A Fat Foil Vortex Induced Vibrations Energy Converter for Alaskan Coastal and Island Communities

Marine Energy Collegiate Competition 2024

WEBB INSTITUTE

Ashmore, B., Calli, W., Coppi, M., Erdos, K., Freischlag, K., Heidenreich, D., Kanemasu, B., Kawabata, E., Kealey, B., Mullan, A., Ng, A., Nicoletti, L., Sanchez, M., Sir, D., Wolfe, W.

Advised by Webb Institute Professors Martin, M. and Royce, R.

Table of Contents

List of Figures

List of Tables

1 Executive Summary

The 2024 Marine Energy Collegiate Competition is Webb Institute's third year participating. Webb Institute is a four-year college where classes starting at 28 students a year receive a Bachelor of Science dual degree in naval architecture and marine engineering. The team is composed of 15 members across all four classes with many more lending their aid in various research and outreach efforts.

This report encompasses the research performed by the team regarding the technical design, construction, and market analysis of a vortex induced vibration (VIV) energy generator for use as the primary energy provider of a small, isolated community. Our team's previous study into VIV generator design was improved for the application to coastal Alaskan communities. The feasibility analysis of the system draws from research surrounding similar offshore energy initiatives, such as wind turbines and tidal turbines, and attempts to optimize the VIV system for its target market and deployment environment. In addition to analyzing its performance, the design was also analyzed on the basis of market opportunity, cost of installation, operation, and maintenance, and suitability for the chosen location.

A model-scale VIV system was designed to assess the performance of a condensed design. []

2 Business Plan

The proposed Vortex-Induced Vibration Energy Generator (VIV) design is simple to build, scalable, and cost effective. In response to the climate crisis and the urgent need for reliable, accessible, and renewable energy generating sources, the VIV generator is a promising alternative that can power remote or developing communities as they transition away from fossil fuels. The current model is to be installed offshore to provide power to remote-Alaskan island communities by utilizing a stacked mount of multiple foils. This location will allow the device to be positioned adequately to take advantage of the current's energy. The ultimate goal of this study is to explore the market feasibility of constructing, implementing, and maintaining the VIV generator. The feasibility of the device will be determined by perceived marketability, ease of construction, public opinion, market opinion, and current market competitiveness.

2.1 Concept Overview

The current design of the VIV generator utilizes an improved foil design and power take-off method to increase the power output, and by extension, feasibility of the concept design. Our team's previous investigation of the applicability of the VIV generator to remote communities of the Alaskan coast will be expanded upon in this study.
The Alaskan remote communities were selected primarily due to the significant tidal energy potential that has been generally overlooked on Alaska's coast. Furthermore, these remote communities utilize microgrids that are driven by fossil fuel generators. The current design can be

implemented to replace these power plants partially or completely, which will lower emissions and costs.

2.2 Relevant Stakeholders

The team reached out and interviewed a few professionals in the marine energy industry for further validation of the ideas presented as well as an identification of power needs. Alana Duerr with Deep Blue Pacific Wind & Simply Blue Group has a PhD in Ocean Engineering from Florida Atlantic University. She worked on energy projects with Deep Blue Pacific & Simply Blue Group to assist with the development of offshore wind in the US. Alana suggested VIV systems could provide coastal and island communities with power and suggested the team analyze a more niche market, such as Alaska. She also mentioned how these communities may need power for heating, desalination, lighting, and agricultural irrigation. Local and state governments have a vested interest in power generation because it is in their interest to provide a reliable source of power to meet the needs of their jurisdiction. They may also be open to clean energy sources because of the social value and financial benefits. Additional government benefits and stricter environmental regulations will also incentivize the use of clean energy sources in the future. In 2022, U.S. Department of Energy announced $35 million in funding to advance tidal and river current energy systems. This is promising for future ocean energy because it shows that the federal government is committed to supporting tidal energy systems.
The end users of this technology will be residents of Alaskan coastal and island regions. The residents are looking for renewable means for electricity generation which would be less disruptive to the environment. One of the main concerns for residents is heating. Remote communities in Alaska struggle to continuously receive supplies such as fuel due to weather and often have to rely on very expensive planes (Loughlin, 2023). Providing a more stable and renewable means of energy generation will lead to a more sustainable economy for Alaskan communities. This technology would also generate more jobs for the local residents for both the installation as well as the maintenance. These jobs help the economy of these communities be more sustainable and independent. Power companies and other investors are vital for the adoption of renewable energy in remote communities. Remote Alaskan communities are unable to fund the capital costs and installation of the VIV system themselves and will need investors for additional financing. Furthermore, installation of a VIV system will require marine assets that these remote communities do not possess. These communities will then have to rely on the power companies and investors to get the financing and assets to install these renewable energy systems. However, some power companies may push back on these communities for fear of losing market control as the green energy market control grows or concerns over the profitability and effectiveness of current green energy systems. This may be a point of contention in the adoption of marine renewable energy generation systems such as VIVs.

2.3 Market Opportunity

2.3.1 Market Definition

Alaska's coast has high precipitation rates and steep topography, which is conducive to its significant hydroelectric power potential. The total wave energy potential of Alaska is more than half of the total wave potential available in the United States, amounting to about 1,250 TWh/year. Furthermore, the currents streaming between the Aleutian Islands are estimated to be 90% of the US's total tidal energy, at 109 TWh/year. Unlike the rest of the continental United States, Alaska isn't connected to large interstate energy grids. Instead, these communities rely on microgrids. This is because over 75% of these remote communities have populations of less than 500 residents. As a result, these remote communities rely on microgrids supported by diesel, gasoline, natural gas, and coal imports. The cost of energy for these communities is higher due to the costs of shipping the fuel and burning it in inefficient, small-scale power plants. The current price of diesel is around $4/gallon in Alaska, and these prices are even higher in remote communities. Furthermore, it is estimated that retail electricity costs three to five times more in rural areas than urban areas in Alaska. This is because the fuel is delivered to these islands via barges, which increases the cost of fuel and emissions consequently. Below, in Figure 1, the cost of energy per kWh is shown for several microgrids; consequently, the wave and tidal energy of these coasts is shown in green and blue, respectively. As seen, there are several remote communities in the Aleutian Islands that struggle with expensive electricity while having the potential to harness wave and tidal energy. The price of these fuels is also highly volatile and can subject residents to detrimental changes in energy prices.

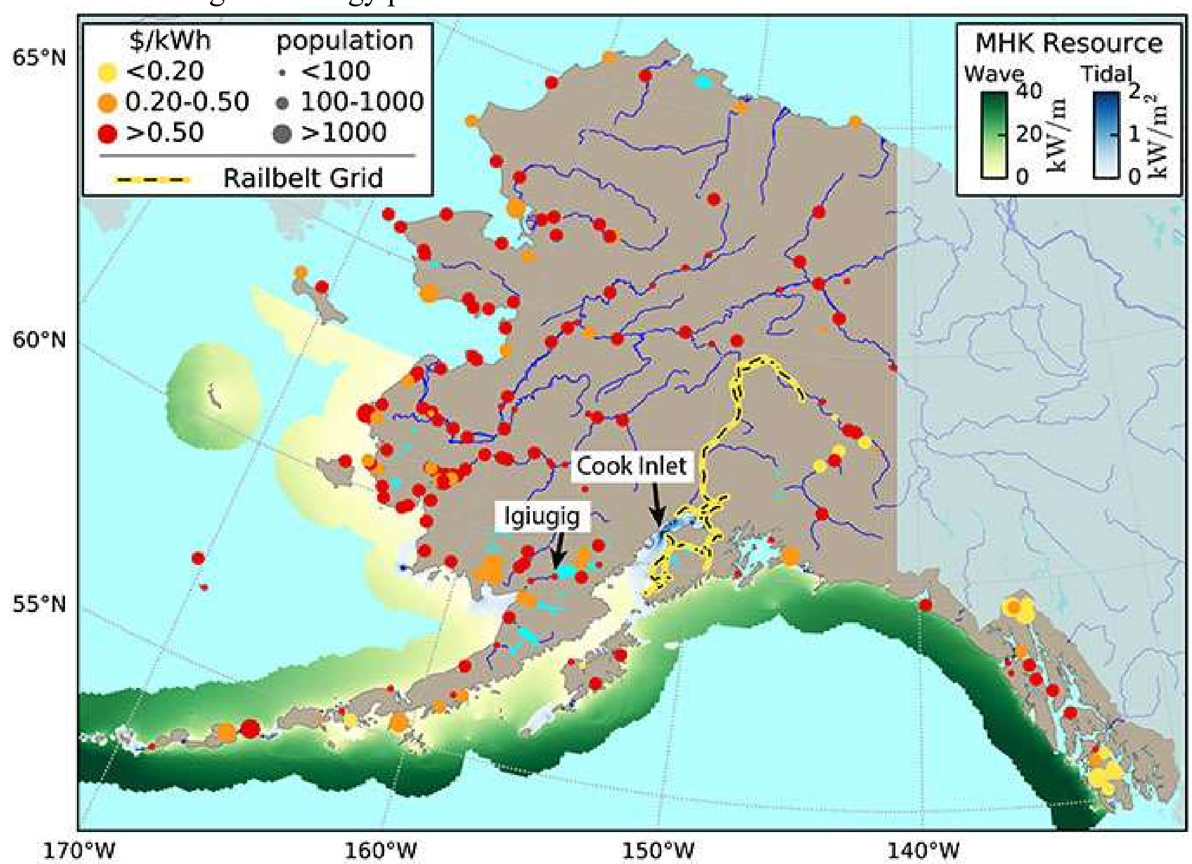

Figure 1. Alaskan Energy Prices and Wave Energy Potential
Source: Levi Kilcher, National Renewable Energy Laboratory

In Figure 2, it is shown that the Aleutian Island's microgrids rely on these petroleum power plants. The burning of these petroleum products increases greenhouse gas emissions and is harmful to the environment. Additionally, the shipping of these fuels also carries the risk of oil spills, which are detrimental to local marine life. Due to the cold weather, energy consumption per Alaskan resident is the fourth highest in the US. As a result, this exacerbates the emissions of these communities. Additionally, these power plants are often short-staffed, and operators tend to have minimal training due to the lack of available workers. This poses a danger to residents of these communities in the event of an accident occurring. As a result, a low-maintenance alternative energy source would significantly help remote communities.

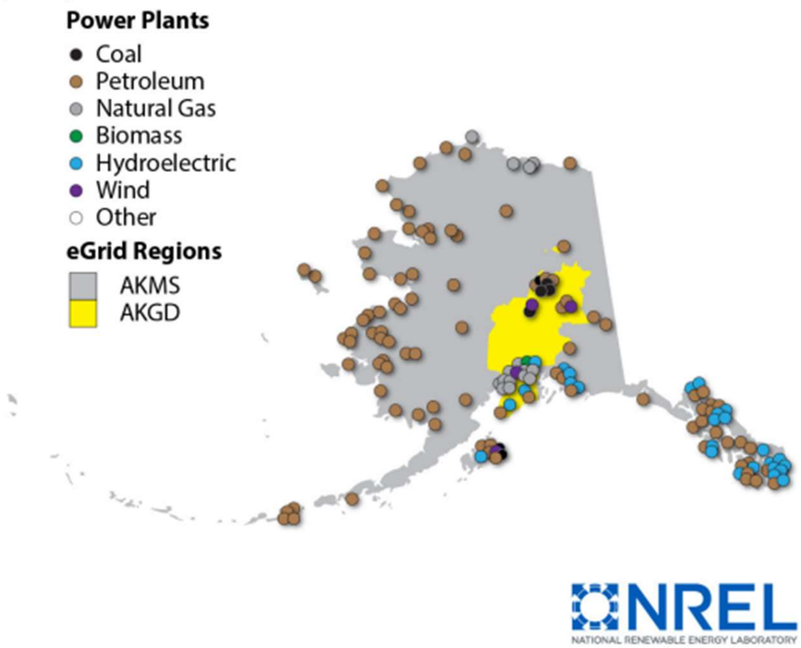

Figure 2. Alaskan Power Plants' Primary Energy Sources
Source: Doubrawa et. al., National Renewable Energy Laboratory

As seen in the figures above, the Fox Islands and adjacent communities have a series of microgrids, which are 93.9% powered by expensive diesel generators (Alaska Energy Authority). Notable examples of this include Dutch Habor, King Cove, Akutan, False Pass, and Umnak. This island chain's location is shown below in Figure 3. These communities have varying power needs; as a result, there are several opportunities for our VIV generator to replace the current diesel generators. In Table 1, the power of generators in these communities has been summarized. The smallest power need, the island of Umnak, has a generator with a power of 196 kW. With this community in mind, a series of VIV generators can potentially be installed to fully replace this microgrid's diesel generator.

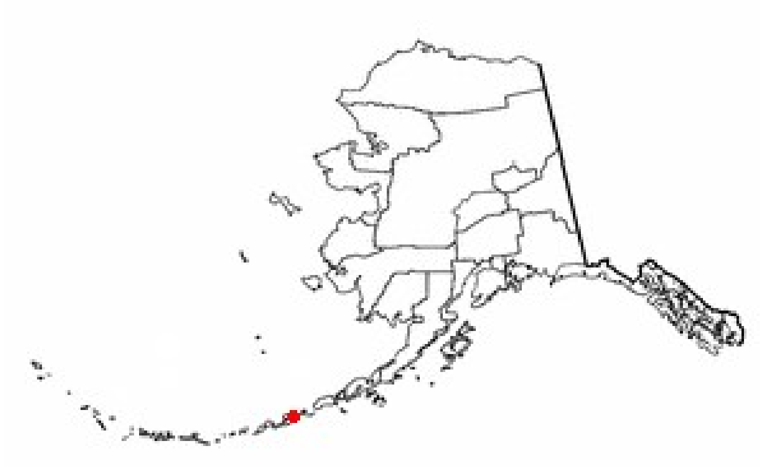

Figure 3. Fox Islands

Table 1. Summary of Diesel Generator Powers for Analyzed Communities
Source: Alaska Energy Authority (2014)

Target Communities' Power Sources		
Community	Generator(s)	Power Supplied (kW)
Dutch Harbor	Generator 1	16600
	Generator 2	1000
King Cove	Generator 1	2700
Akutan	Generator 1	450
False Pass	Generator 1	375
Umnak	Generator 1	196

Given these communities' power needs, it is also worth noting the cost of electricity for these residents. In Table 2, the cost of electricity can be seen for the selected communities. In addition to having the smallest generator, the cost of electricity in Umnak is among the highest amongst the analyzed microgrids, at $0.75/kWh. Given that this data is from 2023, the inflation of energy costs has likely exacerbated this problem for residents. As a result, our power generation can decrease the cost of electricity while consequently decreasing emissions.

Table 2. Electricity Costs in Analyzed Communities
Source: Alaska Energy Authority (2023)

Community	Price of Electricity
Dutch Harbor	$0.48/kWh
King Cove	$0.30/kWh
Akutan	$0.95/kWh
False Pass	$0.72/kWh
Umnak	$0.75/kWh

There is an opportunity for our VIV generator to provide clean marine energy, while requiring less maintenance and labor. Since these Alaskan islands have high-potential currents around them, our technology can harness a sizeable amount of energy. Furthermore, our system can generate power at low water currents, which can allow it to become a reliable power source. A permanent VIV system can significantly replace portions of the current power generation for these communities. The operation of this system will be safer for marine life and residents of the communities. In doing so, the VIV generator system can lower energy costs and decrease emissions.

2.3.2 Competing Technologies

There are several sources of competition for power generation in coastal and islands regions. As previously discussed, fossil fuels are presently the most conventional source of energy for Alaskan remote communities. In addition to tidal energy converters like our system, solar, geothermal, hydroelectric, and wind solutions are other potential alternatives. While these alternatives are less harmful to the environment than the conventional methods, these technologies lack consistent power generation. Since our target market economy utilizes microgrids, excess power during high points cannot be exported and lulls in power cannot be rectified using a larger grid's energy.

Fossil Fuel Generators: These are generators that are fueled by gasoline, diesel, propane, or natural gas. Despite the drawbacks, fossil fuel generators can provide consistent power supply for microgrids and will remain the standard until a strong alternative is offered. However, the generators release greenhouse gases into the atmosphere, which is accelerating global warming. The generators also require operators, which can be difficult to find in small remote communities. Lastly, the price of fuel in remote communities increases the cost of electricity for these residents. As a result, an alternative energy source must be introduced for these remote communities.

Solar: As solar power has become more developed and proven recently, solar power has been considered as an alternative energy source. While it is true that Alaska's solar energy potential is rather significant in the summer, Alaska's seasonal daylight changes mean that parts of the winter will provide no solar energy. Since the peak load is in the winter due to heating loads, this is even more of an issue. The communities microgrids also present an additional challenge for solar energy. During the day, excess power cannot be used in other areas, while lack of power at night cannot be supplemented by a larger power source. As a result, solar power cannot be the complete solution to the replacement of fossil fuel energy in remote Alaskan communities.

Geothermal: Alaska also has the potential for the installation of geothermal power plants. However, most locations applicable for these power plants are inland and far from coastal communities. Additionally, geothermal plants require much more maintenance and operator labor compared to passive wave-energy generators.

Hydroelectric: Hydroelectric plants utilize energy converters on dams of lakes or rivers. However, since hydroelectric energy requires dams, these systems may disrupt marine life. For example, this may prevent fish from reaching breeding grounds and the dam's changes in flow may remove riverside habitats. Lastly, droughts can also impact the reliability of hydroelectric power.

Wind: Wind energy is also a renewable energy source that can be considered for remote communities. However, due to reliance on weather conditions, wind energy will not be able to fully replace fossil fuel generators for remote communities.

Unlike the alternative options, our design addresses the challenges of providing dependable, renewable energy to remote communities. Primarily, the currents of the ocean are relatively consistent and predictable, particularly near the Alaskan coast. Additionally, this current has significant available energy, estimated as 109 TWh/year, which can be converted to provide clean energy. As a result, our energy converter is a strong alternative that can provide dependable, renewable energy to remote communities.

2.4 Development and Operations

2.4.1 Deployment

The first challenge in the deployment process is transporting the VIV generators to the intended communities. The method of transportation of our system does not need to be any different from the existing methods of transporting diesel generator sets to these communities. The most prevalent method for transporting small cargo throughout the Aleutian Islands is the Alaska Marine Highway System. Considering the remoteness of the deployment sites and the potential size of the generating apparatus, the use of a public ferry service is impractical. Delivery by plane is also impractical. Due to the size and weight of the system, chartering a plane to carry it would be far too expensive. The best option for delivery of the system is chartering a vessel from a member of the receiving community. Many of the island communities have their own vessels or special relationships with certain cargo suppliers that they have used previously. These vessels could accommodate multiple VIV generators therefore reducing the number of trips required for delivery and the overall cost of deployment.

2.4.2 Risk Management and Opportunities

Corrosion is a concern for this system, given its location within strong currents. This is considered in the selection of the framing material being 304L stainless steel. The water's cold temperatures may also pose a risk of brittle effects on the material. While this is true, the framing material being stainless steel will still be more durable than a composite alternative. Fatigue within the foil is another material-based risk that is considered for the maintenance aspect of this system.

A risk to the physical system is the effects of the marine debris in the ocean, typically from plant life or waste. The system's design should mitigate this. The materials selected and protective grates should prevent harm to marine life, as well as protecting the VIV generator's functionality. These grates also should have limited impacts on flow into the system, which will prevent an impact on the output.

A potential factor of risk is the interaction with marine life. However, the impact of this system won't affect marine life as drastically when compared to current power generation options. One point of potential concern is the discovery of the eastern North Pacific right whale migration path through the islands in a 2018 NOAA Fisheries study. This should not cause a problem for the VIV generator. Current power generation methods, which utilize barges to ship fossil fuels, likely causes greater underwater vibrations than this system. Additionally, these barges also carry a much larger risk of colliding with marine life, including whales. The VIV generators are also located on stationary offshore mounts, so they will likely not enter the direct path of the migrating whales. The framing and grates of the system's flow entry should also protect marine life from collision with the oscillating foil. These systems are also not planned to be installed on the major potential migration route of the whale species.

2.4.3 Maintenance and Upkeep

The marine environment contains various hazards and properties that can cause damage or degrade the VIV generator. To guarantee that the generator will be able to supply power efficiently throughout its life cycle, the system must be able to be serviced and maintained without considerable cost increases or downtime. Using the current mounting system, this means that the best maintenance option is to service the system using divers, while the system remains mounted in place. The skills required to service machinery and diving in cold water may be difficult to find. The service technicians would have to be capable of making necessary repairs while in freezing conditions and in potentially great depths and currents. The best option would most likely be recruiting Global Services by Moran and chartering them for their maintenance services on a case-by-case basis. They employ many certified cold-water divers with considerable experience in installation and maintenance of underwater structures. This option, however, is expensive with individual divers most likely costing around $100 dollars an hour. It would only be economically viable if the mechanics were chartered to service a large portion of the installed equipment at the same time.

2.4.4 Partnerships

Forming partnerships with the government will be essential to effectively implementing the VIV generator. Primarily, the federal and state governments may be necessary to assist in funding the acquisition cost of infrastructure. Due to the large initial cost of the system, government incentivization may be necessary to assist the transition for energy companies. The US federal government's Inflation Reduction Act has allocated $370 billion to support the development of clean energy solutions for microgrid projects. This funding would be applicable to the VIV generator's systems for the Aleutian Island communities. This funding would support the continued engineering of the design. More importantly, the funding can support the direct costs of manufacturing and installing the VIV system. Presently, to limit the cost of living, the Alaskan and federal governments subsidize electricity costs for remote communities. Given the energy crisis and cost of the subsidization by government, it makes sense that our market plan is applicable to these grants.

Additionally, local power companies must be integrated into this energy solution. This will allow for a process to maintain and operate the system. The government funding for this project can be used as monetary incentivization for the companies to transition away from their current power generation. Power companies that operate in the communities analyzed include TDX Generating Tadak, G&K Incorporated, and Sand Point Generating. Alternatively, several of the target communities have power plants that are owned and operated by the city government. These include King Cove, Unalaska (Dutch Harbor), and Akutan. The implementation of the VIV generator system may be easier for these locations given the local government control the power generation.

2.5 Financial and Benefits Analysis

Given the power need of 196 kW at a rate of $0.75/kWh, the Umnak community will be analyzed as the best economic case. When operating at an assumption that our foil generates double the VIVACE generator, which our technical section implies a significant improvement over, each cylinder at the VIVACE scale generates 15.2 kW. With three modules, two with five foils per module and one module with four foils, this gives a total power output of 212.8 kW. This gives a fair margin to fully replace the identified Umnak generator. The following sections detail the cost breakdown for our foil system, with Figure 4 below showing the overall distribution of costs.

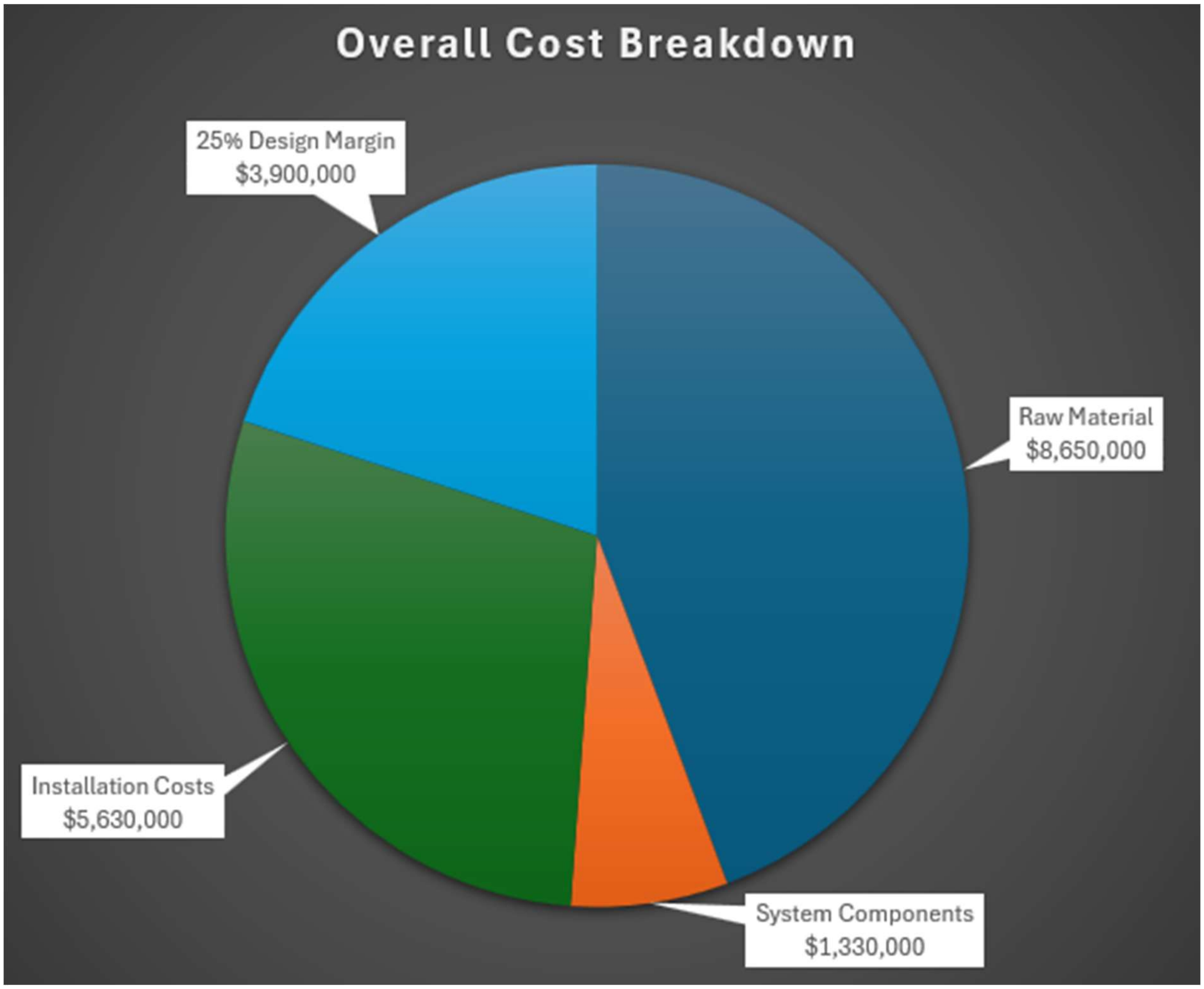

Figure 4. Overall Cost Breakdown of Foil System

2.5.1 Raw Material Cost

The material of choice for this system's framing is 304L stainless steel. This material has a lower carbon intensity than aluminum and is one of the cheaper options available. This material is corrosion resistant, which is a good choice for the marine environment. Steel also has higher fatigue resistance when compared to comparative materials, which is needed considering the vibrations and wave-induced loads that will occur. The cost of the framing can be estimated at $1,000,000. This is a conservative estimate for the stainless-steel angle, brackets, and fasteners needed to support the struts for the foil and withstand the loading. The metal grates on either end of the unit can be estimated at $62,000 based on the cost of stainless-steel expanded metal sheets. We can estimate the cost of the struts to be $9,000 based on the cost of 6" Sch 40 stainless pipe. The foil itself will be constructed from carbon fiber and will have to be strong to handle the loads, but also lightweight. This is why carbon fiber is the ideal choice. Although expensive, carbon fiber has the necessary fatigue resistance, corrosion resistance, and strength to be the foil's material. Given an estimated foil weight of 25,133 kg per foil and a cost of carbon fiber at $21.5/kg, we can estimate a cost of the foils at $7,565,000. The structure will also need bearing supports for the large loading on the foils. Graphite bearings are used in similar systems, such as VIVACE, due to their corrosion resistance during underwater operation. Each module will need graphite bearings, which we can conservatively estimate to cost $500 each, summing to $14,000 total.

2.5.2 System Component Cost

The system is comprised of multiple foils, mounting systems, and electrical components that form part of the capital expenses. The power generation and transmission suite consist of the generators that the foils are attached to, and the power transmission lines tied into the existing land-based power distribution system. The cost of the generators is estimated to be $140,000. Step-up and step-down transformers are needed to carry the AC power across long spans of cable. The cost of these transformers has been estimated at $92600 in total. This is based on sourced three-phase transformers for sale, with a representative cost selected as 133/220 V AC at 20 kVA, which will be sufficient to handle the outputs of our power generation. Additionally, an AC/DC converter is necessary for the power to be run through once it reaches the land-side installation. A representative cost was selected based on a 20-kW capacity converter, and the sum of the converters was estimated as $50400. Given a typical underwater cable cost of $50,000 per km of cable, a series of cables needed, and a distance of 1 km at most, the cost of the underwater cabling can be determined to be $450,000.

2.5.3 Installation Cost

The installation of a VIV generator is a complex process requiring a considerable amount of time and money. Each VIV unit will be constructed on the mainland and would require transport to the installation location in the Aleutian Islands. The primary mainland transportation will be undertaken by contracted semi-trucks at a cost of around $2.50 per mile. Once reaching the departure port, a charter company such as Bowhead transport or the previously mentioned Global Services could be contracted to ship and install the systems for each community. The contracted vessel must be capable of transporting multiple units on its cargo deck, come equipped with a deck crane for installation, and be able to operate in shallow coastal waters. The cheapest option that would fit this description would be utilizing expeditionary landing craft with large deck space, machinery, and shallow draft to land and finish onshore installation. In addition to the landing craft, a separate support vessel would be needed in order to house and transport technicians over the potentially lengthy installation period. These transport services would be utilized to install multiple units per trip to minimize overall cost. Due to the unique mission, detailed installation equipment would likely have to be provided by the customer while the vessel provides positioning services. The actual installation process would also require the presence of technical professionals and cold-water divers, adding considerable cost. The actual installation would also require undersea current testing in order to find the optimal installation locations, adding time and testing costs. Finally, the installed marine apparatus would need to be connected to the communities microgrid and sufficiently tested to guarantee its function. Using DOD resources, the estimated installation cost per watt for small island communities is $5 per watt without considering extremely isolated locations. When the special factors for extreme micro grids are considered, the cost may be up to 4 times as great as mainland-based renewable micro grids. Given the total power of our system at 212.8 kW, this gives an installation cost of $4,256,000. Since the seabed in these high-current zones are often muddy, chain and anchor arrangements can be the mounts for the system in these conditions. Since these are relatively cheaper steel structures, the total cost of this mounting can be conservatively determined to be $600,000 for the system. Additionally, there is a $1,000,000 allowance for replacement components over the lifespan of the system.

2.5.4 Final Cost

The final cost of the system includes design, construction, installation, and maintenance costs. This is the value that the price of power must be compared against in order to validate the power generation method as a genuine competitor against existing methods. The initial costs will mostly be composed of the raw material cost and the installation cost. These components will have to be sourced, manufactured, and shipped to the assembly location. The system is then compiled and constructed. The fully constructed system is then shipped over land to a major Alaskan port such as Anchorage. The system and required installation equipment will then be shipped via water to another port or to the final installation location. Due to the unique installation locations and requirements, traditional waterborne shipping companies such as the Alaskan Marine Highway cannot be used. Chartered landing craft will be used instead in addition to any required technician or crew support vessels. This process all adds up to the initial CAPEX required for the installation of this system. Beyond the initial expense, there will be a need for yearly maintenance estimated at 100 dive hours and 100 land hours per year for a total lifespan of 30 years. The 30-year life span was used based on VIVACE's similarly expected lifespan for their technology. The summation of these costs put the total at $15,650,000 for a full system lifespan. A 25% design margin is then incorporated for unexpected expenses, bringing the total cost to $19,520,000. Using this value, a cost per kwh of $0.35 was calculated. This value is a 53.3% cost reduction for the Umnak community, making this an attractive solution. With consideration of the conservative nature of our cost estimates, the VIV generator's cost per kWh is a promising technology that can replace the petroleum-driven generators of Alaskan microgrids. As a result, the VIV generator system's is an economically feasible system to reduce greenhouse-gas emissions.

3 Technical Design

3.1 Design Objective

The objective of the project is to use vortex induced vibrations (VIV) around a fat foil to provide rural Alaskan communities with an alternative, renewable means of electrical generation. The main end users of the design are the Dutch Harbor, Akutan, and Adak communities. The main energy generation device, referred to as the VIV generator, is a fat foil which uses the current to oscillate vertically through the use of vortex induced vibrations. A generator attached to the fat foil will convert the vertical translational motion of the fat foil into an electrical current. This current will then be connected to the shore for transmission. A shore transmission unit will convert the generated electrical energy into a form that can be utilized by the local community grid. The shore transmission unit will consist of a rectifier and inverter to convert the generated variable alternating current (AC) signal from the VIV generator into a usable AC signal. In support of this, the VIV generator requires an installation configuration for structural support and for proper orientation relative to the incoming current.

3.2 Changes from Last Year

The design for this year improves upon the design from last year. However, due to certain design decisions, a new frame was required for testing. The design for this year improves upon the design from last year. However, due to certain design decisions, a new frame was required for testing. Three main technical aspects were refined for this year's design. The first major change was implementing a mathematical model to predict the power output of a fat foil energy converter. This model gives a method of supporting data collected during prototype testing. It also serves as a metric for sizing full-sized systems for the intended Alaskan communities. The second major addition is the investigation into various full-scale system configurations. Proposed mountings include direct, floating, and stacked configurations. The last new portion of this year's technical report is an environmental analysis of the design. Noise, spill risk, biofouling, and wildlife interactions were all examined. No major ecological impacts were discovered.

3.3 Theory

Vortex induced vibrations is the term used to describe the forced vibration of an immersed body due to vortex shedding. Vortex induced vibrations are caused when the flow around a fully immersed bluff body subject to a free stream separate. The separation of flow off the body is dependent on the Reynolds number, which is a non-dimensional ratio of inertial forces to viscous forces. The Reynolds number is given as:

$$Re = \frac{\rho U L}{\mu} \quad (1)$$

where ρ is the density of the fluid, μ is the dynamic viscosity of the fluid, U is the velocity of the flow, and L is the length of the object. The boundary layer surrounding an object in flow is the thin layer of fluid particles where viscous effects are prevalent. At lower Reynolds numbers, the boundary layer is laminar. When the Reynolds number increases, the boundary layer begins to transition to turbulent flow. Depending on the Reynolds number and the geometry submerged in the flow, separation can occur. Within a boundary layer, there is a pressure gradient along the surface of the body, which has a maximum at the stagnation point on the leading edge. The pressure decreases from the leading edge to the widest point perpendicular to the flow direction; this is called a favorable pressure gradient. After this point, the body becomes smaller and the pressure increases, creating an adverse pressure gradient. When the fluid no longer has enough kinetic energy to flow in the direction of increasing pressure, it stops following the surface of the body, and separates. When or if separation occurs depends greatly on the Reynolds number and specific geometry of the body being considered. When an adverse pressure gradient forms near the trailing edge of the object the pressure gradient can form a separated wake region that will cause eddies to form. These eddies form vortices that will trail the object, due to the inability of streamlines to cross each other. Because the object in question, either a cylinder or fat foil, is symmetrical, these vortices will form on both sides of the object in an alternating pattern for a certain range of Reynolds numbers. This pattern of vortices being shed from the object is known as Von Kármán Street. The Von Kármán vortices cause the object to oscillate perpendicular to the flow.

When a bluff body is immersed at much lower Reynolds numbers ($40 < Re < 3e5$), the flow will separate into a series of vortices that alternate between the lower and upper sides of the body. This is what is known as vortex shedding; the alternating series of vortices is known as the Von Kármán vortex street, which can be seen below in Figure 5.

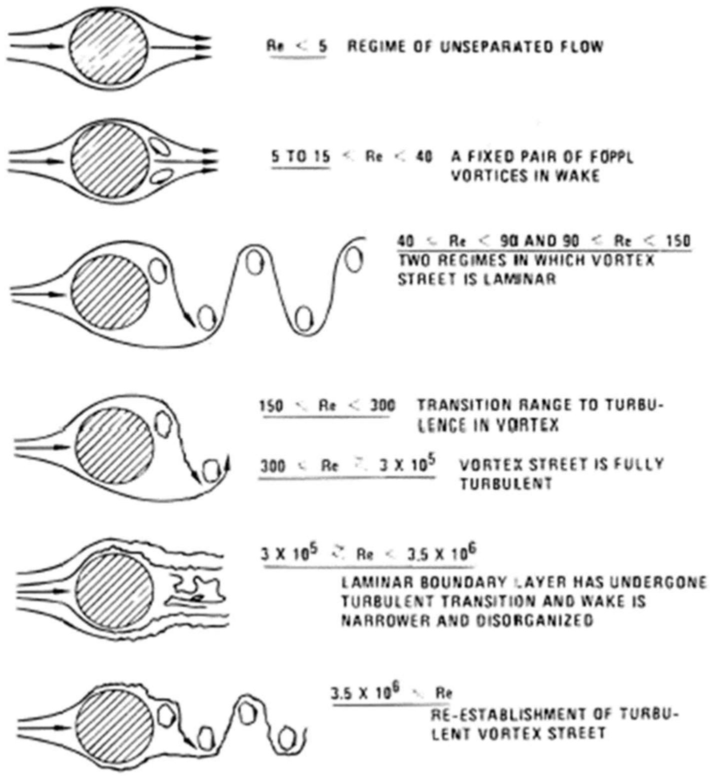

Figure 5. Cylinder Wake Patterns for Varying Reynolds Numbers
Source: Blevins, 1977 – Fig. 3-2 pg. 14

At very low Reynolds numbers (40 <Re <150), the vortex street is laminar, but when the Reynold number increases, the vortex street becomes fully turbulent. The fully turbulent vortex street occurs at 300 < Re < 3e5 and Re < 3.5e6. The vortices develop forces that act on the immersed body; these forces are what cause the forced vibrations known as VIV. Another dimensionless number that can be used to analyze the system is the Strouhal number, which is a ratio of unsteady forces to inertia forces that is used to describe oscillating flow. Equation 2 below shows the Strouhal number:

$$St = \frac{f_v L}{U} \tag{2}$$

where the vortex shedding frequency is f_v, the velocity is U, and the representative length is L.

Vortex shedding has been found to occur at a Strouhal number of 0.21 for Reynolds numbers of less than 1000, see Figure 6 for the relationship at other Strouhal or Reynolds numbers. This Strouhal number serves as the basis for finding the correct flow velocities needed to form the Von Kármán Street wake and oscillate our fat foil.

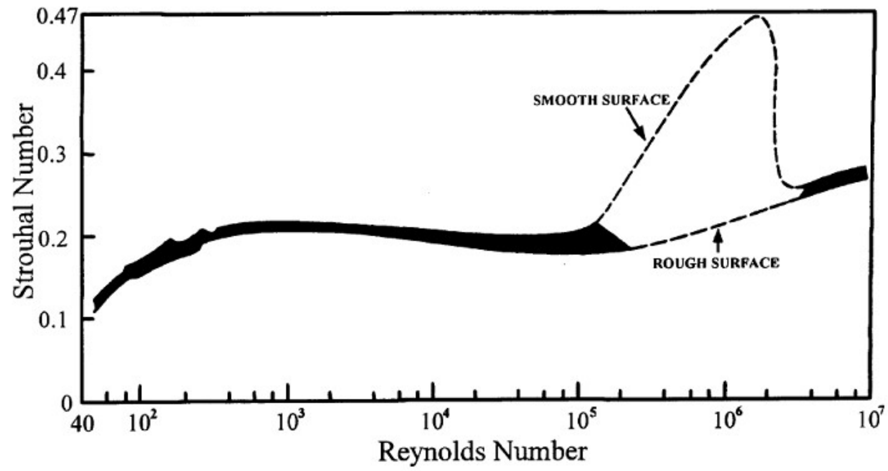

Figure 6. Relationship Between Strouhal and Reynolds Number for Cylindrical Bodies

The foil dynamics for a system undergoing vortex induced vibrations are quite complex and ill defined, which can pose a significant difficulty in developing a complete and accurate predictive numerical model of the systems. The problem is multifaceted in the sense that there has been relatively minimal research into ways to specifically induce VIV, as well as the fact that unless the system is heavily constrained, it is challenging to predict how activation of small instabilities in one of several degrees of freedom can lead to increasing and self-exciting motion coupled across multiple degrees of freedom.

To simplify the understanding of VIV, it can be analyzed as a mechanically forced vibrating system. Mechanical vibrations are a subject that has been extensively studied and can be described mathematically. Fundamentally, the immersed foil apparatus being tested is a linear system with forced excitation. The equation of motion that governs such a system is given by:

$$m_{eq}\ddot{x} + c_{eq}\dot{x} + k_{eq}\mathrm{x} = F(t) \tag{3}$$

Where m_{eq} is the equivalent mass of the system, c_{eq} is the equivalent damping, k_{eq} is the equivalent stiffness, x is the displacement of the body, $\dot{x}$ is the velocity of the body, $\ddot{x}$ is the acceleration of the body, and F(t) is the forcing function. This equation of motion is suitable for examining a system with cylindrical foils, such as the VIVACE converter; however, when examining a system that uses a fat foil, such as the one examined in this design, the complexity increases. Because the foil section is free to rotate about an axis, the system increases from one to two degrees of freedom. Thus, the most accurate equation of motion for the motions experienced in this design is given as:

$$\begin{bmatrix} m_{eq} & 0 \\ 0 & J_{eq} \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{Bmatrix} \dot{x} \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{Bmatrix} x \\ \theta \end{Bmatrix} = \begin{Bmatrix} F(t) \\ M(t) \end{Bmatrix} \tag{4}$$

Where J_{eq} is the equivalent inertia, θ and its derivatives are angular displacement, velocity, and acceleration, and M(t) is the angular forcing function.

An additional degree of complexity can be further added when considering the effects of the foil's self-excitation, and the dynamic instability present in the system. The self-excitation is caused by the pitching motion of the foil, which is a component part of the heave forcing function alongside the forces resulting from the vortex street. The dynamic instability is a result of the coupled motions caused by the addition of the springs.

The vortex shedding off the foil results in lift and drag forces on the foil. Lift forces are perpendicular to the flow direction and drag forces are parallel to the flow. Since the foil is constrained in the direction of the flow, the drag forces will not contribute to the motion of the foil and therefore will not be analyzed in detail. However, lift forces contribute to motion in the heave direction and thus will be analyzed further. The non-dimensional coefficient of lift on the foil, C_L, can be seen in the equation below:

$$C_L(t) = \frac{L(t)}{\frac{1}{2}\rho U^2 \mathrm{A}} \qquad (5)$$

where L(t) is the time-varying lift force of the foil, ρ is the density of the fluid, U is the flow velocity, and A is the characteristic plan form area, which is a function of the foil's geometry, specifically span and chord. This design uses a constrained airfoil with only 2 degrees of freedom: heave and pitch. When considering a system like this, there are additional considerations that need to be made. To illustrate the point, a free body diagram of a horizontally constrained airfoil can be seen below in Figure 7.

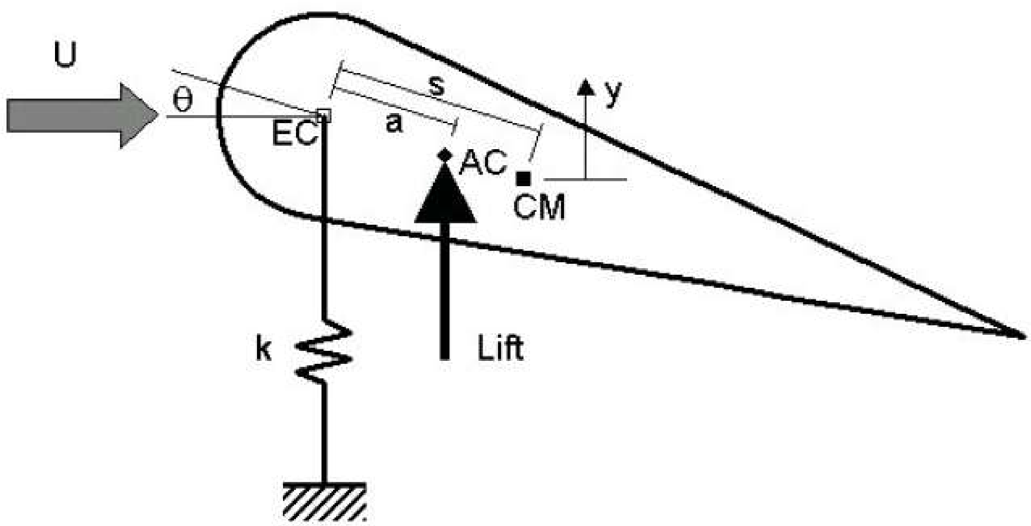

Figure 7. Free body diagram of a foil constrained to 2DOF.

For the purposes of this analysis lift will be modeled as an instantaneous function of angle of attack. The Kutta-Joukowski theorem provides a relation between the instantaneous change in lift coefficient and angle of attack for finitely thick foils:

$$\frac{\partial C_L}{\partial \alpha} = 2\pi\left(1 + 0.77\frac{t}{c}\right) \qquad (6)$$

where $dC_L/d\alpha$ is slope of the lift coefficient based on the angle of attack, and t/c is the thickness to chord ratio, which is a geometric property of the foil. This equation is based on 2D potential flow approximations. Using these equations, the lifting force in terms of pitch angle, α (t), can be written as:

$$L(t) = \frac{1}{2}\rho U^2 cS \frac{\partial C_L}{\partial \alpha}\alpha(t) \quad (7)$$

where the characteristic plan form area, A, is the span, S, times the chord length, c. The instantaneous lifting force can then be used to estimate the kinematics of the foil using the approach developed by Slocum, 2004.

Using the established Strouhal number in the range of 0.21, it is possible to determine the flow velocity needed to form the Von Kármán Street wake. This method was developed by Slocum in his paper, "Flutter Instability in Riser Fairings." Slocum assumed that the object is fixed in the direction of the flow but can oscillate in the crossflow direction and can rotate, thus neglecting drag. Damping is also neglected, and lift is the only hydrodynamic force that is considered. Lift in this scenario is a function of the instantaneous angle of attack. The natural frequency for an oscillating system is given as:

$$\omega_n = 2\pi f_n = \sqrt{\frac{k_{eq}}{m_{sys}}} \quad (8)$$

where ω_n is the natural angular frequency, f_n is the natural frequency, k_{eq} is the equivalent stiffness constant, and m_{sys} is the equivalent mass of the system. The natural frequency of the vortex shedding must match the natural frequency of the system in order for the foil to resonate. Equation 2 can be arranged in order to find the frequency of the vortex shedding, ω_v, and is given as:

$$\omega_v = 2\pi f_v = 2\pi \frac{StU}{L} \quad (9)$$

Equation 6 and 7 can be set equal to each other given that $\omega_v=\omega_n$, forming Equation 8:

$$2\pi \frac{StU}{L} = \sqrt{\frac{k_{eq}}{m_{sys}}} \quad (10)$$

This equation can be rearranged to solve for the flow velocity U in terms of the other components which are provided. The Strouhal number is replaced with the value 0.21, as it has been established as the value needed to form vortex induced vibrations. The mass of the system must also be equal to the mass of the foil and the added mass experienced by the foil due to accelerating fluid particles around it. The equation for U, after substituting in 0.21 for St is given as:

$$U = \frac{L}{0.21 * 2\pi}\sqrt{\frac{k_{eq}}{m_{foil} + m_{added}}} \quad (11)$$

In the absence of any power takeoff device, there exists a theoretical steady state solution for the forced-damped vibration of the foil. The amplitude of this solution is governed by the equation,

$$A = \frac{L_{max}}{2k_{eq} * \zeta} \quad (12)$$

where A is the steady state amplitude, L_{max} is the max lifting force enacted upon the foil, and ζ is the damping ratio. This equation makes the reasonable assumption that the frequency of the lifting force is equal to the natural frequency of the foil. The power generation model developed for the energy converted assumes a damping ratio of 0.48. This value was determined from empirical results for a previous design's testing.

The energy stored in the system can be approximated by analyzing the extremities of the foil's motion. When the foil reaches its max amplitude, the kinetic energy is virtually zero while the spring potential energy is at its highest. This means that the energy in the system can be estimated with the following equation for spring potential energy:

$$E_{total} = \frac{1}{2} k_{eq} A^2 \quad (13)$$

where E_{total} is the total spring energy stored in the unconverted system. The attached power take-off device must not deprive the foil of too much energy, or the foil will stop its vibrations. Additionally, the energy taken by power take-off can thought of as work done by the device, and can be modeled by the equation,

$$E_{total} = 4 * F_{take-off} * A_{adjusted} \quad (14)$$

where E_{taken} is the energy taken by the power take-off over a complete cycle, $F_{take-off}$ is the force needed to actuate the device, and $A_{adjusted}$ is the amplitude adjusted for the lost energy taken by the take-off. To maximize the energy converted, the minimum $A_{adjusted}$, that will not completely stop the stop the system, must be considered. Based on testing observations, the minimum amplitude including the impact of the power take-off is half the initial unobstructed amplitude, or 1.5 times the cord of the foil if this value is larger. Applying the law of conservation of energy and multiplying the result by the natural frequency of the system will get the equation,

$$P = \frac{1}{2} k_{eq} (A^2 - {A_{adjusted}}^2) f_n \quad (15)$$

where P is the estimated power of the converted for the system.

Until recently, research in vortex induced vibrations prioritized minimizing dynamic instability and vortex shedding, as these effects were observed to negatively impact various structures. Thus, studying dynamic instability and ways to negate its effects have been topics of interest for aeronautical applications. An infamous example of negative effects of flutter instability and vortex induced vibrations is the collapse of the Tacoma Narrows Bridge. According to the Washington State Department of Transportation, the bridge was in danger of collapsing from a combination of vortex shedding due to wind force and significant deflection. Ultimately, torsional flutter incited by the vortex shedding surpasses the bridge's poor torsional resistance, resulting in a collapse. Torsional flutter is self-exciting, meaning that the motion of the bridge developed forced which further moved the bridge. While catastrophic for the Tacoma Narrows Bridge, vortex shedding, and torsional flutter are extremely favorable for kinetic energy converters. Thus, the recent surge of interest in green energy has yielded research into how to incite dynamic instability and extract energy. Some popular methods of extracting energy from a fluid use flapping foils, rigid heaving cylinders, or rigid heaving foils. This project utilizes large amplitude coupled motions of a passive elastically supported rigid foil, of which the science and mathematical models are still being developed.

3.4 System Design

Various components are required for effective operation of the VIV system. The system design is guided by the assumption that the VIV will produce variable AC power through its scotch yoke mechanism and the interaction with the current. One way to clean the AC power generated by the VIV is to convert and filter the power in DC. Conversion to DC will reduce the variation in the voltage and stabilize the frequency of the generated power. A conversion back to AC will allow for transmission with the local power grid. Because the VIV is being evaluated for its role in assisting Alaskan communities, the final output must be capable of interaction with 60 Hz systems and 120 VAC (Department of Energy).

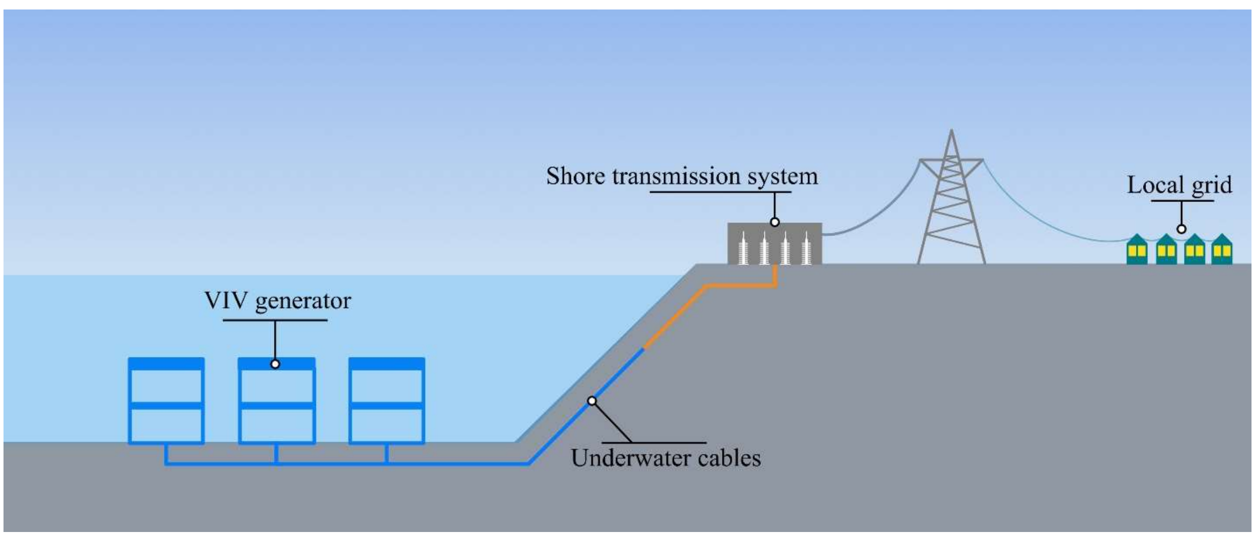

Figure 4. System Concept Design

3.4.1 Design Overview

The VIV generator requires additional components to connect with local electrical grids and provide power for its users. As currents raise and lower the foil, a generator is required to convert rotary motion into electrical power. The generated electricity needs a method to travel to the shore for transmission and distribution. This will require transformers and cables. Once on the shore, the electricity needs to be cleaned and filtered into a usable form for consumption. This will involve, at a minimum, rectifiers, inverters, and additional transformers. Other devices are required for the detailed operation of the system, but the previously described major components are the focus of the system design. These major components are broken down into generators and the transmission system.

3.4.2 Generator

The VIV generator uses a rack and pinion mechanism to convert the vertical oscillatory translational motion into a rotary motion for the generator. The fat foil is connected to the rack, which will move with the fat foil. The pinion is connected to the rotor of the generator which will produce AC power (IEEE, 2016). However, the power is predicted to be very volatile and require filtering. Both the voltage and frequency of the generated power will need to be controlled and continuously monitored to ensure compatibility with the power grid. The transmission system will both filter and clean the generated power as well as connect the devices to a power grid.

3.4.3 Transmission System

A transmission system allows one or multiple VIV generators to connect to the local grid./ Because the generating electrical signal will not match the corresponding electrical standard of the local grid, the transmission system must be able to filter and scale the output voltage into something usable by the community. To fulfill this goal, transformers, rectifiers, and inverters will be incorporated into the transmission system.

3.4.3.1 Transformers

Transformers are devices that can increase or decrease the AC voltage of a system depending on their wiring configuration (Bureau of Reclamation, 2005). Because the VIV generators may be installed far from the shore transmission system, there could be major cable losses. Reducing these losses will increase the efficiency of the VIV generator and thus the electricity supplied to the power grid. If the cable losses are not deemed to be significant, then the transformer can be installed as a part of the shore transmission unit. If the cable losses are deemed to be significant, then an underwater transformer enables the system a method of increasing the AC voltage to minimize cable losses. An example underwater transformer is the Hitachi Energy subsea transformer, which can operate in depths of 3,000 meters and voltages up to 15,000 VAC (Hitachi Energy). The high voltage limit of the Hitachi Energy subsea transformer is extremely useful for minimizing cable losses, and the 3-kilometer depth rating allows the transformer to be used in the Aleutian islands. This specific underwater transformer exceeds the needs of the Alaskan plan but is feasible for larger generation operations. Transformers will lower the current and thus lower the losses as electricity travels through the underwater cables to the shore installations. On shore, additional transformers will step down the voltage for use with the remainder of the transmission system. An example of a shore transformer is the Medium Voltage Step Up 35kV Indoor Dry Type Transformer from Zhegui Electric (Zhegui Electric). This transformer has a model to output 12kV, which matches typical utility pole voltages (American Electric Power, 2010). This allows for generated electricity to interact with the Alaskan power grid.

3.4.3.2 Rectifiers

Rectifiers convert AC voltage into DC voltage. Since flow through the system is volatile, the input AC voltage will also be volatile. However, rectifiers help solve this issue because they filter the signal and produce a cleaner DC voltage signal. Depending on the irregularities of the electricity generation, additional filtering on the DC voltage may be required. An example rectifier is the CP2000 from Digikey. The CP2000 is capable of an output of 54 VDC but is only rated for 2 kW of power (DigiKey). This can be scaled up depending on the scale of electrical generation.

3.4.3.3 Inverters

Because our end users rely on AC power instead of DC power, an inverter is required to convert the filtered DC voltage into usable AC voltage. Together, the rectifier and inverter work to filter the output voltage and scale the voltage appropriately accordingly. The selected inverter changes the possible output frequency and voltage. An example inverter is the Phoenix 12/375 VE.Direct from Victron. The Phoenix 12/375 VE.Direct is capable of outputting either 120 VAC or 230 VAC, at either 50 Hz or 60 Hz, at various power ratings depending on the selected device (Victron Energy, 2022). Models like the Phoenix 12/375 VE.Direct are versatile in terms of output voltage and frequency allowing for the possible use in many global regions for further expansion. However, for the purposes of our end users which are using the same voltage and frequency as the United States electrical grid, the 120 VAC and 60 Hz option would be selected. Although the microgrids are disconnected from the national electrical grid, their electrical infrastructure uses the same standards. The ability for the inverter to modify the output signal into something usable in other countries and other national grids is not required for the selected end users.

3.4.3.4 Cables

Two types of cables were considered for the power transmission between the fat foil energy generation device and the shore transmission unit: floating and underwater cables. Floating cables come with the benefit of being cheaper and easier to install by using cable floats or other methods of providing buoyancy. However, they provide a significant disruption to ships or other activities on the water's surface. If a ship were to sail over the cables, then there could be significant damage to the ship and the system. Wildlife may also run into the floating cables and get tangled. To prevent impact with shipping and wildlife, underwater cables will be utilized. Although costlier, underwater cables are commonly used for connections also major bodies of water. For example, major international telecommunications networks are connected via underwater cables. One example of underwater cable usage for electrical transmission is the Martha's Vineyard underwater cables (Maloney, 2019). Martha's Vineyard, an island off Cape Cod, Massachusetts, uses just four underwater cables to connect to the main electrical grid. For reference, Martha's Vineyard uses hybrid fiber optic and electrical cables with a diameter of 5.5 inches to transmit power from the mainland to the island (Comcast, 2012). A similar method would connect the fat foil energy generation devices to the shore transmission unit. The generators of multiple fat foil devices could combine into a one or few larger cables to minimize electrical losses and decrease installation expenses. By being buried under the surface, underwater cables are well protected from all types of disturbances and separate from any water activities the local communities wish to perform.

3.4.3.5 Other Devices

Beyond the main devices listed for voltage conversion, many smaller devices should be included in the transmission device. Capacitor banks can reduce the reactive power generated through power conversion. Circuit breakers should be implemented to ensure safety and automatically terminate electrical connection in the case of faults or failures. A lack of circuit breakers can result in damage to the equipment and danger to personnel. Lighting arresters are useful to prevent damage from electrical strikes to the system. These are a few devices that should be considered as a part of the transmission system, but the exact details and models recommended are beyond the scope of this report.

3.5 Power Analysis and Configurations

3.5.1 Power Performance Analysis

Based on the theory outlined previously regarding the power generation of the VIV generator, there are some inefficiencies to be considered. One proposed power take-off uses a scotch yoke mechanism to spin an AC generator. Then, the generated power from the AC generator would pass through a rectifier and inverter before sending it to shore. This would ensure proper voltage regulation for transmission. Every step in the process has an efficiency factor to implicate in power estimation. Early design estimates from a previous study (Shami, Mayberry, Zhang, & Wang, 2023) suggest a peak efficiency of 49%. With further design improvements, this efficiency should increase significantly. The model uses an improved efficiency of 65%, which is a more palatable number for consumer and energy generation.

The benefit of the model for this system is its scalability. By putting in the characteristics of the foil geometry and the flow speed of the water, an ideal system is generated, predicting the power output. This model was used to estimate the power output for the build and test prototype. The estimated power output of the prototype was estimated to be 5W with a flow channel speed of 2 ft/s. Further use of the power model was implicated in the sizing of the full-scale systems discussed in the business report. Since the individual power generation of a single VIV generator is very low given a current of 2 ft/s, a large array with more energy would be required to provide sufficient power for the end users.

3.5.2 Installation Configurations

There are three configurations best suited for fixing the VIV generator to the seafloor: direct mount, floating mount, and stacked mount. The stacked and direct mount methods are preferable in most cases, while the floating mount should only be used if circumstances require it.

3.5.2.1 Direct Mount

The direct mount method utilizes four screw jacks affixed to the device to anchor it to the seabed. These jacks are motor operated and must be able to drill sufficiently deep to anchor the unit against lateral dynamic forces. This configuration is advantageous for sea floors with a relatively high clay or rock content because these materials are less likely to shift from the current. The addition of screw jacks may add up to 100 pounds weight and additional costs, depending on the size of the unit. However, a significant amount of force can be generated from relatively small power screws, so this system is more economical as the size of the unit increases. Moreover, this system does not require divers as the on-board motors could be operated remotely to fix the screws to the seabed. Figure 8 shows the direct mount configuration in an isometric perspective.

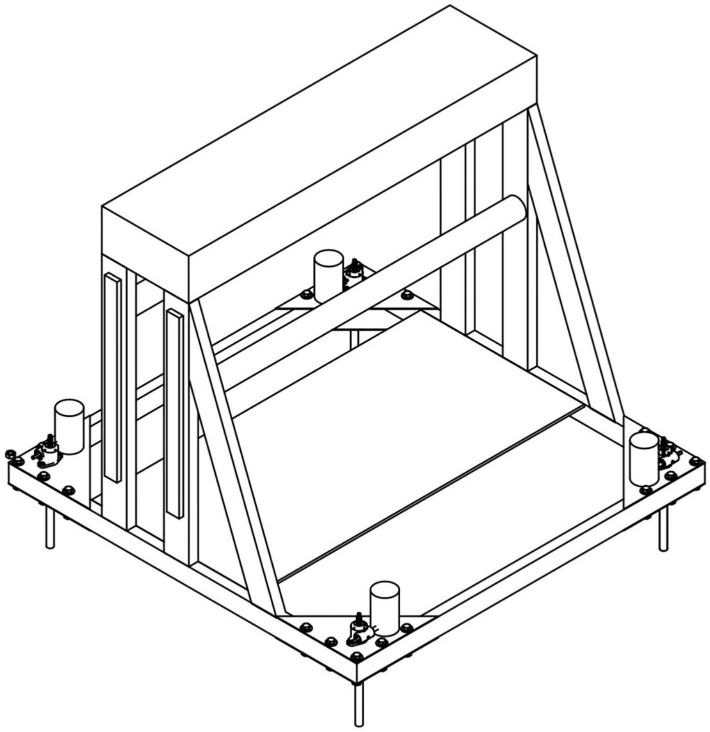

Figure 8. Direct Mount Configuration

3.5.2.2 Floating Mount

The second installation system is the floating mount. The floating mount employs an inflatable bumper around the unit and four cables that hold the unit to the seafloor. In this scheme, the unit's cables are attached to the seabed, and the bumper is inflated from an inflation valve that releases CO_2. The inflation of the bumper raises to unit in the water column to its predetermined depth. This configuration allows the unit to access specific elevations in the water column and therefore different current strengths. The cables that hold the unit to the sea floor are best used with seabeds that have a high rock or clay content to allow for greater holding forces. The unit is to be affixed with a minimum of four cables, but more can be added to reduce the tension in each. Divers are necessary in this configuration to install the cable and activate the inflation valves. This option is best suited for areas where the seafloor is not suitable for a direct mount and should not be for larger units owing to the risk of CO_2 leakage. Figure 9 depicts the floating mount configuration in an isometric perspective.

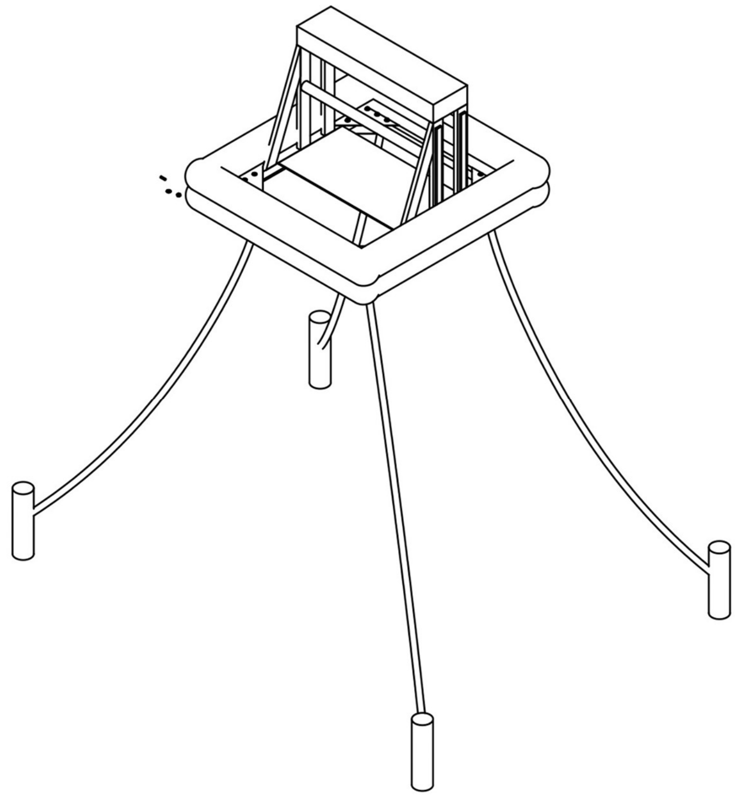

Figure 9. Floating Mount Configuration

3.5.2.3 Stacked Mount

The final configuration is the stacked mount. The stacked mount consists of stacking up to four smaller units vertically, fixing the combined unit to the seafloor with cables. The units are mechanically coupled with bolted flanges. This system is advantageous because it allows the combined unit to extract energy from a larger portion of the water column. The stacked mount is the most space efficient option because it makes use of vertical rather than horizontal area on the seabed. This system is best suited when smaller units are being deployed because it reduces installation time and centralizes their location. Four or more cables are necessary to sufficiently hold the combined unit, requiring the use of divers. Figure 10 shows the stacked mount configuration in an isometric configuration.

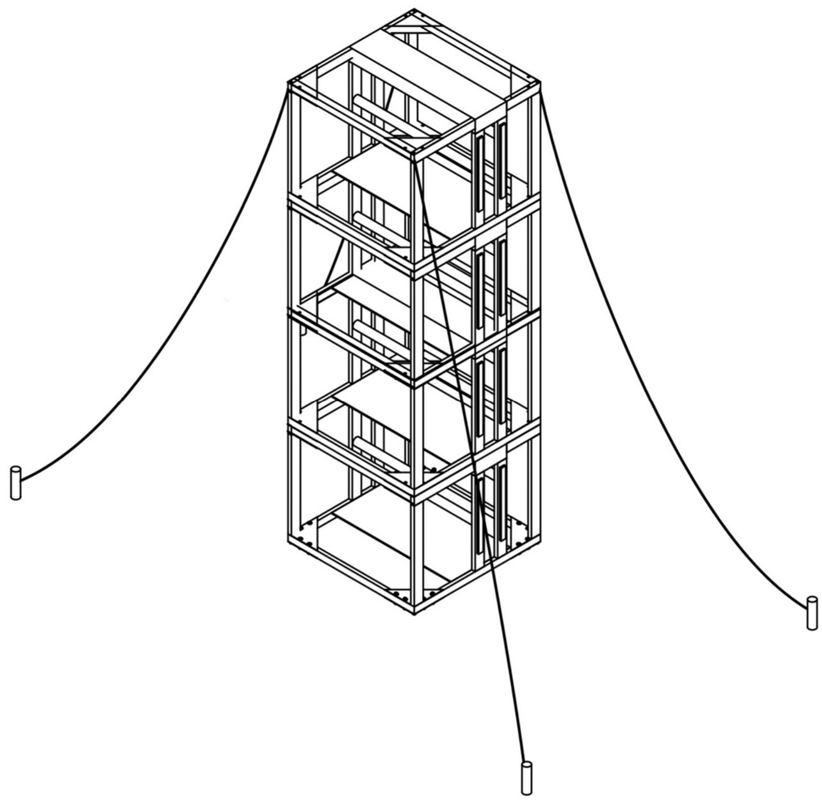

Figure 10. Stacked Mount Configuration

3.6 Potential End Users

The three potential end users identified for the VIV generator are the Dutch Harbor, Akutan, and Adak remote communities in Alaska. Alaska was selected both for its high current and high hydroelectric potential as well as its numerous communities reliant on microgrids. Each of these three end users are a part of Alaska's Aleutian Island chain, which are not connected to the major interstate energy grid. Currently, these communities rely on petroleum power plants or diesel generators for electrical generation. Petroleum power plants expose the communities to emissions, poor air quality, risk of oil spills as oil is transported to the power plant, and other numerous health and environmental hazards.

Dutch Harbor: Of the three communities, The Port of Dutch Harbor, within the city of Unalaska, is the largest community with respect to population and power demand. Dutch Harbor is the largest fishing port in the United States and requires large amounts of electrical power during peak fishing season for processing. Currently Dutch Harbor is powered by two generators to provide a total of 17600 kW to the city of Unalaska and its 4,432 permanent residents, according to the 2020 census (The City of Unalaska, Alaska, 2020). Since the major activities of birding, fishing, kayaking, berry picking, and beach combing draw in an additional 5-6,000 additional people during peak season, it is vital to provide power in a way that does not damage the natural beauty and ecosystem of Dutch Harbor (Alaska Marine Highway System, n.d.). The average price of electricity in Dutch

Harbor $0.46/kWh. The Port of Dutch Harbor lies near three pivotal passes: the Unalga, Baby, and Akutan passes. These three passes possess a total tidal generation potential of 215,000 kW. Implementing an array of wave energy converters into any number of these passes will provide Dutch Harbor with sufficient electricity for its residential power demand as well as its industrial power demand.

Akutan: Akutan is another remote community located on the Aleutian Islands east of the Port of Dutch Harbor. Akutan has a population of 1,589 according to the 2020 census (Department of Labor and Workforce Development, 2020). Similar to Dutch Harbor, Akutan is dependent upon its fishing industry, which requires a healthy environment for fish to live in and enough power for fish processing during peak season. This would be another ideal location for our design to utilize the local tidal energy with minimal negative impact to the environment or the islands livelihood. Akutan and Dutch Harbor share the same passes with high tidal energy potentials, so an array of devices set up along the pass would serve to benefit both communities.

Adak: Adak, or Adak Island, is further west as a part of the Andreanof Islands within the Aleutian Islands in Alaska. These islands are even more remote than the previous communities. While consisting of most of the population of the Andreanof Islands, Adak itself has a population of 248 (Census Report, 2022). Adak previously served as a major American military base during the Cold War and is now a quiet little town 1200 miles from Anchorage, AK. Similar to the other end users, Adak is known for its hiking, fishing, birding, photography, and wildlife viewing (Travel Alaska, 2024). Currently, Adak relies on diesel generators for power. Adak is even more isolated from the mainland United States compared to Dutch Harbor and Akutan. Since there are less people, a smaller array of devices would be required to match the electricity demand of the islands. Adak also possesses extremely high wave energy potential compared to the previous two locations, which would be utilized to provide electricity.

3.7 Environment and Sustainability Factors

3.7.1 Noise

Since the goal behind harnessing marine energy is to generate a clean and sustainable source of energy, there are various environmental and sustainable factors that must be considerable for this design to be successful. A major, yet invisible, pollution type that affects marine environments is sound pollution. As the device is intended for underwater operation, the noise produced by the device could have an adverse effect on local wildlife. The hearing ranges of marine wildlife depend quite heavily on the individual species, but there are general hearing ranges for animals. Marine life is generally able to hear frequencies between 10 Hz and 200 kHz (National Research Council, 2003). However, different species have different hearing ranges that affect them the most. For example, many odontocetes are echolocators, which rely on reflections of higher frequency noises. Because of this, odontocetes have peak sensitivities to ultrasonic sound ranges and moderate sensitivity to frequencies between 1 and 10 kHz (Baber, 2023). However, a study found that wave energy converters do not significantly affect marine mammals (Tougaard, 2015). They placed a microphone 25 meters away from a similar wave energy converter and found that noise levels were barely audible aside from short bursts indicating the start and stop of a hydraulic pump. Compared to the noise level and frequency of ship and wave noises, it is unlikely for the wave energy converter to significantly harm or confuse marine wildlife.

3.7.2 Spill Risk

Another important environmental and sustainability factor is the consequences of failure. Because Alaska has been home to major oil spills, such as the Exxon Valdez oil spill which spilled 11 million gallons of oil, the goal of this device is to minimize environmental risk (National Oceanic and Atmospheric Administration, 2020). Since there are no tanks or hazardous materials included in the construction of the fat foil energy generators, there is minimal risk to the environment if failure occurs. However, there is a risk of ships sailing over the devices so there needs to be markers indicating seabed installation of the fat foil devices. Dive flags and buoys serve a similar purpose of alerting vessels where there are divers nearby, so a similar system could be implemented to prevent collisions and potential environmental or safety risks.

3.7.3 Biofouling

Biofouling is the process of microorganisms, plants, or animals accumulating on the surface of a structure. Microfouling refers to the accumulation of microorganisms and biofilm while macrofouling refers to the accumulation of organisms such as seaweed or barnacles (Sofar Ocean, 2021). Biofouling is not favorable because it causes flow to separate earlier than expected and harms the efficiency of the wave energy converter. To prevent biofouling, protective coatings will need to regularly be applied on all exposed surfaces of the wave energy converter. Most modern antifouling coatings can harm human and environmental health because of the use of toxic or chemical paints to prevent growth on the coatings. Recent EU-funded research in the ZABIO project aims to use zosteric acid as an environmentally friendly antifouling agent (Cysbio, n.d.). As this project has not yet developed the coating for widespread use, the wave energy converter must use traditional antifouling coatings. The typical lifespan of marine fouling coatings is 1.5 years (Drisko, 1977), which will need to be accounted for in yearly maintenance of the wave energy converter.

3.7.4 Other Wildlife Interactions

Another important aspect to consider for an environmentally friendly and sustainable device is how the device interacts with marine wildlife. Vortex Hydro Energy's VIVACE converter is a device very similar to our wave energy converter. In the technical report for the VIVACE converter, Vortex Hydro Energy dedicates a portion of the background to discuss how their VIVACE converter affects wildlife. Because their VIVACE converter does not oscillate fast and does not use fast spinning element, there is no physical risk for fish or other marine wildlife. Interestingly, fish thrive on the wake produced by the oscillations of the cylinder (Bernitsas, 2008). Figure 11 demonstrates how fish utilize the vortices produced by the VIVACE converter to swim faster. This indicates how the wave energy converter poses little risk to the environment.

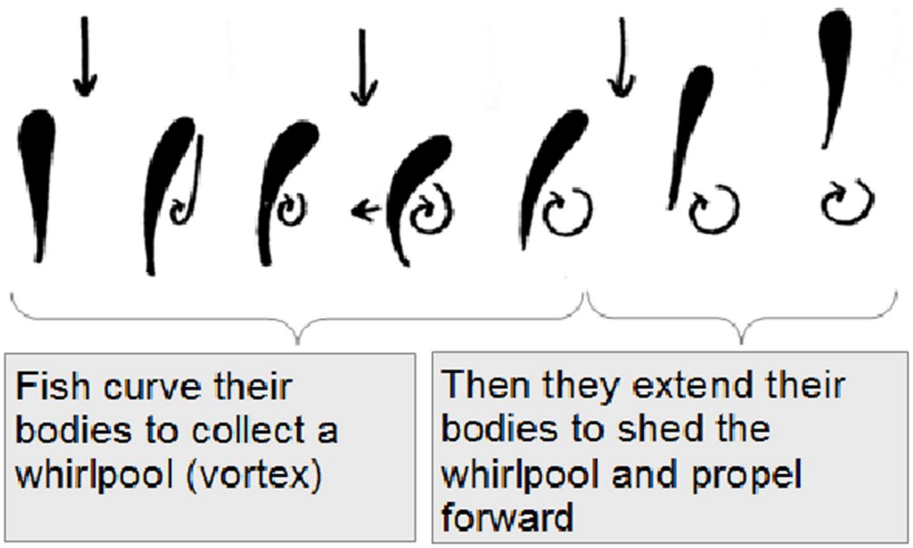

Figure 11. How Fish Swim with Vortices

4. Build and Test

4.1 Objectives

The objectives of the build and test challenge this year were twofold; to create a modular, easily assembled, and robust generator that could produce power through the oscillation of a fat foil driven by VIV; and to construct a mechanism by which pitch stiffness could be added to the fluttering foil and test its effects on power generation when compared to past research done on free-fluttering fat foils.

4.2 Design Process

The design of this prototype was challenging because it had to take inspiration from the devices used by past research, but also include innovative solutions to the problems faced by these earlier devices. The requirement to integrate previous methodology ensures that gatheres data has a constant baseline of comparison which allows direct comparisons to be drawn with past data. Another challenge is that this device needs to have increased functionality, allowing for modulating torsional stiffness while simplifying the design and construction process.

This device was created for use in Webb Institute's Circulated Water Channel (CWC), located on campus in the Haeberle Laboratory. Due to the limited size and high demand for use of the CWC, the device was designed to be easily removable in a short amount of time. This project was designed around the standard $5000 budget allotted to the Build and Test Challenge.

One of the most important aspects of the device this year was its modularity. The devices used in previous research tend to be complex, heavy, and difficult to work with. Having the ability to easily assemble, transport, and install the device was a huge boon for the construction process, especially when considering the iterative nature of that process. In order to facilitate modularity, the device was split up and constructed in three main sections: the plexiglass insert, aluminum frame, and foil carriage (Figure 12).

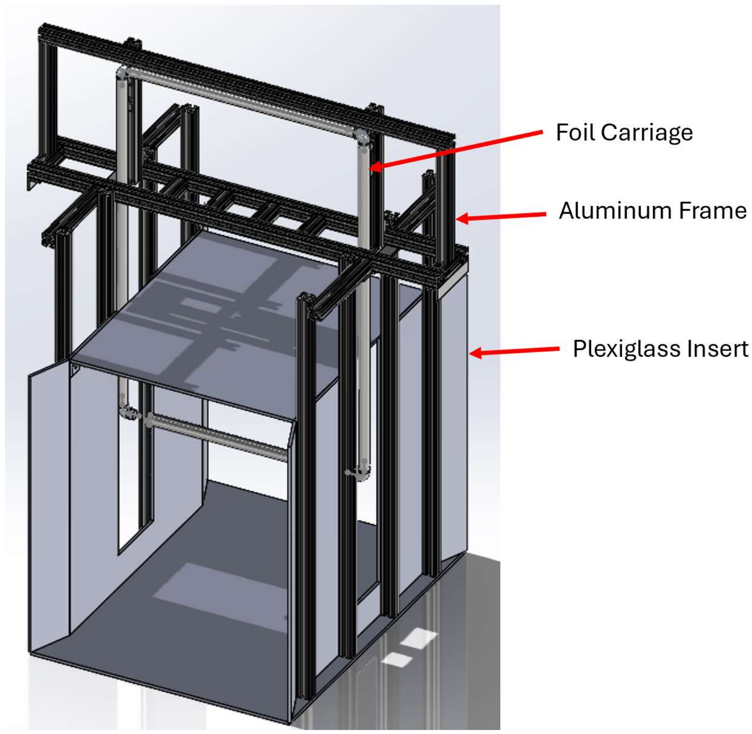

Figure 12. VIV Testing Apparatus

A previous method of construction separated the frame and carriage from the insert, but not from each other; for this project, all three sections were combined for ease of installation, as well as improving the strength of the apparatus. Another major change made to this version of the design was to change the materials and components used. Previously, the frame was constructed with 1" 80/20, and the carriage was constructed with extruded aluminum square tubing. This updated design kept the 80/20 material, but the structure was redesigned to use less material and take up less space. The biggest changes, however, were the modifications to the foil carriage. The material was changed to carbon fiber tubing; this significantly reduced the weight of the foil carriage. The next major change was to directly attach the plexiglass insert to the 80/20 framing. In the previous design, these two components fit together, but were not mechanically connected, a decision which led to rigidity issues during the installation and testing phases. Finally, the last major change is the installation of a new style of linear guide on the foil slider. Since the foil needs to be constrained to two degrees of freedom (pitch and heave), an appropriate method of constraining the motion of the sliding assembly to only move in the vertical direction (perpendicular to the flow) is essential. The previous model used a series of skateboard wheels attached to a static frame, which aligned the movement of the foil slider while lowering friction as the sliding assembly heaved. For this, the skateboard wheel system was abandoned in favor of a linear slider system that introduces much less friction and "wiggle" into the system. Originally, linear slides from Thomson were chosen, but these proved to introduce unacceptable levels of friction to the system and were removed. In their place, several slider blocks were installed; these blocks interface with the channels present in 80/20 extrusions. The blocks drastically reduced the friction acting against the carriage. The largest issue with the skateboard wheel system was their allowance of unacceptably large shaking and twisting moments due to high clearances between the wheels and the foil slider; the use of the new linear sliding system alleviates this problem, since the blocks are specifically designed to fit the given rails with a minimum of free space. A model of the testing apparatus can be seen in Figure 12.

4.3 Fabrication

Due to the necessity to ensure modular functionality of the system, 80/20 aluminum extrusions were used. These allowed for constant changes to be made "on-the-fly" to the arrangement of the system as different ideas iterated upon. Some ideas required changes to tolerances and spacing of framing and the 80/20 T-slot system allows for that level of flexibility. Over the course of the fabrication process, many changes were made to improve upon the original design, and to overcome variations from the original schematic. Pieces could be moved around to increase support in areas of excessive motion in the framing, or to better align the foil carriage to reduce systematic friction.

3D printing also played a critical role in the fabrication of the testing apparatus as it allowed for custom parts to be designed to fit our specific needs. 3D printing also allowed for better control over the weight of the sliding system as minimizing the inertia of the foil carriage is paramount to the success of the device. We utilized the 3D printer slicing software Cura which allows for the generation and modification of G-Code, the programming language interpreted by 3D printers and other CNC machines. Cura also allows for a high-resolution weight estimation to be generated allowing us to further iterate to reduce printed parts' weight without modifying the 3D part files themselves. This is primarily done by modifying the percentage of the solid that is filled with material and by modifying the wall thickness until a part of the desired strength and weight is generated for printing. This, combined with the availability of rapid CAD modeling software like SolidWorks, allowed for the rapid iteration of design based on results of flow channel testing. 3D printed parts included the 90-degree elbow pieces to connect the carbon fiber tubing, a pipe length extender when we realized that the carbon fiber tubing on hand was not long enough, the mounts for the foil itself to allow for the implementation of torsional stiffness and nearly frictionless pivoting.

During the fabrication process, an unexpectedly large amount of play was found in the foil carriage system that added to the friction in the system by binding on the linear sliders within the

80/20 T slots when loaded with drag forces from the flow. This was overcome by adding brackets to the top corners of the foil carriage, the resulting stiffness enabled us to

An additional change made during the fabrication process was increasing the size of the cylindrical foil section. The cylindrical section we had been using was a carbon fiber tube with an outer diameter of 1.25in. This was found to generate insufficient forces to overcome the inertia in the system, and despite every attempt being made to reduce the frictional opposition to motion, there just was no viable solution to use that size foil. A 2-inch nominal outer diameter PVC pipe was procured (with the minimum commercially available wall thickness to reduce weight) and a new mounting hardware was 3D printed to integrate the larger sized cylinder with the rest of the carbon foil carriage system. This resulted in our first self-excited vortex induced vibration, though due to remaining friction in the system, the heave was not sustained for long.

The final source of friction to eliminate was the binding of the plastic insert linear sliding system. As the flow induced drag on the foil, a moment was created. The plastic slides nearest the foil exerted more normal force on the 80/20 T-slot resulting in a greater frictional force too significant to sustain vibration for long. This was overcome by removing those slides and implementing wheels tied into the 80/20 framing to constrain the foil in the direction of flow while offering the extremely low inertial impact of rolling friction. These wheels were custom printed to be concave and nearly match the foil section, further constraining the foil carriage transverse to the flow, and preventing binding in the remaining linear slides due to racking.

4.4 Testing Procedure

Due to the delays suffered during the construction process, the team was only able to conduct limited testing of the device. The original goal was to complete a comprehensive testing matrix of the device, which would include the use of a purely cylindrical foil, a free-fluttering faired fat foil, and a fat foil with added pitch stiffness, all tested over a range of heave stiffnesses and flow speeds. Due to the time constraints, however, a reduced testing matrix was conducted so as to gather baseline data that could be scaled up to predict performance of the full-scale device. This reduced matrix was only conducted on a cylindrical foil, and tested combinations of two heave stiffnesses and five flow speed. In these conditions, the oscillation amplitudes in heave were measured. This amplitude is to be maximized in order to create the largest amount of energy generation.

As described earlier in the theory portion of the Technical Design section, the relationship between stiffness and flow speed can be mathematically defined. This relationship is useful for determining a baseline of testing variables, but it does not provide the whole picture. Since the generally accepted VIV inducing Strouhal Number is an empirically derived approximation, and VIV can occur at Strouhal numbers in a small range around that value, large testing matrices have to be conducted to determine an accurate picture of what stiffness and flow speeds will induce VIV. In order to correctly measure the flow velocity, a Pitot tube is submerged in clean flow ahead of the device and connected to a manometer. The Bernoulli equation is used to convert the pressure difference measured by the manometer to a steady-state flow speed measurement. The stiffness can be varied by using different combinations of springs connected to the foil in parallel with each other. These springs are attached so as to keep the foil in a neutral position within the water column. Generally, the relationship between flow speed and stiffness is such that lower flow speeds induce VIV with lower stiffness.

For each testing condition, a linear encoder was used to measure and digitally record the amplitudes of oscillation over a set time period. For these tests, a period of 10 seconds was used, and at 200 samples per second, 2000 samples were collected. Using this data, the energy present in the system, and therefore the theoretical power output, was calculated using Equation 1. In equation 1, U is the average energy of the system, ω is the angular velocity of the oscillation, and t is time.

$$P := \frac{\int_0^{2\pi} U \cdot \cos(\omega t)^2 \, dt}{\text{Period}}$$

Equation 12. Power formula for oscillating harmonic system.

A sample power calculation for one of the runs conducted can be seen below in Figure 2.. The average energy of the system is approximated by calculating the potential energy at the maximum excursion where the kinetic energy of the system is 0.

Energy Calculation Example

$k := 4.62 \frac{\text{lbf}}{\text{in}}$ Total Spring Constant

$x := 1.531\text{in}$ Average Maximum Excursion

$U := 0.5 \cdot k \cdot x^2 = 0.451 \text{ ft} \cdot \text{lb}$ Average Energy

$\text{Period} := 0.5\text{s}$ Average period of oscillations

$\omega := \frac{2 \cdot \pi}{\text{Period}} = 12.566 \frac{\text{rad}}{\text{s}}$ angular velocity

$P := \frac{\int_0^{2\pi} U \cdot \left(\cos(12.566t)^2\right) dt}{0.5\text{s}} = 5.179 \times 10^{-3} \text{ hp}$ Power of the oscillating harmonic system

Figure 13. Sample Power Calculation

4.5 Analysis of Results

Despite the seemingly small power output of the device that was found during testing, when commercially scaled, we are confident that this device will be able to produce sufficient power for the purposes outlined in the preceding sections. Though testing has so far been limited, as we undergo testing of more conditions, and expand the scope of testing to include the fat foil faired section, and later the torsional stiffness component we are estimating, based on previous work, that we will be able to nearly triple the power output of the cylindrical system by achieving resonance and greatly magnifying the oscillation amplitudes.

4.6 Lessons Learned

The team learned several valuable lessons over the course of this project. The most significant of these lessons is the importance of proper time management. Schedules often fall behind, especially when unforeseen problems arise. In our case, the myriad of problems faced during the construction process caused significant delays to our testing schedule, which forced us to reduce the scope of testing and the amount of data collected.

List of References

Alaska Marine Highway System. (n.d.). *Dutch Harbor*. (Alaska Marine Highway System) From https://dot.alaska.gov/amhs/comm/unalaska.shtml#:~:text=The%20Island%20of%20Unalaska%20is,berry%20picking%2C%20fishing%20or%20kayaking.

Alaska Profile. (2023, March 16). Retrieved April 9, 2023 from EIA: https://www.eia.gov/state/print.php?sid=AK

American Electric Power. (2010, October 10). *What's on an Electric Power Pole?* Retrieved April 23, 2023 from AEP.com: https://www.aep.com/assets/docs/safety/What's%20on%20Pole_AEP.pdf

Baber, C. (2023, June 12). *The truth about marine noise pollution – the effect of anthropogenic sound in the sea*. (Blue Planet Society) From https://blueplanetsociety.org/the-truth-about-marine-noise-pollution-the-effect-of-anthropogenic-sound-in-the-sea/#:~:text=Marine%20mammals%20collectively%20have%20hearing,these%20relatively%20low%20frequency%20ranges

Bernitsas, M. M. (2008). *OMAE06-92645 VIVACE (Vortex Induced Vibration for Aquatic Clean Energy): A NEW CONCEPT IN GENERATION OF CLEAN AND RENEWABLE ENERGY FROM FLUID FLOW.* Ann Arbor: University of Michigan.

Bureau of Reclamation. (2005, April). *Transformers: Basics, Maintenance, and Diagnostics.* Retrieved April 23, 2023 from Bureau of Reclamation: https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/Trnsfrmr.pdf

Census Report. (2022). *Adak, AK Population*. (Census Report) From https://censusreporter.org/profiles/16000US0200065-adak-ak/

Comcast. (2012, October 31). *Martha's Vineyard Hybrid Cable Project.* Retrieved April 23, 2023 from Martha's Vineyard Commission Powerpoint: https://www.mvcommission.org/sites/default/files/docs/Hybrid_presentation_MVC_2012_11_01_red.pdf

Cysbio. (n.d.). *The first green, non-toxic antifouling agent for sealants, coatings and paints to transform the construction and marine industries*. (Cysbio) From https://cysbio.com/partnership/zabio-a-healthy-alternative-for-antifouling-paints/

Department of Energy. (n.d.). *Electricity 101.* Retrieved April 23, 2023 from Department of Energy: https://www.energy.gov/oe/electricity-101

Department of Labor and Workforce Development. (2020). *2020 Census Data - Akutan*. (State of Alaska) From https://live.laborstats.alaska.gov/census-data/redistrict?value%5B0%5D=4611

DigiKey. (n.d.). *CP2000AC54TEZ ABB Power Electronics Inc. | Power Supplies - External/Internal (Off-Board) | DigiKey.* Retrieved April 24, 2023 from Digikey: https://www.digikey.com/en/products/detail/abb-power-conversion/CP2000AC54TEZ/2704891

Drisko, R. W. (1977). *Protective Coatings and Antifouling Paint that can be Applied Underwater.* Houston: OnePetro.

Energy Department Funding Helps Transform Alaskan River into Renewable Energy Source. (2019, August 8). Retrieved April 9, 2023 from Department of Energy:

https://www.energy.gov/eere/water/articles/energy-department-funding-helps-transform-alaskan-river-renewable-energy-source

Hitachi Energy. (n.d.). *Subsea transformers.* Retrieved April 23, 2023 from Hitachi Energy: https://www.hitachienergy.com/us/en/products-and-solutions/transformers/special-application-transformers/subsea-transformers

IEEE. (2016, September 27). *Generator Basics.* Retrieved April 23, 2023 from Generator Basics: https://r5.ieee.org/houston/wp-content/uploads/sites/32/2016/10/2016-09-27-2-Generator-Basics-1.pdf

Loughlin, E. (2023, January 21). *How an Alaska village's switch to renewable energy helps local Native economies.* Retrieved April 23, 2023 from PBS: https://www.pbs.org/newshour/show/how-an-alaska-villages-switch-to-renewable-energy-helps-local-native-economies

Maloney, P. (2019, February 15). *Eversource Pushes Ahead with 14.7-MW Battery Project on Martha's Vineyard.* Retrieved April 23, 2023 from Microgrid Knowledge: https://www.microgridknowledge.com/distributed-energy/article/11429907/eversource-pushes-ahead-with-147mw-battery-project-on-marthas-vineyard

McKinley Research Group, LLC. (2021, July). Alaska's Renewable Energy Economy. Retrieved April 9, 2023 from The Nature Conservancy: https://www.nature.org/content/dam/tnc/nature/en/documents/AlaskaRenewableEnergy2021.pdf

National Oceanic and Atmospheric Administration. (2020, August 17). *Exxon Valdez*. (NOAA Damage Assessment, Remediation, and Restoration Program) From https://darrp.noaa.gov/oil-spills/exxon-valdez

National Research Council. (2003). Effects of Noise on Marine Mammals. In *Ocean Noise and Marine Mammals* (pp. 83-108). Washington, D.C.: The National Academies Press.

Pollard, A. (2022, October 12). *Martha's Vineyard News | Eversource to Begin Major Underwater Cable Project.* Retrieved April 23, 2023 from The Vineyard Gazette: https://vineyardgazette.com/news/2022/10/12/eversource-set-begin-underwater-cable-project-major-upgrade-island-electrical-grid

Schroeder, D. (n.d.). *A Detailed Wind Turbine Blade Cost Model - P. Bortolotti, D. Berry, R. Murray, E. Gaertner, D. Jenne, R. Damiani, G. Barter, and K. Dykes.* From NREL: https://www.nrel.gov/docs/fy19osti/73585.pdf

Schroeder, D. (n.d.). *Marine Energy in the United States: An Overview of Opportunities.* Retrieved April 9, 2023 from NREL: https://www.energy.gov/eere/water/articles/marine-energy-united-states-overview-opportunities

Shami, E., Mayberry, L., Zhang, R., & Wang, X. (2023). *A preliminary study of a novel wave energy converter of a Scotch Yoke mechanism-based power take-off.* Sustainable Energy Technologies and Assessments.

Sofar Ocean. (2021, February 3). *What is biofouling and how can we stop it?* (Sofar Ocean) From https://www.sofarocean.com/posts/what-is-biofouling-and-how-can-we-stop-it

The City of Unalaska, Alaska. (2020). *Population*. (The City of Unalaska, Alaska) From https://www.ci.unalaska.ak.us/community/page/population

Tougaard, J. (2015). *Underwater Noise from a Wave Energy Converter Is Unlikely to Affect Marine Mammals.* Bethesda: National Library of Medicine.

Travel Alaska. (2024). *Adak*. (Travel Alaska) From https://www.travelalaska.com/Destinations/Cities-Towns/Adak

Victron Energy. (2022, April 19). *Phoenix Inverters.* Retrieved April 23, 2023 from Victron Energy: https://www.victronenergy.com/upload/documents/Datasheet-Phoenix-Inverter-VE.Direct-250VA-1200VA-EN.pdf

Zhegui Electric. (n.d.). *Medium Voltage Step Up 35kV Indoor Dry Type Transformer from China manufacturer - Zhejiang Zhegui Electric Co., Ltd.* Retrieved April 23, 2023 from Switchgear, Circuit Breaker, Load Switch, Transformer, Compact Substation – Zhejiang Zhegui Electric Co., Ltd.: https://www.giant-electric.com/Medium-Voltage-Step-Up-35kV-Indoor-Dry-Type-Transformer-pd44116582.html

Amazon: Brushless Permanent Magnet Generator, 2000W low RPM permanent magnet synchronous generator alternator PMA Pure Copper AC/DC Alternator : Patio, Lawn & Garden. (n.d.). https://www.amazon.com/Brushless-Permanent-Generator-Synchronous-Alternator/dp/B0BBGCY5PF

Bernitsas, M (2015). Vortex Induced Vibration Aquatic Clean Energy: A New Concept in Generation of Clean and Renewable Energy from Fluid Flow. *Journal of Offshore Mechanics and Arctic Engineering*. 130, 041104-1. DOI: 10.1115/1.2957913

Bradstock, F. (2023, December 28). *Subsea Power Cables: The future of global energy transport*. OilPrice.com. https://oilprice.com/Energy/Energy-General/Subsea-Power-Cables-The-Future-of-Global-EnergyTransport.html#:~:text=AC%20cables%20are%20usually%20used,over%20%242.5%20million%20a%20km.

Community-Scale Isolated power Systems (2019). *Department of Energy*.

Harnessing Marine Energy at All Scales, from a Village Microgrid to a Vast Tidal Inlet (2020). *National Renewable Energy Laboratory*. https://www.nrel.gov/news/program/2020/harnessing-marine-energy-at-all-scales.html

Keep the Power on When in Matters with an Intelligent Microgrid System (2024). *Eaton*. https://www.eaton.com/us/en-us/company/news-insights/stronger-future/microgrids.html#:~:text=Through%20the%20Inflation%20Reduction%20Act,economic%20payback%20for%20microgrid%20projects

Loughlin, E (2023). How an Alaska Village's Switch to Renewable Energy Helps Local Native Communities. *PBS*. https://www.pbs.org/newshour/show/how-an-alaska-villages-switch-to-renewable-energy-helps-local-native-economies

Metalsdepot® - buy Stainless Pipe Online. MetalsDepot® - Buy Stainless Pipe Online. (n.d.). https://www.metalsdepot.com/stainless-steel-products/stainless-steel-pipe?gad_source=1&gclid=CjwKCAjw3NyxBhBmEiwAyofDYabyedSNsMh7vn3r0tOb8Cq-4zodfVrNfxL9LHiwufkMuPZ-sQOWVhoCEMwQAvD_BwE

New Study Sheds Light on Mysterious Movements of Rarest Great Whale (2023). *National Renewable Energy Laboratory*. https://www.fisheries.noaa.gov/feature-story/new-study-sheds-light-mysterious-movements-rarest-great-whale

Report to Congress: Affordable and Reliable Options for Meeting Energy Needs and Reducing Emission (2020). *US Environmental Protection Agency*. https://www.energy.gov/node/4592765#:~:text=The%20communities%20in%20remote%20areas,Alaska%20are%20generated%20with%20diesel

Simiao, G. (2014, March 21). *Advanced integration of power take-off in Vivace*. Advanced Integration of Power Take-Off in VIVACE (Technical Report) | OSTI.GOV. https://www.osti.gov/servlets/purl/1124124

Stainless expanded metal. MetalsDepot®. (n.d.). https://www.metalsdepot.com/stainless-steel-products/stainless-expanded-metal?gad_source=1&gclid=CjwKCAjw3NyxBhBmEiwAyofDYeoEhIxhN8KZaKq2oDcMrBovPuj-Tn7imhAxz_T77nn3FabhcMkztRoCmSoQAvD_BwE

Thayer, C (2023). Power Cost Equalization Program: Statistical Report. *Alaska Energy Authority*. https://www.akenergyauthority.org/Portals/0/Power%20Cost%20Equalization/2024.02.26%20FY23%20PCE%20Statistical%20Report%20by%20Community%20(Final%20Optimzed).pdf?ver=om4p4ZK_A-xwHiFPOHfvDQ%3d%3d

Three phase transformers. Three Phase Transformers - Grainger Industrial Supply. (n.d.). https://www.grainger.com/category/electrical/transformers-ups-power-supplies/transformers/three-phase-transformers?attrs=VA%2BRating%2B-%2BTransformer%7C20%2BkVA&filters=attrs