Harnessing the Power of the Seas When Generating Sustainable, Floating Wind Power

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

History

Floating offshore wind power is a relatively new field, and there has not been extensive research done to fully understand the benefits it could have. The world's first floating wind turbine was built off the coast of Italy in 2007, but currently there are only two operational floating wind farms in the world -- Hywind, Scotland began operation in 2017 and Windfloat, Atlantic began operation in 2020 (Gourvenec, 2020).

Most wind farms currently in operation are placed on land, mainly in large, open fields to avoid the turbulence created by nearby infrastructure or forests. Additionally, some wind farms have been built offshore to take advantage of the absence of turbulence from buildings and trees and the higher winds present at sea; however, they are not of a floating nature. These wind farms require extensive time, energy, and money to build, as it is very difficult to construct these turbines while working in very deep waters.

Floating wind turbines offer a compromise -- they can utilize the favorable conditions present in deep waters while being easier to construct on land and then tow out to sea. Since they do not need to be built in the water, with more research and development, they could utilize modern construction technologies on land and then be brought out to sea and anchored for a comparatively low cost. An efficient and effective way of constructing them must first be researched and accepted before these turbines can be produced on a larger scale. Floating wind turbines, currently, are expensive to construct since they are a new technology that has not been researched and improved upon extensively. Although floating wind turbines currently have additional costs due to the floating structure and power distribution system, these are offset by

better energy production due to higher winds in deeper waters and greater public acceptance due to lower visual and environmental impacts. Additionally, since 40% of the world's population lives within 100 km of a coastline, offshore, floating wind turbines would be in close proximity to the energy needs of many populations (United Nations, 2017).

Objective

Our group's objective is to determine the optimal substructure configuration to stabilize a floating offshore wind turbine. Our group is using a model based on Principle Power's WindFloat, a floating support structure for offshore wind turbines and shown below in Figure 1, as a control base ("Principle Power, Inc. - Globalizing Floating Wind", n.d.). We will focus on improving a barge configuration that generally allows for lower environmental impact, cheaper manufacturing, easier maintenance, and greater access to ocean area independent of water depth, as well as being mechanically viable. Challenges experienced by the Principle Power WindFloat design include surviving hurricane-speed winds, which can reach almost 60 m/s, and tsunami-height waves, which have been recorded at almost 20 m ("Massive Atlantic Wave Sets Record, Says World Meteorological Organization", 2016; "Saffir-Simpson Hurricane Wind Scale", n.d.). WindFloat has survived winds up to 41 m/s and waves up to 17m, so our group hopes to research structure designs that withstand disturbances more effectively ("Principle Power, Inc. - Globalizing Floating Wind", n.d.).

Figure 1

Image of Principle Power's WindFloat structure in operation.

Note. As shown on Principle Power's website. Citation: Principle Power, Inc. - Globalizing Floating Wind. (n.d.). Retrieved April 24, 2021, from https://www.principlepowerinc.com/.

Types of Structures

There are three main types of substructures for floating wind turbines researched and published by the International Renewable Energy Agency (IRENA) (IRENA, 2016). They are as follows:

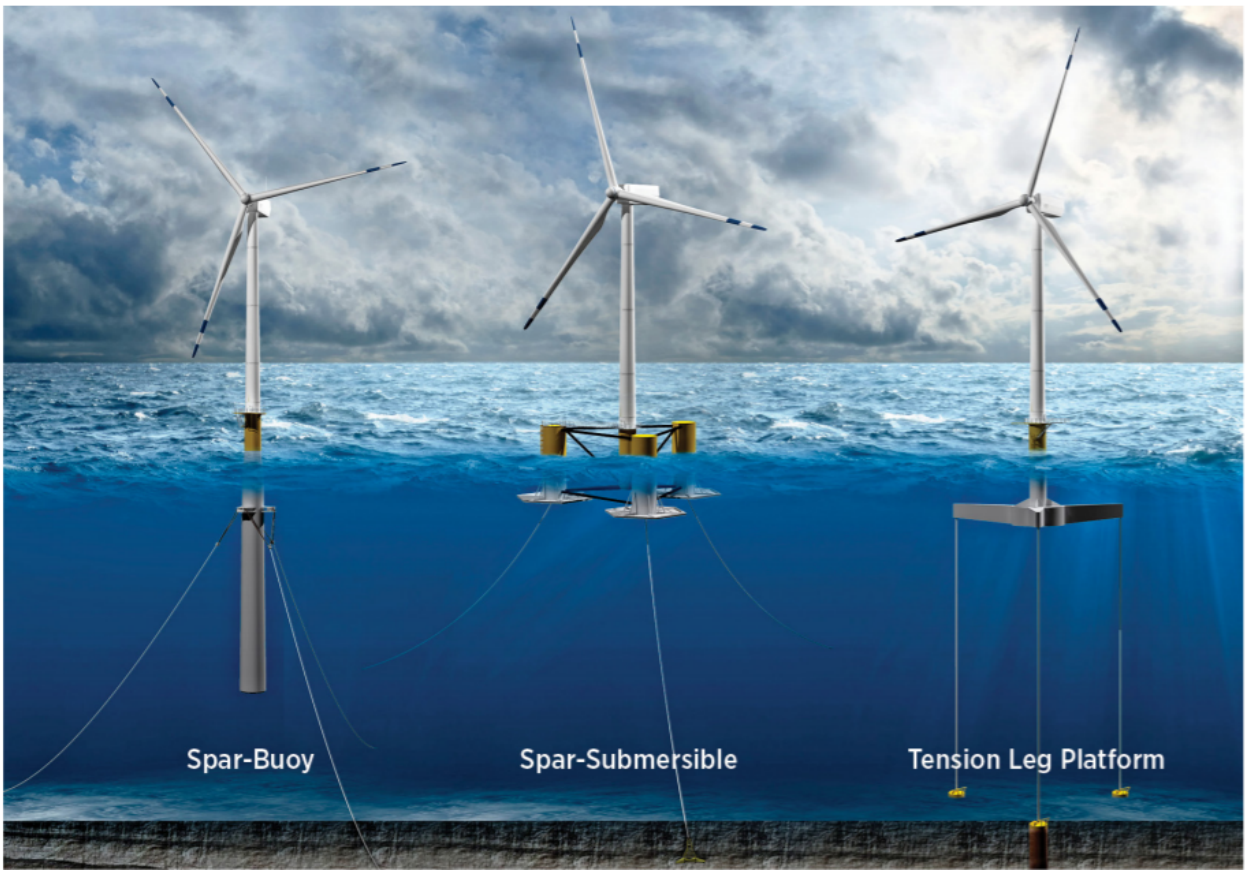
1. Spar-Buoy: Achieves stability through a ballast (weight) that's installed below the main buoyancy tank.
    a. Challenges: Deep drafts limit port access
2. Spar-Submersible: Achieves static stability by distributing buoyancy widely at the water plane.
    a. Challenges: More exposure to waves; more of the structure is above the water line
3. Tension-Leg Platform: Achieves static stability through mooring line tension with a submerged buoyancy tank.

a. Challenges: Unstable during assembly; high vertical load moorings.

These types of substructures can be seen below:

Figure 2

Three main types of floating wind turbine substructures



Note. As shown in IRENA (2016), Floating Foundations: a Game Changer for Offshore Wind Power, International Renewable Energy Agency, Abu Dhabi.

Why Floating Wind Turbines are Needed

Power generation using fossil fuels, such as oil, coal, and natural gas, is the leading cause of greenhouse gas emissions in the world ("Why Clean Energy is Important", *n.d.*). Carbon dioxide, the most abundant harmful greenhouse gas, is the leading cause of human-induced climate change ("Causes of Climate Change", 2019). Because it is emitted during the burning of

fossil fuels, which can remain in the atmosphere for up to 1,000 years. Countries all over the world must commit to reducing their carbon emissions to prevent causing further pollution that will continue to affect populations for hundreds of years (Buis, 2019).

According to a study performed by the Intergovernmental Panel on Climate Change (IPCC), the world is currently on a trajectory to experience an increase in global mean surface temperature (GMST) above pre-industrial levels of 1.5°C in the next 7 years and 2°C in the next 25 years if drastic measures to reduce climate change are not taken immediately (IPCC, 2018). An increase of 1.5°C will mean an increased frequency of heatwaves and droughts, increased intensity of storms, and loss of coral reefs and other biodiversity (IPCC, 2018). An increase of 2°C will intensify these issues further, with 420 million more people being subjected to extreme heat waves (Maximum Heat Wave Magnitude (HMWid) of over 40) and 65 million more people being subjected to exceptional heat waves (HMWid of over 80) (Dosio et al., 2018; IPCC,, 2018).

Renewable sources of energy, such as wind, solar, geothermal, and hydroelectric, emit little to no greenhouse gases when generating electricity (Nunez, 2019). Expanding the use of these types of energy systems will help drastically reduce carbon emissions, slowing climate change and improving the quality of life for future generations.

Wind power only generated approximately 2.8% of the United States' energy needs in 2020, but it has a potential to generate much more electricity than it currently does (Center for Sustainable Systems, University of Michigan, 2020). The United States has the resources to generate 11,000 GW of onshore wind energy and 4,200 GW of offshore wind energy; however, it has only deployed 103.6GW, or 0.94%, of its onshore potential and 30 MW, or 0.0007%, of its offshore potential (Center for Sustainable Systems, University of Michigan, 2020).

Employing more floating wind turbines will increase the amount of area that can be used for energy production, as they are able to be anchored over deeper waters and utilize more space at sea than traditional off-shore wind turbines. This will help the U.S. take better advantage of wind energy's potential for providing clean, reliable, carbon-free energy.

Why Floating Wind Turbines are Special

Many people oppose the construction of more onshore wind turbines. They require large areas of land to be cleared to operate effectively, causing deforestation, destroying natural habitats of the local wildlife, and taking up land that could be developed for other human use. They can also harm populations of flying wildlife, as the noise can burst their eardrums and they can get caught in the blades. They can also be both loud and an eyesore to those who live close to them, causing many local populations to protest their construction.

Traditional offshore wind turbines lack some of the issues onshore wind turbines present. For example, they are placed out at sea, so they do not take land away from local wildlife or prevent it from being developed for human use. There is also less flying wildlife far out over the sea that could be harmed by the noise or blades. The construction of traditional offshore wind turbines, however, could disrupt sea life since the base of the turbine is very large and must be drilled deep into the ocean floor. Additionally, these offshore wind turbines cannot be placed far enough away from the shoreline to go unnoticed by populations living near the coastline. This causes many people who live in beach communities to protest their construction, as they can obstruct ocean views. They are also very dangerous, difficult, and expensive to build since construction must occur over waters that can be up to sixty meters deep, and their base must be drilled deep into the earth's crust ("What Are the Advantages and Disadvantages of Offshore Wind Farms?", 2019).

We feel that floating wind turbines offer a promising alternative to other types of wind turbines. They can utilize the abundant space over the ocean. They will be less intrusive to sea life, as they will simply be anchored into place as opposed to having large bases drilled deep into the ocean floor. These floating wind turbines could also be placed farther out at sea, over deeper waters since they are simply anchored by cables, rather than large bases, to the ocean floor. This would prevent populations living near the shoreline from having their view of the horizon disrupted by wind farms. There will also be fewer birds farther over the sea to be negatively affected by the presence of the turbine. Lastly, it will be simpler, safer, and more cost effective to construct them since they do not need to be built at sea over deep and rough waters -- they can be built on land and subsequently towed into place to be anchored.

Background

Bases in Operation

Hywind Scotland

In 2001, Equinor introduced its Hywind concept for a floating wind turbine and subsequently began research and testing on different iterations of base designs ("The Future of Offshore Wind is Afloat", n.d.). Equinor theorized that floating wind turbines could be situated over deeper waters than traditional offshore wind turbines and be produced more easily on land and towed to sea to be anchored. Once a base design was finalized, Equinor built and operated an experimental Hywind 2.3 MW turbine off the shore of Karmøy, Norway for eight years to test their concept ("The Future of Offshore Wind is Afloat," n.d.). In 2015, after observing this lone turbine's success, Equinor and partner Masdar gained approval from the Scottish government to begin construction for a larger wind farm situated 25 kilometers off the coast of Peterhead, Scotland ("The Future of Offshore Wind is Afloat", n.d.; Hill, 2018). This first floating wind

farm, comprising five 6 MW turbines, generating enough energy to power 36,000 homes, began operation in 2017 (Hill, 2018; "Hywind Scotland", n.d.).

The wind farm spans 4 square kilometers over water depths of 95-120 meters ("Hywind Pilot Park, Aberdeenshire", n.d.). The ability of floating wind turbines to be situated over deep waters introduces many more location options for the installation of floating wind farms, as traditional wind turbines cannot be installed in waters deeper than 60 meters ("The Future of Offshore Wind is Afloat", n.d.). With 80% of the world's possible offshore wind locations having depths over 60 meters, floating wind turbines will allow wind energy to increase dramatically ("The Future of Offshore Wind is Afloat", n.d.).

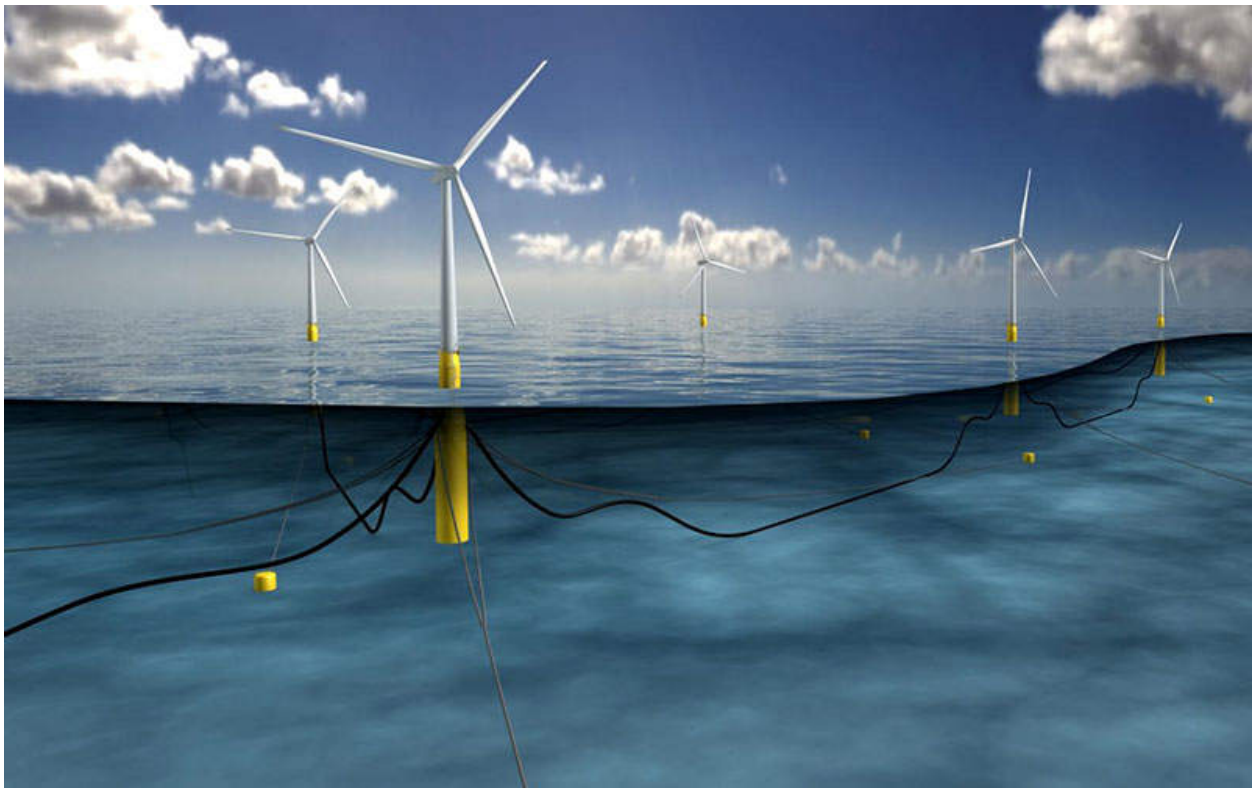
The Hywind wind turbines were built on land and then towed 25 kilometers away from the coast to be anchored (Harrabin, 2017). While these first turbines were very expensive and received government subsidies to help fund their construction, researchers believe that the turbines' ability to be constructed quickly on land and then towed to their final location at sea will help drive the cost down as more turbines are put into production in the future (Fialka, 2020; Harrabin, 2017). These cost saving benefits are already being realized, with the Hywind Scotland turbines costing 60-70% less than the experiential Hywind project ("Hywind Scotland", n.d.).

Since it began operation, Hywind's Scotland wind farm has consistently outperformed all existing traditional offshore wind turbines in the United Kingdom ("Hywind Scotland Remains the UK's Best Performing Offshore Wind Farm", 2021). The capacity factor of a wind turbine demonstrates the ratio of actual energy output to the maximum possible output over a period of time ("Hywind Scotland Remains UK's 'Best Performing' Offshore Wind Farm", 2021). During the wind farm's first two years of operation, it performed at an average capacity factor of 54%, while the UK's traditional offshore wind farms performed at a capacity factor of 40% during the

same period (“Hywind Scotland Remains UK's 'Best Performing' Offshore Wind Farm”, 2021). Between March 2019 and March 2020, the Hywind Scotland wind farm demonstrated an average capacity factor of 57.1%, a new record for the UK (“Hywind Scotland Remains UK's 'Best Performing' Offshore Wind Farm”, 2021). The success this wind farm has demonstrated during its operation confirms theories that these turbines, which can be placed over deeper waters where better wind conditions are present, can produce more energy than traditional offshore wind turbines that are more restricted in their placement.

Figure 3

Image of Hywind Pilot Park off coast of Scotland



Note. Image obtained from Hywind Pilot Park, Aberdeenshire. (n.d.). Retrieved April 27, 2021, from https://www.power-technology.com/projects/hywind-pilot-park-aberdeenshire/.

WindFloat Atlantic

In 2011, Principle Power deployed WindFloat 1, a demonstration 2 MW turbine off the coast of Portugal to test their semi-submersible floating foundation design ("Windfloat Atlantic", 2018). After five years of successful operation and producing 17 GWh of electricity, the turbine was decommissioned, disassembled at sea, and brought back to shore ("Principle Power Announces the Successful Completion of Its Windfloat 1 Pilot", 2016). Principle Power then began work on WindFloat Atlantic, a project off the coast of Viana do Castelo, Portugal consisting of three 8.3 MW turbines, enough to power 60,000 homes, using the same substructure design ("Windfloat Atlantic", 2018). The wind farm is situated in 100-meter-deep waters, a depth inaccessible to traditional offshore wind turbines ("WindFloat Atlantic Project Starts Supplying Clean Energy in Portugal", 2020). The project was completed and began operation in 2020 (Durakovic, 2020).

The WindFloat bases, too, utilized the ability to be constructed on land and subsequently towed out to sea to be anchored. Two bases were constructed in Portugal and the third in Spain before being towed to sea and anchored in their final locations ("WindFloat Atlantic Project Starts Supplying Clean Energy in Portugal", 2020). This ability to outsource construction helps save costs, accelerate the process of building more wind turbines, and stimulate many economies by creating jobs in different countries. Principle Power's bases can also be brought to shore for major maintenance should it be more cost effective to do so, another benefit of the mobility of floating turbines (Dodd, 2020).

Figure 4

Image of WindFloat Atlantic off coast of Portugal

Note. Image obtained from Larson, A. (2020, September 01). Floating Platforms Are an Offshore Wind Gamechanger. Retrieved April 28, 2021, from https://www.powermag.com/floating-platforms-are-an-offshore-wind-gamechanger/.

How Our Bases Function

Principle Power Base

The Principle Power base is a semi-submersible floating wind turbine base which consists of three hollow cylinders connected in a triangular shape. On our Principle Power base, the wind turbine tower is situated in the center of this triangle in order to achieve optimal stability. The tower inserts into a platform which bridges the three cylinders and strengthens the base.

Without Chain (Control)

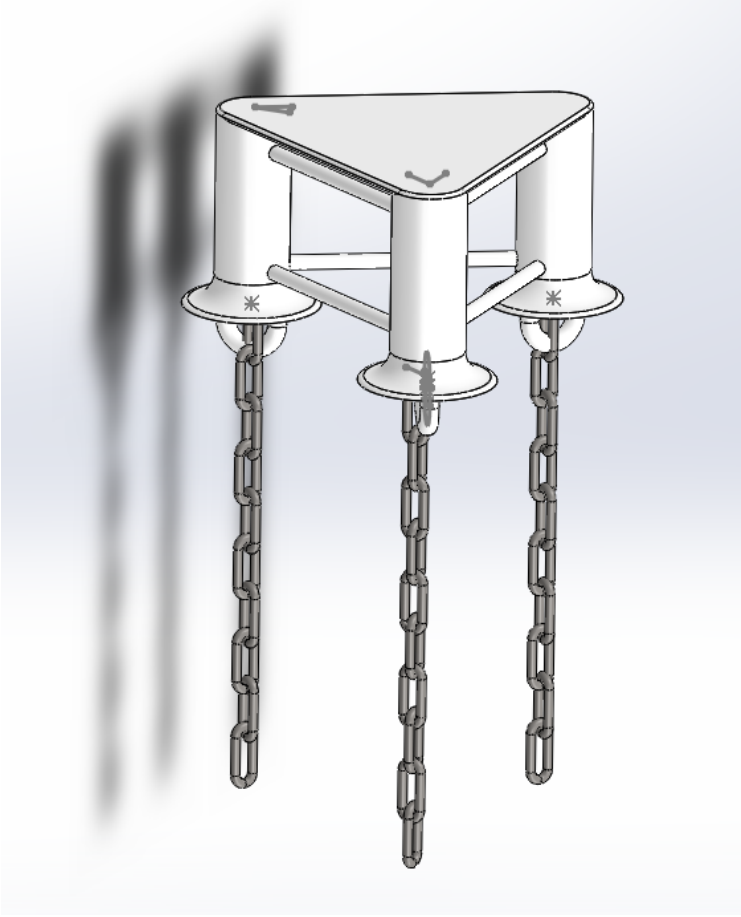
The Principle Power base without the chain, shown in Appendix B1, stabilizes itself using the hollow cylinders which provide its buoyancy. When this base encounters a wave, the lower cylinders provide an upward buoyant force and the higher cylinders provide a downward gravitational force. This allows the base to reach a level position which allows the wind turbine to perform optimally.

With Weighted Chain

The addition of weighted chains, shown in Appendix B2, increases the stability of the Principle Power base. The chains are implemented by connecting a chain to the bottom of each cylinder and joining them together into a single chain that would then be anchored to the ocean floor. This design increases stability since the function of the chain is to add more downward force to the higher cylinders when equilibrium is disturbed. The weight of the higher chain is concentrated through the connecting chains and the lower chains have slack, which allows the higher chain to provide a higher correcting force.

Figure 5

Solidworks drawing of Principle Power base with addition of weighted chains. (Image source: Boenisch, 2020).



Naturally Pressurized Base

The Naturally Pressurized Base (NPB) is a semi-submersible floating wind turbine base which is shaped in a square prism. This base passively stabilizes the turbine with the use of differently sized orifices throughout sections of the base. The tower attaches to the center of the base where a recessed platform joins the perimeter of the base in order to achieve a low and stable center of mass.

With Holes

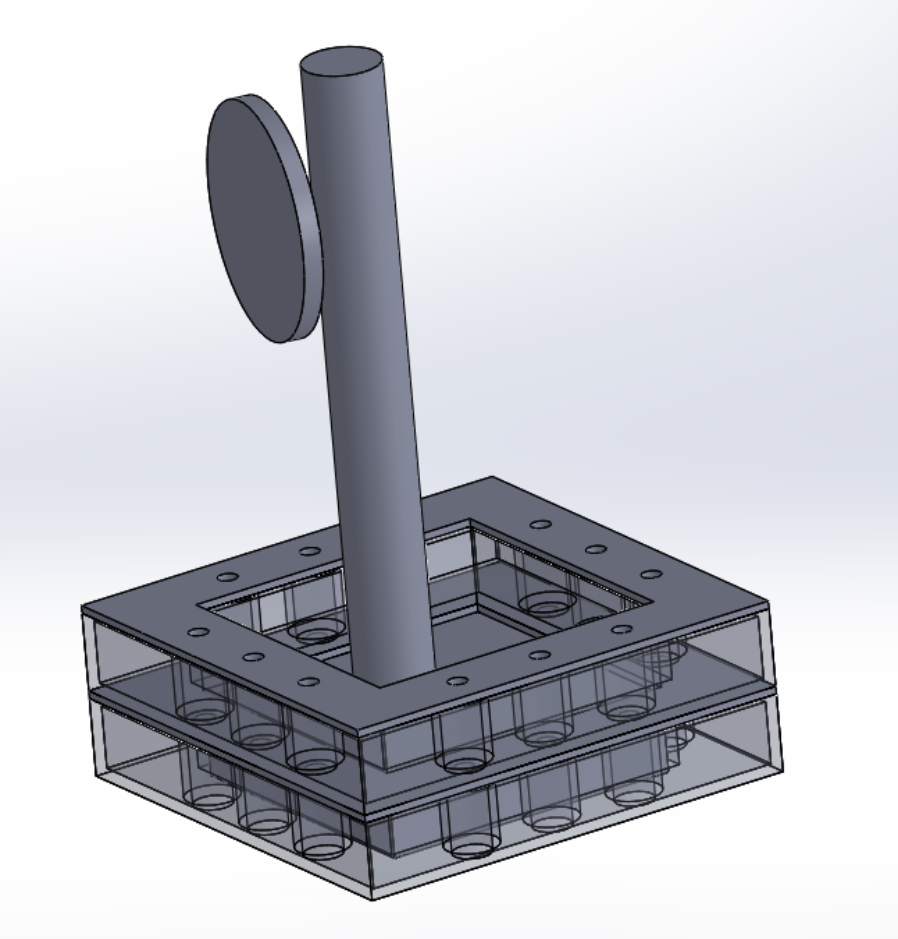
The holes in the NPB, shown in Figure 6 and Appendix B3-B6, function by allowing controlled volumes and rates of water to enter and exit the base as it oscillates. When placed in the water, three layers of small holes starting at the bottom of the base allow for water to fill in isolated reservoirs inside the base. When the water enters, it gives the base higher stability through the weight of the water. As the base is met with a wave or disturbance, water is allowed to enter the reservoirs at a rate dictated by the diameters of the holes on the lower side and water is allowed to exit the reservoirs on the high side of the base. When this happens, the water dampens the movement of the base by weighing down the high side with a slow release of water and providing resistance to the lower side with a slow intake of water. This pattern constantly occurs throughout the oscillation of the base until equilibrium is met with equal volumes of water in all reservoirs.

Without Holes

The base without holes does not use any passive stabilization and thus does not use the weight and controlled flow of water to balance the base. The NPB without holes is essentially a barge platform which floats but does not provide high stability. This was tested by taping off the holes and the base was clearly less stable without this feature.

Figure 6

Computer-Aided Design of Naturally Pressurized Passive Stabilizer Base with Representative Turbine Tower and Blade Circle (Image Source: Golson, 2020).



Codes and Standards

There were several codes and standards we had to consider when designing our bases. The National Renewable Energy Laboratory (NREL) published a report encompassing design, safety, and operations standards, which we used when designing our bases (Sirnivas et al., 2014). Some of the guidelines in the report, such as procedures concerning hurricane and cyclone

impacts, did not apply to our designs since they are prototypes and cannot be tested under certain conditions.

The International Electrotechnical Commission (IEC) has several technical standards for all electrical, electronic, and related technologies, including wind energy. The most important IEC regulations that were considered are: IEC 61400-1, which mainly addresses structures; IEC 61400-3, which addresses offshore requirements; and IEC 61400-22, which lays out methods for both type certifications and project certifications (Sirnivas et al., 2014).

Specifications

Original Specifications

Originally, there were five criteria that our designs had to meet:

1. Stability for High Waves; tilt from normal
    a. Ideal: 0 degrees tilt from normal
    b. Maximum: 10 degrees tilt
2. Stability for High Winds
    a. Ideal: 85 m/s at max hurricane speeds before breaking
    b. Minimum: 40 m/s max hurricane speed before breaking
3. Cost Effectiveness
    a. Ideal: $57/MWh
    b. Maximum: $300/MWh
4. Durability: Lifetime
    a. Ideal: 20 years
    b. Minimum: 15 years
5. Portability

a. Ideal: ⅛ of total turbine height beneath the water when floating
b. Maximum: ⅓ of total turbine height beneath the water when floating

To test the stability of the turbine for high waves, we created large ripples of water and analyzed the displacement of the turbines' bases in the y-direction. Additionally, we plotted graphs of the y-displacement for all our tests, as well as graphs of the velocity in the y-direction, which we used to determine the period of oscillation and damping time for each test. The Principle Power base exceeded our expectations in terms of stability, while the Naturally Pressurized Base proved to be less stable than expected. The portability of both turbines also met our criteria, as both turbine bases never submerged more than about a fourth of the total turbine length when in water, even when weights were added for the various tests. More in-depth calculations that advised our design process to ensure these aspects are available in Appendix C.

Changes Made to Specifications

We were unable to test the stability of the turbines in high winds, as we simply could not generate the required conditions to test this particular criterion. Cost effectiveness was also difficult to determine, mostly due to the fact that our designs focused on the base of the turbine and not the blades, which made it impossible to test for the turbine's efficiency in harnessing wind power. Finally, durability was not tested either, since it requires actual real-world deployment of our design in order to be tested properly.

Testing of Bases

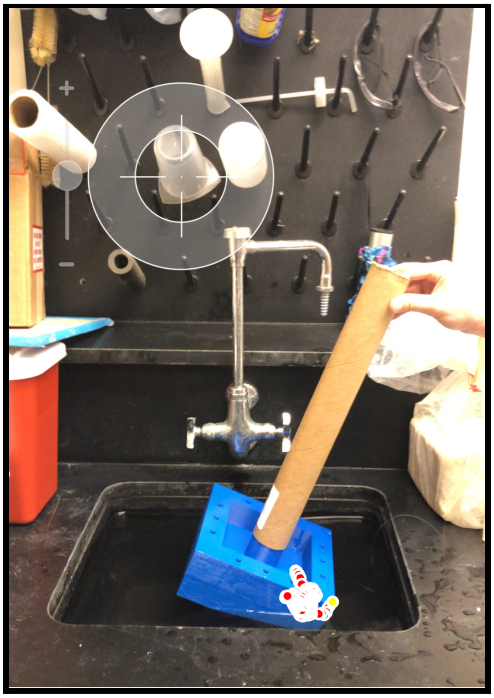
To test the efficacy of both the Principle Power and Naturally Pressurized Base systems, we performed a number of tests to elucidate how the bases responded to disturbances while floating in water. Specifically we measured how quickly the systems rocked back and forth as well as how long it took for different configurations to dampen out completely in the water.

Procedure

Each base was outfitted with a central rod to mimic the weight of a turbine tower and placed in a water-filled sink. The base was then tilted to the side and released while another team member recorded the motion. The Vernier Video Physics app was used to analyze the motion, tracking a point on the structure to show how quickly the base oscillated and how soon it reached equilibrium in the water. Below is an image of a video in the analysis application. One may note the dots surrounding the lower right point on the structure that tracked the motion of this point throughout the video.

Figure 7

Image depicting the analysis process using Vernier Video Physics mobile application.



A number of modifications were made to the bases in order to test different concepts for achieving better stability. Chains were attached to the Principle Power base, as well as styrofoam

to the legs. A number of tests were run in different configurations. Weights were added to the corners or hung from the bottom of the Naturally Pressurized Base.

Analysis

The most reliable metric utilizing this system were the graphs of the vertical velocity of the analysis point over time. Finding the points at which this line crossed the zero indicates where the rocking motion changes direction, and could be used to determine the period of oscillation. Damping time was defined as the point at which the base largely stopped rocking in the sink, though sometimes this was difficult to determine because of residual waves in the space.

Summary of Findings

Both the Naturally Pressurized Base (NPB) with holes and Principle Power (PP) base with chains exceeded the performance of their respective controls. This means that having the exposed holes and chambers on the NPB helped to dampen its motion through the water, while having the extra weight of the chains on the PP base did the same. The best performance of the PP base came from adding styrofoam to the legs as well as attaching chains to the bottom. This likely came from the fact that the added buoyancy from the styrofoam resisted the reentry of the base in the water as it was rocking, while the extra chains pulled down the lifting side in the motion. Adding weights to the corners of the NPB caused the base to oscillate at the same frequency, but lengthened the damping time. Hanging weights in the water from each corner of the NPB caused the same effect. Therefore, the NPB with exposed chambers but no modifications performed the best with respect to stability in high waves. The system did not, however, perform better than the control Principle Power base. It therefore did not meet

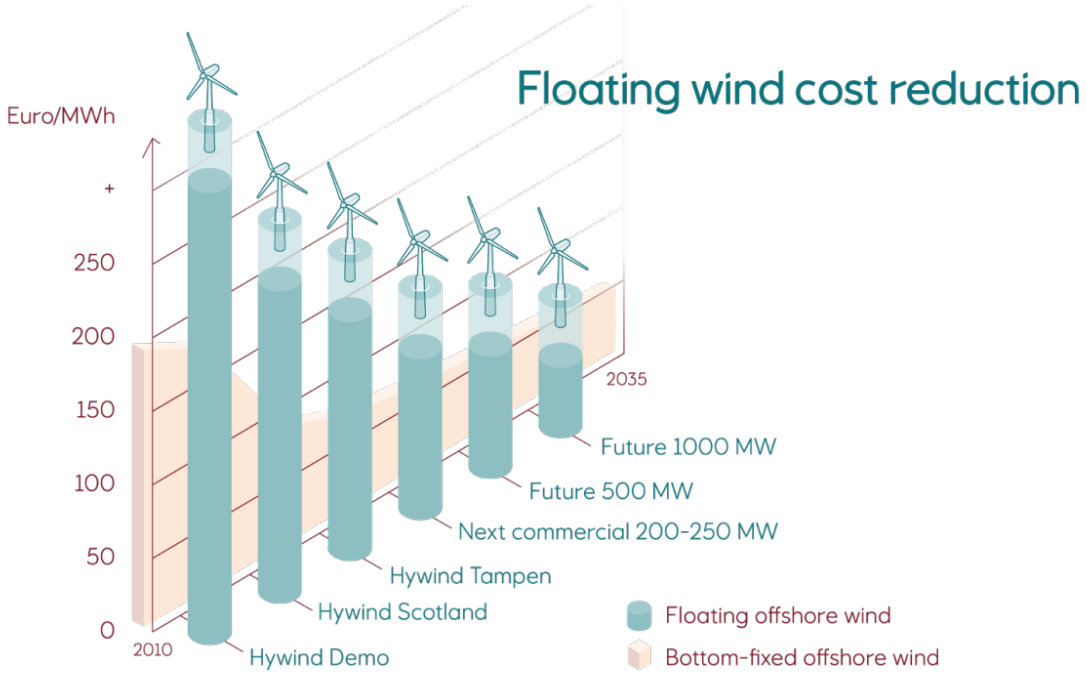
specifications with respect to overpassing this state-of-the-art design. More detailed results with regards to period of oscillation and damping time may be found in Appendix D.

Cost Analysis

Equinor has found that project scale is the best cost reduction technique (“Hywind Scotland Remains UK's 'Best Performing' Offshore Wind Farm”, 2021). It saw a drastic, 70% reduction in cost per megawatt-hour (MWh) between its 2.3MW Hywind Demo project and its 30 MW Hywind Scotland project (“Hywind Scotland Remains UK's 'Best Performing' Offshore Wind Farm”, 2021). Equinor is now in the construction phase of an 88 MW Hywind Tampen project off the coast of Norway, and it continues to realize cost reductions with this larger project (“Hywind Scotland Remains UK's 'Best Performing' Offshore Wind Farm”, 2021). Equinor has estimated a further 40% reduction in cost between their Scotland and Tampen projects (“Hywind Scotland Remains UK's 'Best Performing' Offshore Wind Farm”, 2021). Equinor expects that by 2035, floating wind turbines will surpass traditional wind turbines as the cheapest option for offshore wind as technology and experience allows them to become larger and more easily constructed (“Hywind Scotland Remains UK's 'Best Performing' Offshore Wind Farm”, 2021). Figure 6 visualizes this estimated progression.

Figure 8

Chart tracking cost reduction of floating wind turbines over time



Note. Figure obtained from Hywind Scotland Remains UK's 'Best Performing' Offshore Wind Farm. (2021, March 24). Retrieved April 28, 2021, from https://www.energylivenews.com/2021/03/24/hywind-scotland-remains-uks-best-performing-offshore-wind-farm/#:~:text=Hywind%20Scotland%2C%20the%20world's%20first,for%20the%20third%20consecutive%20year.

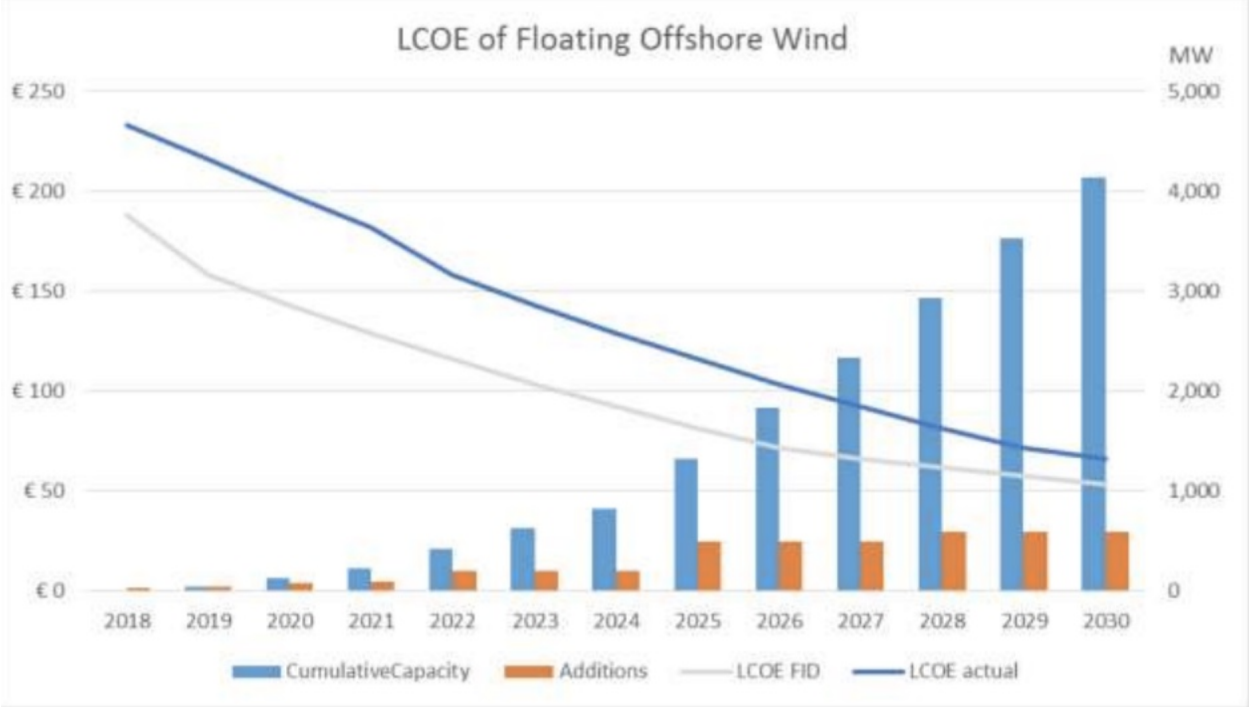
A study performed by Principle Power suggests that industrialization of the floating wind turbine construction process will drive down costs ("Commercial Floating Wind - The WindFloat Role", 2019). It believes that scale and a commitment to continuous improvement of this technology will drive costs to record lows, just as was seen with traditional offshore wind turbines ("Commercial Floating Wind - The WindFloat Role", 2019). The study suggests that

wind turbines placed in areas with low waves and high winds, like waters near Scotland or in the Mediterranean sea, offer the best conditions for wind turbines to produce energy most efficiently, thus creating the best return on investment ("Commercial Floating Wind - The WindFloat Role", 2019).

The Hywind Scotland project, which was the first commercial grade floating wind farm, cost a total of $253 million for 5 wind turbines that are equivalent to 30 MW. This is very expensive since traditional turbines usually cost around $5 million per MW, or $100 million less than Hywind Scotland. However, there is a new floating project in Norway called Hywind Tampen which plans to reduce costs by 40%. They will do this by tweaking installation practices and materials of the base. Instead of offshore assembly, the new project will have a design that can be done onshore with less complex crane assemblies. Additionally, more concrete will be used to reduce the costs of steel that Hywind Scotland used. With the new designs that are being implemented here, floating wind turbines will have a reduced levelized cost of energy (LCOE) as shown in Figure 7. LCOE is a measure of lifetime costs divided by energy production. By decreasing this metric, floating wind will be more competitive and accessible ("Equinor Cuts Floating Wind Costs by 40% in Design Revamp", 2019).

Figure 9

Chart illustrating the planned decrease in levelized cost of energy for floating wind with the implementation of less costly design and installation.



Note. Image obtained from Equinor Cuts Floating Wind Costs by 40% in Design Revamp. (2019, December 4). Retrieved May 11, 2021, from https://www.reutersevents.com/renewables/wind-energy-update/equinor-cuts-floating-wind-costs-40-design-revamp

One of the greatest costs associated with floating wind turbines is the substructure, as it differs from traditional wind turbines the most when compared to other aspects of the structure (Ghigo et al., 2020). It is the least researched and most technical portion of the wind turbine.

Using Hywind's upcoming Tampen project as an example, the following calculations determine the amount of time it currently takes to begin to receive revenue for a floating wind

turbine project. The estimated cost of the project is currently $569 million and will have a capacity of 88 MW (Beckman, 2020).

The average cost of electricity in the United States in April of 2021 is $0.13/kWh ("Electric Rates by State", 2021). Additionally, the Hywind Tampen project is estimated to produce 384 GWh of electricity annually (Petrova, 2019). Assuming the rate charged for electricity is relatively steady throughout the seasons and years, the Hywind Tampen wind farm would produce revenue as calculated below:

$$\text{Revenue} = (\$0.13/\text{kWh})\ (384\ \text{GWh/year})(1\text{x}10^6\ \text{kWh/GWh})$$

$$\text{Revenue} = \$49{,}920{,}000/\text{year}$$

The cost of operation and maintenance is difficult to estimate, since currently existing floating wind turbines have only been in operation for a very short time. However, traditional wind turbines can be estimated to cost approximately 1-2 cents per kilowatt-hour produced (Blewett, 2020). Assuming floating infrastructure has comparable operating costs, the annual cost of maintaining these structures would be as follows:

$$\text{Maintenance costs} = (\$0.015/\text{kWh})(384\ \text{GWh/year})(1\text{x}10^6\ \text{kWh/GWh})$$

$$\text{Maintenance costs} = \$5{,}760{,}000/\text{year}$$

Using the above information, the number of years (n) it would take for a wind turbine's revenue to offset its construction costs is calculated below:

$$\$569{,}000{,}000 = (\$49{,}920{,}000/\text{year} - \$5{,}760{,}000/\text{year})\ n$$

$$n = 12.88 \approx 13\ \text{years}$$

This is competitive with the number of years it takes to see revenue from traditional wind turbines. Traditional wind turbines can take 10-15 years to be completely paid off, so floating wind turbines offer a competitive alternative (Eyerly, 2021). Additionally, as mentioned above,

the cost of producing floating wind turbines is expected to continue dropping and the size of floating wind turbines able to be constructed is expected to continue increasing. Due to this, it will take less time to pay for these turbines that are both cheaper to produce and can generate more electricity and, therefore, more revenue. These floating wind turbines not only are competitive with traditional wind turbines now, but they will become the cheaper alternative with more research and development, specifically of their substructure.

The findings presented previously will help aid the development of floating substructures for wind turbines and continue to lower the cost of building these systems. Utilizing a weighted chain on the Principle Power base helps add stability for a much cheaper cost than complex computerized systems. The holes on the Naturally Pressurized base help add stability and save costs on materials since much of the base is hollow to allow water to flow through. These design techniques can be incorporated into wind turbine bases to add additional cost-saving measures in the future.

Conclusion

After completing our design and testing, the group learned that the Principle Power base with chains was the most stable and robust base. This base performed optimally, however, extra floatation was necessary in the form of styrofoam since the buoyancy of the base was limited by support material remaining from 3-D printing. Moving forward, efforts to improve the device would include increasing air volume in the base for higher buoyancy and testing more aspects of a floating wind turbine. This future testing includes adding stability sensors, using a larger basin, and using a wind tunnel. Testing with stability sensors could be implemented by adding holes that expand and contract on the NPB to reduce and increase water flow through the base accordingly or that can use propellers to add stability to individual legs on the Principle Power

base that need additional support recovering from a disturbance. Putting the base in a wind tunnel with a proper turbine attached to the tower would be important because it will test the performance of the base in windy conditions. Using a larger basin would eliminate reflecting waves from interfering with the base and therefore supply future researchers with less skewed results. With this future research, the performance of the base would improve greatly and could lead to a more approachable design that can be used in the coming years.

Appendix A

Summary of Project Costs

Table A1

Summary of all costs incurred during testing of wind turbines.

BOM for Turbine Base Testing		
Title	Cost	Bought From
10 ft plastic chain	$10.90	Home Depot
Principle Power Base	$128.56	UVa Rapid Prototyping Lab
6 ft Metal Chain	$9.99	Amazon
Naturally Pressurized Base	$167	UVa Rapid Prototyping Lab
Total Cost:	$316.45	

Appendix B

Detailed Drawings

Figure B1

SolidWorks drawing of base inspired by Principle Power's design

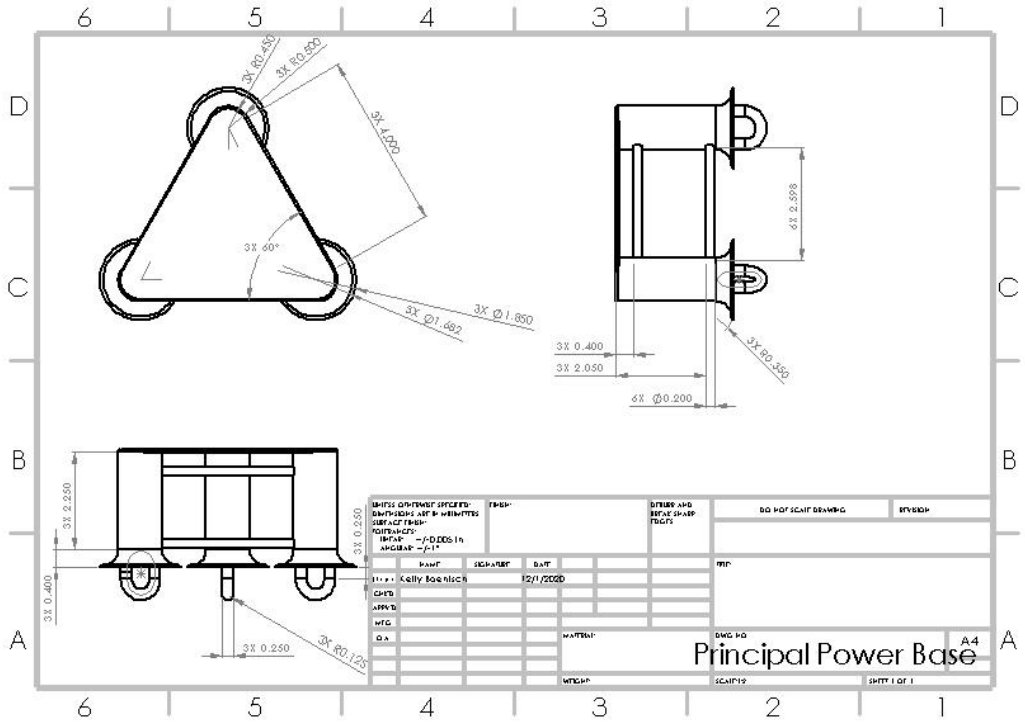


Figure B2

SolidWorks drawing of Principle Power Base with weighted chains

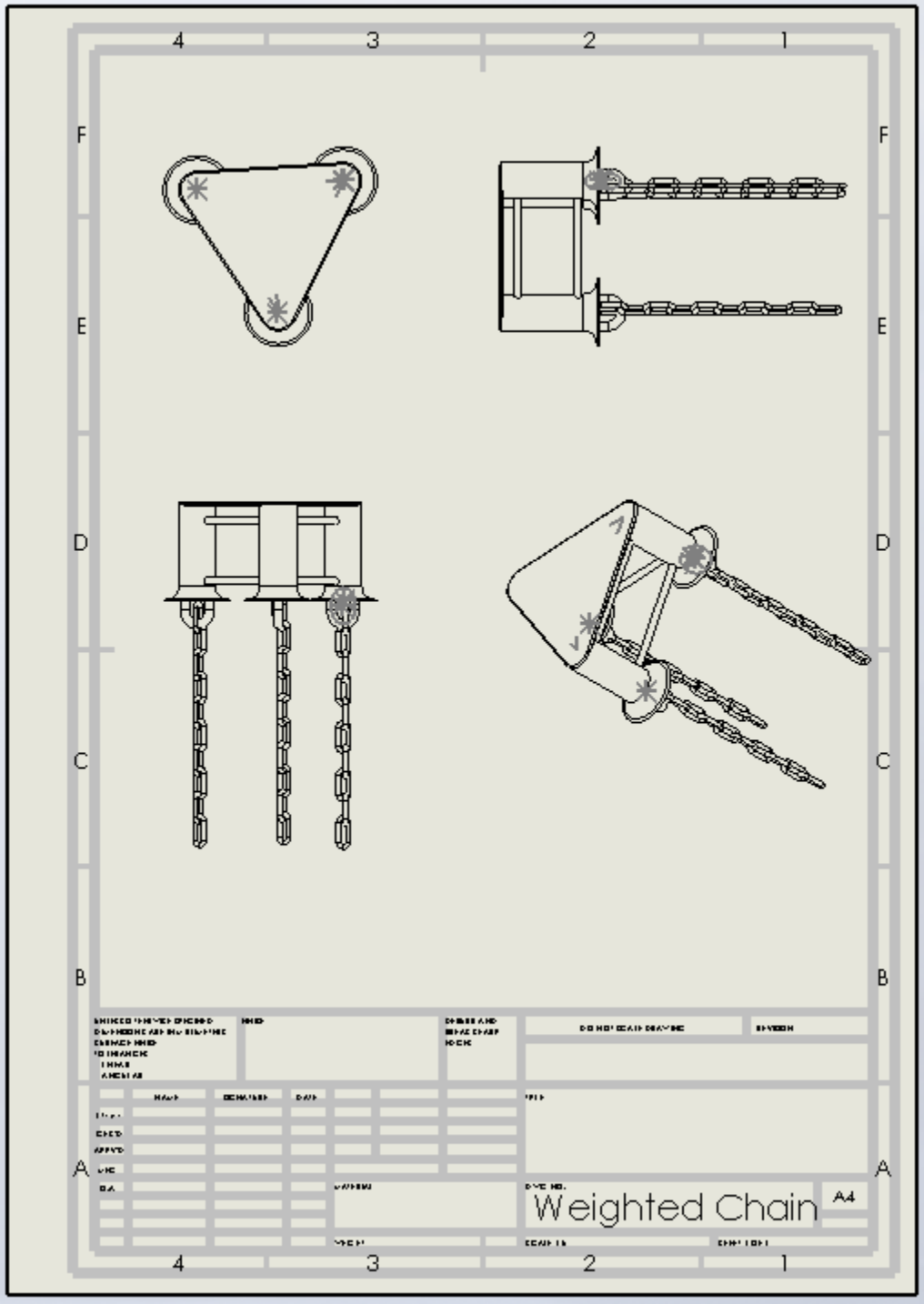


Figure B3

SolidWorks drawing of naturally pressurized base design with dimensions (view 1)

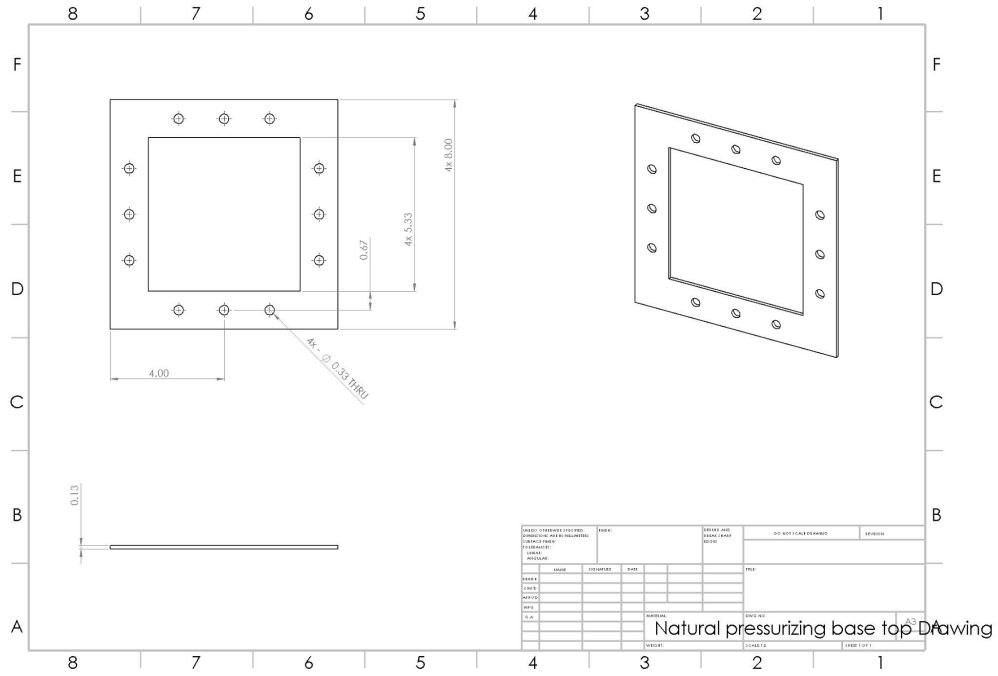


Figure B4

SolidWorks drawing of naturally pressurized base design with dimensions (view 2)

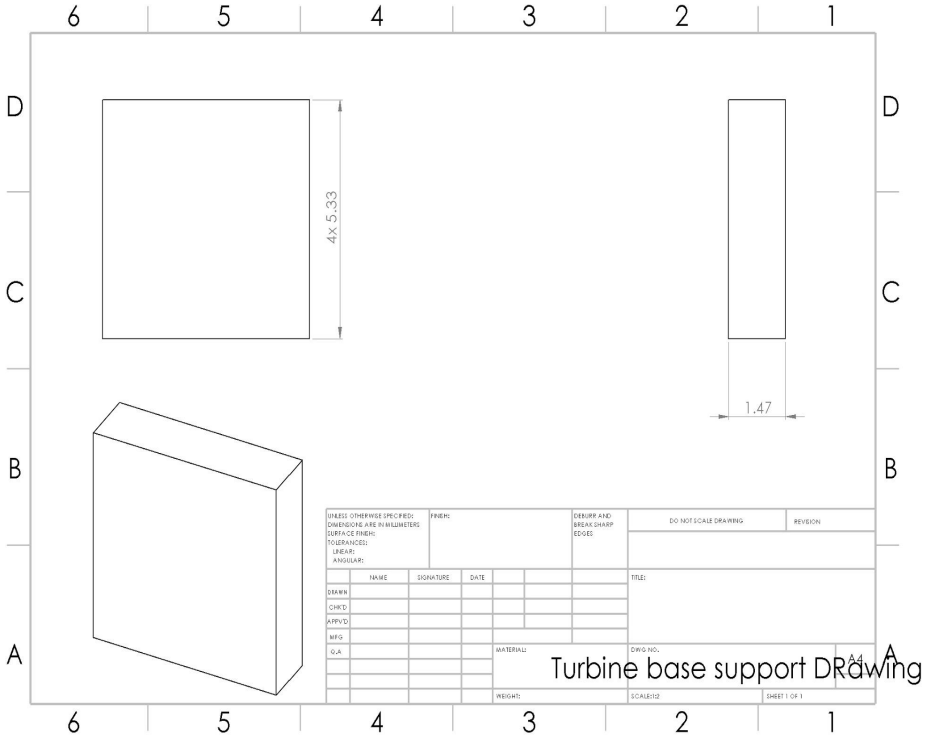


Figure B5

SolidWorks drawing of Naturally Pressurized Base with a weighted ballast and mockup of turbine blades for reference of sizing

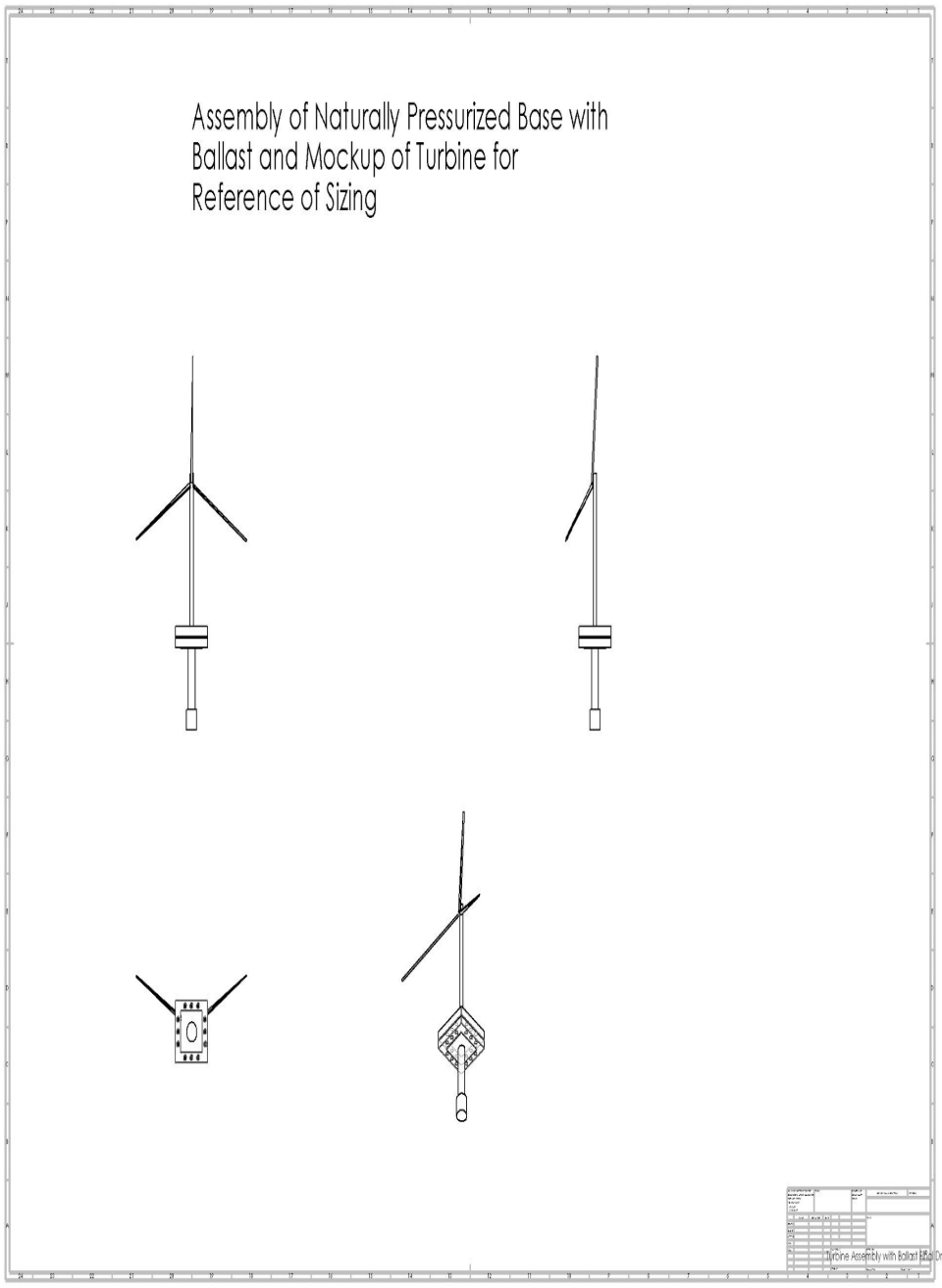
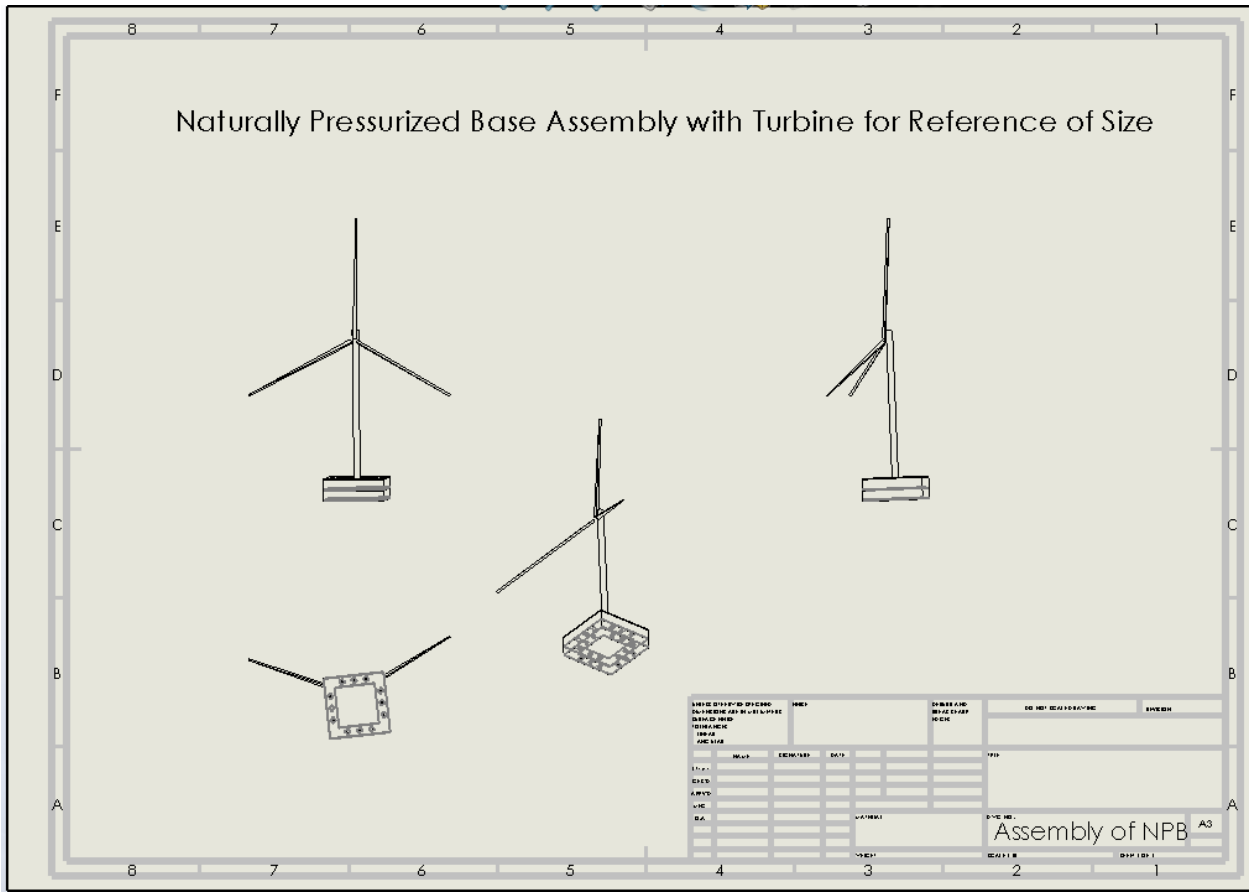


Figure B6

SolidWorks drawing of Naturally Pressurized Base with a mockup of turbine blades for reference of sizing



Appendix C

Detailed Calculations

Naturally Pressurized Base with Ballast Buoyancy

For base made of abs plastic and air floating in salt water:

$\rho_{water} = 0.03684984$ lb/in^3

$\rho_{air} = .00004425593$ lb/in^3

$\rho_{abs} = 0.0386562$ lb/in^3

The base has an outer shell of abs plastic and has an air cavity in the center.

Tolerances:

On Stratasys 3D Printer, parts are produced within an accuracy of +/- .200 mm (.008 in)

Real-life size:

- 350 feet tall
- 135 foot wide base
- 14 foot diameter tower
- 275 foot blade radius

Scale = **1:202.5**

Model size with scale:

- Base = 8 inches wide
- Tower = 20.7 inches tall
- Tower diameter = .83 inches
- Blade radius = 16.3 inch

Volumes of model parts:

- Base top: 4.6 in^3 (3)
- Base bottom: 28.05 in^3 (2)
- Base support: 41.72 in^3 (1)
- Tower: 11.36 in^3 (1)
- Blades: 1.27 in^3 (3)
- Ballast: 29.93 in^3 (1)

Finding average density:

$V_{abs} = 156.72 \text{ in}^3$

$V_{air} = 11.5 \text{ in}^3$

$$\rho_{avg} = \frac{(V_{abs})(\rho_{abs}) + (V_{air})(\rho_{air})}{(V_{abs} + V_{air})} = \frac{(156.72)(.0386562) + (11.5)(.00004425593)}{(156.72 + 11.5)} = .036 \text{ lb/in}^3$$

Finding Height of Waterline and Center of Buoyancy:

Height of Waterline $= \frac{(.036)}{.03684984}$*(3 in) = .97 * 3 = 2.93 in

Height of Waterline = 1.269 in from bottom of base

Center of buoyancy = height of waterline / 2 = 2.93/2 = 1.466 in

Center of Buoyancy = 1.466 in from bottom of base

Naturally Pressurized Base Dynamic Analysis:

Torricelli's Principle:

$V = \sqrt{2gh}$

r = 1/6 in

Finding volumetric flow rate to determine how quickly water enters and exits the base:

$Q = AV = \pi r^2\sqrt{2gh} = \pi(.167in)^2\sqrt{(2)(386.4\ in/s^2)(3in)}$

$Q = 4.2\ in^3/s$

Weighted Chain Base Buoyancy:

For base and chain made of ABS plastic with air pockets floating in saltwater:

$\rho_{water} = 0.03684984\ lb/in^3$

$\rho_{air} = .00004425593$ lb/in^3

$\rho_{abs} = 0.0386562$ lb/in^3

The base has an outer shell of ABS plastic and has air cavities within the three cylindrical corners of the base.

Tolerances:

Stratasys 3D Printer Parts produces pieces with an accuracy of +/- 0.200 mm (0.008in)

Real-Life Size:

- Chain link width = 11.5 ft
- Chain link length = 21 ft
- Full chain length = 154 ft
- Base (max side length) = 135 ft
- Height of base = 62 ft
- Height of base + chain = 216 ft

Scale = 1:277

Model size with scale:

- Chain link width = 0.5 in
- Chain link length = 0.9 in

- Full chain length = 6.65 in
- Base (max side length) = 5.850 in
- Height of base = 2.70 in
- Height of base + chain = 9.35 in

Volumes of model parts:

- $V_{base} = 5.21\ in^3$
- $V_{3\ cylinders} = 3.77\ in^3$
- $V_{chain} = 0.66\ in^3$

Finding average density:

$\rho_{ABS} = 0.0386562\ lb/in^3$

$\rho_{air} = 0.00004425593\ lb/in^3$

$\rho_{water} = 63.9\ lb/ft^3 = 0.03697917\ lb/in^3$

$$\rho_{avg} = \frac{(V_{base})(\rho_{abs}) + (V_{cylinder})(\rho_{air}) + (V_{chain})(\rho_{ABS})}{(V_{base} + V_{cylinder} + V_{chain})} = \frac{(5.21\ in3)(0.0386562\ lb/in3) + (3.77\ in3)(0.00004425593\ lb/in3) + (0.66\ in3)(0.}{(5.21\ in3 + 3.77\ in3 + 0.66\ in3)}$$

$$= 0.025\ lb/in3$$

Finding Height of Waterline and Center of Buoyancy

Height of Waterline = $\frac{\rho_{avg}}{\rho_{water}}$(height of base) = $\frac{0.025\ lb/in3}{0.03697917\ lb/in3}$* 9.35 in = 6.32 in

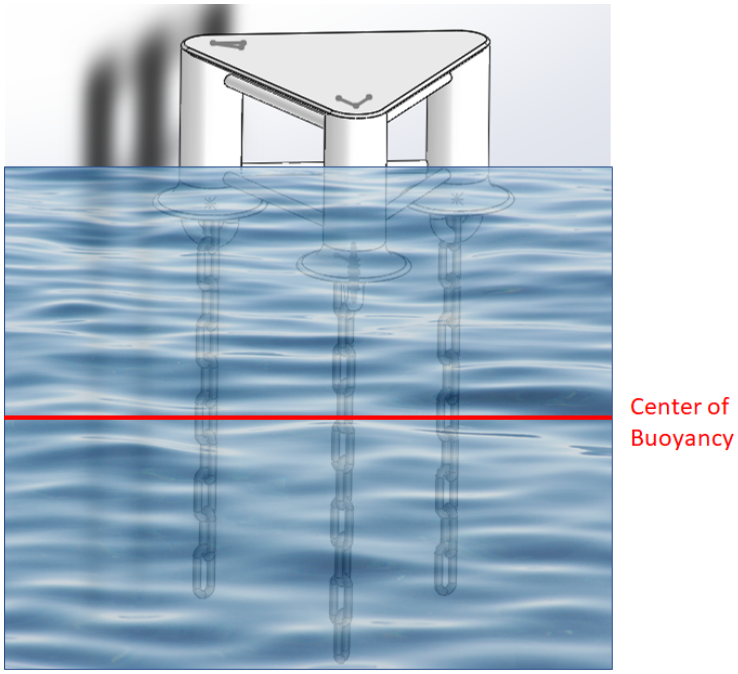
Height of Waterline = 6.32 in from bottom of base

Center of Buoyancy = height of waterline /2 = 6.32 in = 3.16 in

Center of Buoyancy = 3.16 in from bottom of base

Figure C1

Diagram depicting the center of buoyancy and estimated water height on the Principle Power base with weighted chain



Appendix D

In-Depth Results

Table D1

Key for Analysis

Abbreviation	Meaning
NPBE	Naturally pressurized base (holes exposed)
NPBC	Naturally pressurized base (holes covered)
WNPB	Weights on base (Naturally pressurized)
HWH	Heavy weight hanging in center (naturally pressurized)
WOEC	Weight on each corner (naturally pressurized)
WIOT	Weight inside of tube (naturally pressurized)
PP	Principle power
PPC	Principle power with chains
PPS	Principle power with styrofoam
PPSC	Principle power with chains and styrofoam

Table D2

Principle Power Period of Oscillation and Damping Time

Name of Run	POO (s +/- .1)	Damping Time (s) +/- .1	Notes
PP1	1.6	3.7	
PP2	1.7	4.9	
PP3	1.6	2.6	
PP4	1.4	4.2	
PP5	1.5	5.4	
PP6	1.4	3.7	Perhaps hadn't finished oscillating when the video ended
HWH1			Appeared to exhibit double harmonic behavior because of the swinging of the pendulum internally, inconsistent results on the period of oscillation and does not dampen in the video

HWH2			Appeared to exhibit double harmonic behavior because of the swinging of the pendulum internally, inconsistent results on the period of oscillation and does not dampen in the video
PPS1	2.7	6.8	seemed like very mellow and slow oscillation. Does dampen out over time
PPS2	2.7	6.9	
PPS3	2.6	4.6	
PPS4	2.6	6.4	
PPSC1		1.1	dampened out so quickly it did not really oscillate
PPSC2	2.3	3.5	
PPSC3		0.8	didn't really oscillate
PPSC4	0.8	1.5	
PPC1	0.6	0.8	
PPC2	0.8	1	
PPC3		3	jostled around so no regular period
PPC4	1.4	3.8	

Table D3

Naturally Pressurized Base Period of Oscillation and Damping Time

Name of Run	**POO (s +/- .1)**	**Damped Out After (s) +/- .1**	**Notes**
NPBC1	0.8	5.2	
NPBC2	0.8		Didn't seem to dampen
NPBC3	0.9	6.4	
NPBC4	0.8	5.6	Dampening seemed to stall towards the end
NPBC5	1	5	
NPBC6	0.9	5.6	
NPBE1	0.8	3.5	
NPBE2	0.8		Didn't seem to dampen; maybe video was too short
NPBE3	0.8	3.5	

NPBE4	0.8	3.3	
NPBE5	0.8		Didn't seem to dampen
WIOT1	1.8	8.5	
WIOT2	1.3	6	
WIOT3	1.8	8.4	
WIOT4	2	8.2	
WNPB1	1.1		Didn't seem to damp
WNPB2			Data was too erratic
WNPB3	1.2	5.1	
WNPB4	0.8	3.2	
WNPB5	1	4.4	
WOEC1	1	6	
WOEC2	0.8	6.5	
WOEC3	0.9		Didn't seem to dampen; maybe video was too short
WOEC4	0.8	5	

Appendix E

Names of Who Contributed to Each Part

Naturally Pressurized Base: Ahmed Abdelnabi, Kyle Dana, Cydnie Golson

Principle Power: Kelly Boenisch, Emily Fedroff

Appendix F

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