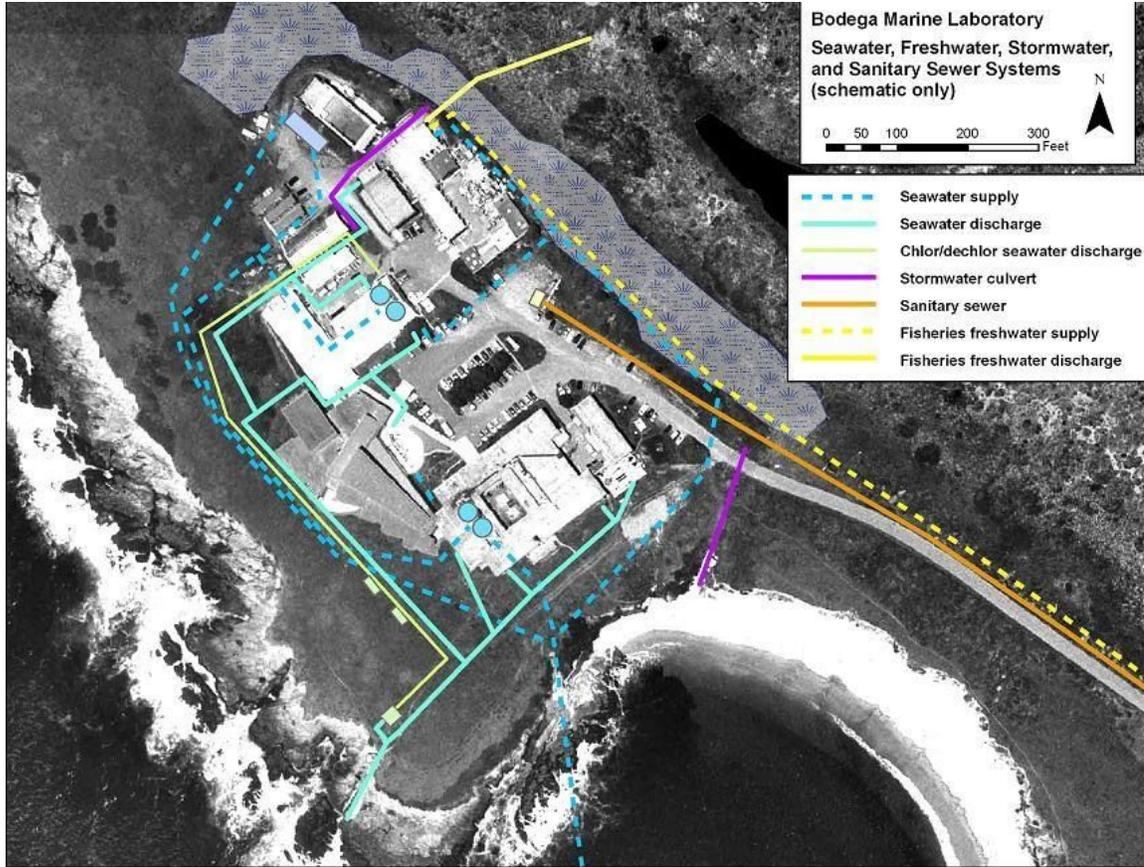
Appendix C: Manning's Equation for Partially Full Pipe Flow

Manning's equation allowed us to calculate the approximate depth and velocity of the effluent flow at our point of interest.

$$Q = VA = \frac{1.49}{n}AR^{\frac{2}{3}}\sqrt{S}$$

		Flow Rate (ft3/s)	.85 ft^3/s = 550 GPD
Q			
A		Flow Area (ft2)	3.14 ft^2
n		Manning's Roughness Coefficient	0.013
R		Hydraulic Radius (ft)	Calculated
S		Channel slope (ft/ft)	0.333

Given the two unknown variables (velocity and hydraulic radius), computational methods were necessary. An excel spreadsheet provided by the USDA was used to perform the calculations [19].

Results:

Velocity = 14 ft/s
Depth = 10 in