University of California, Berkeley

Mechanical Engineering — Product Design

Final Capstone Report – Master of Engineering

Oscillating Wind Power: Sail Design, Optimization, and Testing

Chapter I, Sections 1 to 4 and 6; Chapter II - Team written

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Executive Summary

The 2016-17 Oscillating Wind Power capstone project was focused primarily on exploring the scale-up potential of the oscillating wing concept, which was developed as a joint effort between last year's capstone team and industry sponsors. The oscillating concept represents an effort to introduce an aesthetically pleasing, wildlife safe, quiet, and height limited wind energy device for use in wind energy dense coastal regions that face stringent anti-wind turbine regulations due to perceived losses in property value. This paper outlines the problem, explores existing solutions, and specifically focuses on methods of improving the sail design to optimize power generation potential. Though it has been determined that a uniquely uninhabited design space exists for a device that meets the aforementioned design constraints, it is concluded that the oscillating wing concept is inherently too inefficient to be economically and sustainably viable, especially as compared to traditional wind turbine design.

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Chapter I: Technical Contributions

1 Project Definition

1.1 The Problem and Opportunity

The Oscillating Wind Power (OWP) team aims to develop a novel, aesthetically pleasing wind power device for use in windy areas where traditional wind turbines are unsuitable due to their visual disruption, large size, noise pollution, and the potential harm to wildlife. Coastal regions are some of the country's most wind energy dense locations, and are thus prime locations for siting wind energy, but the aforementioned drawbacks of traditional horizontal axis wind turbines have contributed to negative public perceptions of turbine-based wind power, and, in some cases, have led to regulations restricting turbine height in coastal regions. Considering that even 'small' (~1kW rated) horizontal axis wind turbines (HAWTs) have tower heights well above 100 feet, siting them in coastal regions like Marin County, is very difficult (American Wind Energy Association [AWEA], 2009). Therefore, in order to take advantage of the available wind energy in these locations, the OWP device must target the shortcomings and regulatory hurdles of existing wind turbines. This chapter explores the feasibility of scaling such a device within the identified design constraints (see section 1.2 for more detail), and focuses on how the 2016-17 OWP team prototyped mechanical designs to improve the power generation potential of the oscillatory concept, control the motion of the device, and maximize its efficiency. The team has iterated on a few different possible configurations of the device, and in doing so, has identified four primary subsections of the device to optimize: the sail, sail flipping mechanism, body structure, and output power conversion. Due to the high level of collaboration across all aspects of the device's design, fabrication, and testing, the first four sections (Project Definition, Knowledge Domain, Approach, Design) as well as the sixth section (Conclusion) are co-authored by all four team members. In Section 5, each team member focuses on one of the four subsections of the device to describe in detail.

1.2 Design Constraints

Both this year and last year's OWP teams determined that for the device to become a viable competitor to turbine based wind power, it needs to adhere to the following design constraints: to be bird and human safe, operate silently, be aesthetically pleasing, and be small enough to operate under regional height restrictions. The underlying reasons for these design constraints are described in greater depth in the Public Perceptions and Ethical Challenges section of Chapter 2. Through discussions with Tom Flynn, our project sponsor, and Dave Warner, founder of the Marin Agricultural Wind Co-Op, additional design constraints were uncovered, including a desired payback period of seven years, a total height restriction of 40 feet, and no moving parts lower than 10 feet above the ground (Warner, 2016; Flynn, 2017). The desired payback period of seven years constrains the cost of the device, and requires that it produces as much usable power as possible per dollar spent. For example, if the device is capable of producing 100 W during 12 daylight hours (when wind is assumed to be most consistent), it would be capable of producing 438 kWh/yr. According to the US Energy Information Administration (EIA), the cost per kWh of electricity in California was 14.88 cents in December 2016 ("U.S. Energy Information Administration - Independent Statistics and Analysis," n.d.).

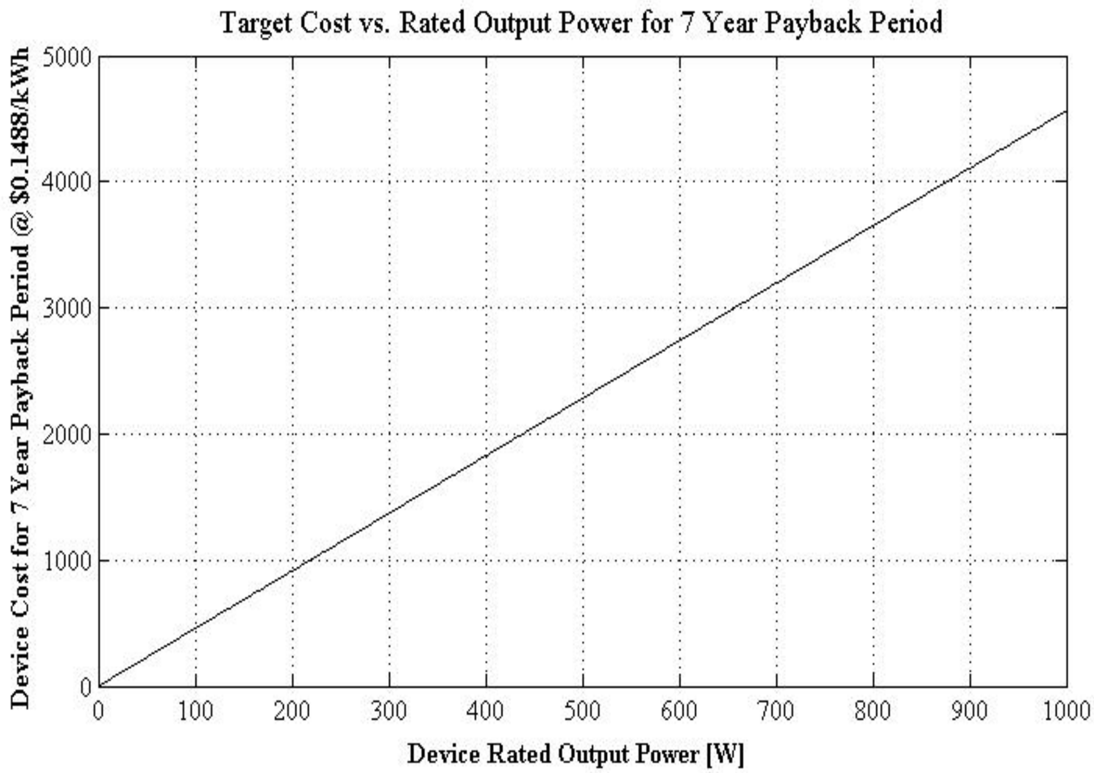

Figure 1: Effect of Output Power on Cost of Device for a 7 year payback period

If the device is to pay for itself over the course of seven years at this $0.1488/kWh rate, it would then need to cost less than $456 to the end user. Figure 1 above shows a comparison of the output potential of the device (in Watts) versus the purchasing cost required to achieve a seven year payback period, with the same 12 active hours/day and 0.1488 $/kWh assumptions. In many ways, the plot above represents the highest level design constraint for our device, insofar as it must be both efficient in its extraction of energy from the wind and cost effective in order to pay for itself within a reasonable window to be a viable alternative to turbine based wind power.

2 Knowledge Domain

2.1 2015-2016 OWP Team Findings

This year's OWP team is building on the work done by the Fung Institute's 2015-2016 OWP team. Last year's team built an initial prototype shown in Figure 1.2 to verify CFD simulations of optimal sail profiles (Clark, 2016). The prototype consisted of a single sail, which rotated about a horizontal shaft. A counter weight at the bottom was employed to facilitate the oscillation of the sail. This small prototype produced 0.0024mW peak power when a small DC motor was mounted to the horizontal shaft (Clark, 2016).

Figure 2: Last year's team's initial prototype (left) (Clark, 2016) and 2.5x scaled final prototype (right) (Mardini, 2016)

Last year's team also fabricated a 2.5X scaled version of their first prototype, which is also shown in Figure 2. They incorporated the key learnings from the first prototype and performed field testing. Using the best performing sail, the device produced peak power of 1.44mW (Mardini, 2016). This number is an increase of 600X over their first prototype (Clark, 2016). The work done by the previous team relied on the lessons learned from their prototypes but also on the work done by others, namely Wallace Kempkey, the founder of Pterofin Inc.

2.2 Collaboration with Pterofin Inc.

Through their research, last year's team discovered that Pterofin Inc., a company founded by Wallace Kempkey, had developed various clean energy devices that capture energy by mimicking the motion of a bird's wing. Kempkey had developed two wind power devices, the Terrafin and Dragonfly, as shown in Figure 3 (Kempkey, 2017). The 2015-2016 OWP team collaborated with Kempkey and used his designs for inspiration. They looked at Pterofin's Terrafin design, a single-winged wind power device, and incorporated its single sail and counter weight features into their design (Clark, 2016).

Figure 3: Pterofin's Terrafin (left) and Dragonfly (right) (Kempkey 2017)

This year's OWP team continued the partnership with Kempkey, and drew inspiration from his Dragonfly design, a double-winged wind power device, as well as his Terrafin design. Although Pterofin's designs successfully oscillate, Kempkey has not measured electrical power and therefore the designs have not been optimized for maximizing electrical output power.

3 Approach

Based on the 2015-16 OWP team's work, the academic advisors Professor Alice Agogino and Jeremy Faludi, as well as the industry advisor Tom Flynn, set the project deliverable to build a medium to large scale prototype and increase the device's power output. A first iteration of the prototype was expected at the end of the first semester. The team and the advisors agreed on a hands-on design approach with a focus on quick prototyping and testing iterations as opposed to a theoretical design approach for two reasons. First, the project's industry advisor Tom Flynn expressed the desire for a tangible prototype for marketing reasons (Flynn 2016). The prototype is meant to communicate the functionality and design to potential customers in Marin County and make them excited about the product. Second, due to the high complexity of the device's motion and nonlinear dynamic behavior—demonstrated by Simon Farthing in his dynamic analysis of the Oscillating Wing Concept—a thorough theoretical analysis requires advanced simulations with a combination of Computer Aided Engineering (CAE) applications, such as Computational Fluid Dynamics (CFD), Multibody Dynamics (MBD) and other simulation software (Farthing, 2014). Considering the fact that the team's main experience and expertise lays in designing, fabricating, and testing, a computational approach would require additional time to build an expertise in modeling and simulating. Considering the limited duration of the project, it was determined that building and testing prototypes was the most efficient way to understand and improve the device's functionality.

Figure 4, below, shows the project's milestones and main tasks. The development process begins with designing and building a modular small scale prototype. It is modularly designed in order to allow variations within the four subsystems described in the first section of this paper: the sail, sail flipping mechanism, body structure, and output power conversion. The first stage is used to determine key components and parameters that influence the system's performance. The results are also used to inform specifications for the next iteration stage. The second iteration is based on the first stage's results and represents an improved and more refined design. The final deliverable is to build the prototype, measure its performance, and identify which factors within the design have the most significant impact on the device's performance.

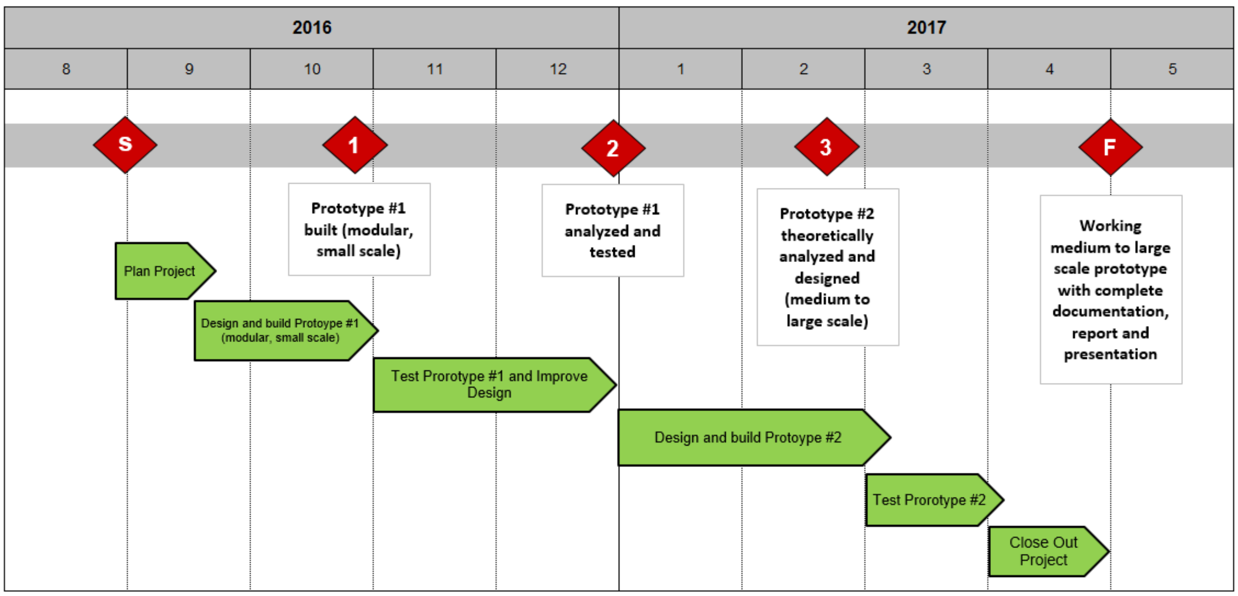

Figure 4: Milestone Plan and main tasks for OWP team 2016-2017

The most important factors influencing the prototype's size are cost, scaling accuracy, and portability. While a full-size prototype (about 40 ft tall) would provide the most accurate results, a small scale version offers significant advantages. First, it is more feasible and faster to build the prototype with the given resources (tools, workshop). Second, transportation and testing is significantly easier. Due to the fact that there is no wind tunnel available, testing has to be done outdoors at temporary locations. Third, the cost of building the prototype is drastically lower at a smaller scale. However, results from a small scale prototype have to be scaled and are therefore not as accurate. Considering the design approach based on quick prototyping and testing iterations, small to medium sized prototypes provide the best trade-off and were therefore chosen by the team.

4 Design

4.1 Components of the design

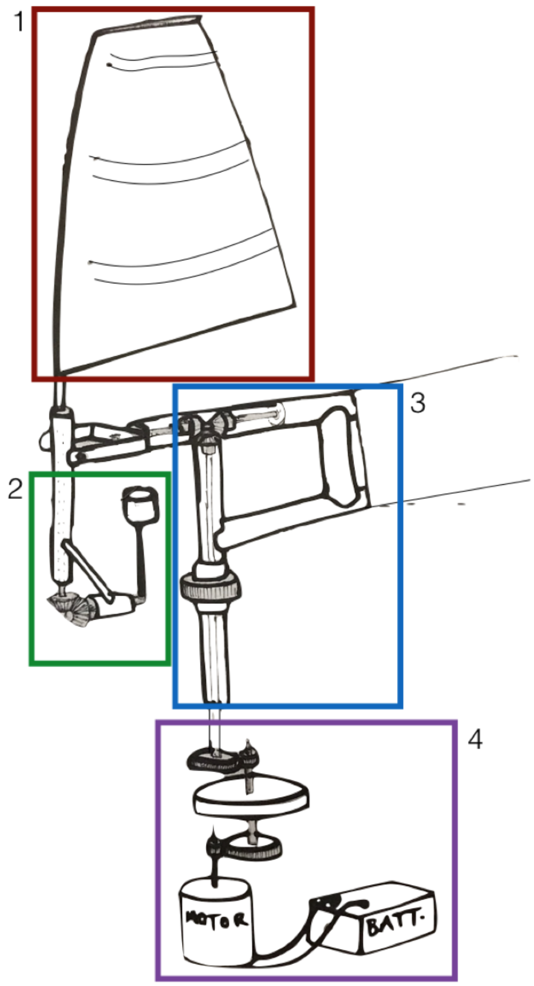

Figure 5: Four major components of the OWP [Sketch by Saba Fazeli]

The four major components of the device, as shown in Figure 5 above, are: (1) the sail, (2) the sail flipping mechanism, (3) the body structure, and (4) the output power conversion. The sail is the airfoil of the device instead of a blade as on a traditional wind turbine. The sail flipping mechanism switches the orientation of the sail with respect to the wind. The structure stabilizes the device, houses the gearing and shafts that convert the bidirectional oscillatory motion of the sail into one directional motion of an output shaft. The output power conversion converts the mechanical power to electrical power and includes step up gearing and the generator. Figure 6, below, shows the final prototype of this year's team. Each team member discusses one of the four components in detail in Section 5. This paper focuses on the sail design, Laura Sverchek's paper discusses the sail flipping mechanism, Roberto Ortiz-Soto writes about the body structure and Patrick Hartmann's individual section is about the power conversion system (Sverchek, 2017; Ortiz-Soto, 2017; Hartmann, 2017).

Figure 6: OWP 2016-17 final prototype during field testing in Marin County

4.2 Oscillating Motion of the Device

Rather than rotating continuously in one direction like a traditional wind turbine, the OWP device oscillates back and forth. By oscillating back and forth, the device's peak rotational speed is kept low, allowing the device to remain quiet, and be safe for birds. Additionally, the oscillating motion is aesthetically pleasing and makes the device look more like a piece of kinetic sculpture than a wind turbine.

The oscillating motion is created as follows: the sail is angled into the wind; the wind imparts force on the sail and rotates the sail partially around the horizontal axis; once the sail reaches a high enough angle, the direction of the sail is flipped so the other side of the sail is angled into the wind; the wind now forces this side of the sail to rotate back around the shaft in the other direction until the opposite flipping point is reached; the sail flips again so that the original side is angled into the wind again, and the cycle repeats. The mechanism utilized to create such an oscillating motion is based on Pterofin's Dragonfly inverted pendulum sail flipping mechanism design, which is described in more detail in section 5 of Laura Sverchek's paper (Sverchek, 2017).

4.3 Theoretical Limit of Available Power Output

The available power output of a wind turbine is governed by the following equation:

$P = \frac{1}{2}\rho v^2 A C_p$ Equation (1) (Abdulqader, Jadallah, and Mahmood, 2014);

Where:

ρ = density of the wind, kg/m^3

v = freestream wind velocity, m/s

A = swept area of the turbine, m^2

C_p = efficiency of the turbine

Although this equation is for traditional wind turbines, the equation was applied to the OWP device to approximate the theoretical limit of the potential power output. This allowed the team to determine the magnitude of power expected from the small scale and full-scale designs.

According to the work from last year's team, the wind speeds most frequently occurring in Marin County range between 2 and 7 m/s [~4.5 to 15.7 mph] (Koh, 2016: 19). Therefore, the power output was calculated for wind speeds across this range and then averaged. Since the operating angle range (the range that the sail rotates around the horizontal shaft) is about 180°, the swept area was calculated as half of a circle, 0.5πr2. The maximum value of the turbine efficiency, C_p is 16/27 (Abdulqader, Jadallah, and Mahmood, 2014). This is known as Betz Law and means that no turbine can capture more than 59.25% percent of the kinetic energy in the wind (Abdulqader, Jadallah, and Mahmood, 2014). Using these values it was determined the maximum potential power output averaged over the range of wind speeds is 115 W for the small prototype and 1144 W for a full-scale design (see Equation 1). The full-scale design is assumed to have a 4 m [13.1 ft] tall sail.

5. Sail Design, Optimization, and Testing

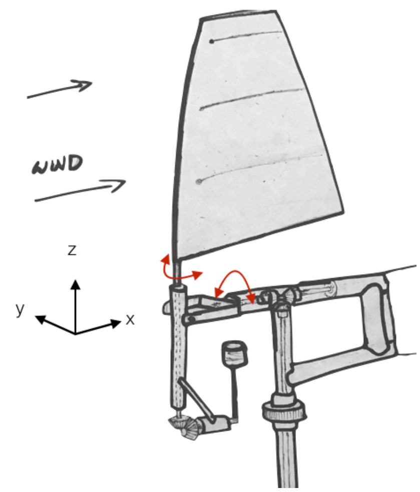

Figure 7: Coordinate axes and degrees of freedom

5.1 Introduction

The purpose of this section is to discuss the theoretical and experimental methods of sail design optimization explored by the 2016-17 OWP team. By taking inspiration from traditional sail and airfoil design theory, the team was able to prototype an improved version of the sail design featuring a thin, lightweight fabric material that allows the sail to form a lift-optimized cambered airfoil shape that can effortlessly change shape for each respective direction of oscillation in the wind. To maximize the capture of wind energy, the sail must create as much torque about its horizontal axis of rotation (x axis, as shown in Figure 7 above) as possible, and the sail flipping mechanism must aid the sail in following a smooth path of motion by holding the sail in an optimal orientation to the wind in each direction of oscillation, delivering consistent power to the rest of the device. These two aspects of the OWP device combine to constitute the device's method of capturing wind energy, and thus, are integral to the success of the device as a whole. This paper aims to explain the critical functions of sailboat and windsurfing sails, as well

Figure 8: 0.5m^2 and 1m^2 Prototype Sails

as the methods used to experimentally characterize the two fabric sails constructed by the team.

There are four pertinent aspects of sail design and selection: the 2D sail profile and total area, 3D camber (airfoil shape), and, most critically to the oscillating concept, an ability to easily 'switch' camber geometry to optimize the foil shape when sailing across the wind in two different directions (or, in sailing terms, two 'tacks') as the device oscillates (Larsson, Eliasson, & Orych, 2014). In the fall semester, the team constructed a 0.5m^2 sail made of three kites (rip-stop nylon) sewn together into a semi-rectangular shape, held rigid in two dimensions by a vertical wooden mast sewn into the leading edge, a horizontal thin walled aluminum tube 'boom' sewn into the bottom of the sail, and a fiberglass 'batten' support extending from the mast to the top outermost corner of the sail. The larger 1.0m^2 sail produced in the second semester was built very similarly, except for the addition of another batten, an aluminum tube mast, and use of a sheet of rip-stop nylon. The sails were built with similar aspect ratios and camber depth, to allow direct experimental comparison between the two. The aspect ratio is defined as the ratio between the height of the mast and half of the length of the boom, and because it is generally accepted that sails with larger aspect ratios (>2) have higher coefficients of lift, both sails were designed to target an aspect ratio of 3.0 (Larsson, Eliasson, & Orych, 2014). The soft sail design was pursued to complement the inverted pendulum flipping mechanism developed by Mr. Kempkey in his twin-sailed Dragonfly prototype, pictured in section 2.2 of Chapter 1, and allows the sail to change its shape to perform optimally in both directions of oscillation. The flipping mechanism, which serves to reverse the direction of oscillation by rotating the sail relative to the wind via coupled motion with an inverted pendulum, is described in greater depth in Laura Sverchek's individual contribution section (Sverchek, 2017). After building and testing this working prototype, it was determined that the team needed to assess theoretical output power of the sail in varying wind conditions, with varying angles of attack, both in order to better characterize the existing performance of the device, and to provide a better estimation of how the device's performance will scale within the operating height limits determined in Section 1.2.

5.2 Sail Design Optimization

Last year's OWP team used CFD to analyze a variety of sail profiles, discovering that the 2D geometry which provides the most torque to the oscillating device is a rectangular (or semi-

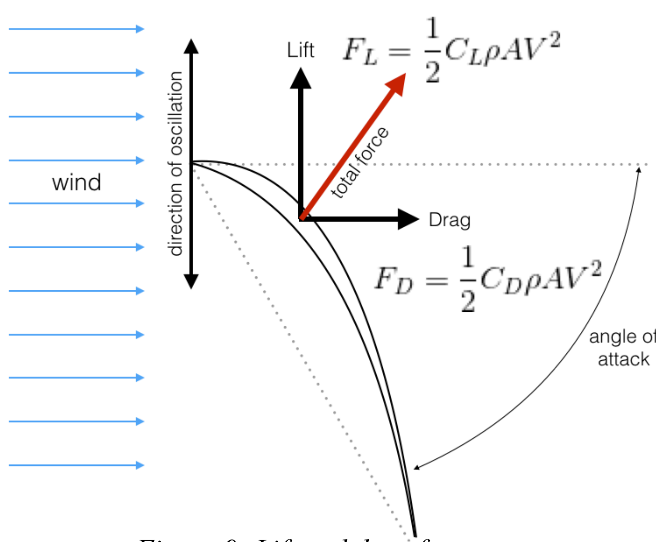

Figure 9: Lift and drag forces on sail

rectangular) shape (Soundararajan, 2016). The CFD model also developed a supposed exponential cubed relationship between increasing the rectangular sail surface area and the resulting torque on the device (Soundararajan, 2016). The resultant torque about the horizontal axis is a function of the sail force times the distance between the horizontal axis and the sail's center of effort. Airfoil theory characterizes the lift and drag forces on a sail as perpendicular to and parallel to the apparent wind direction, respectively. From a fluid mechanics perspective, sails are airplane wings turned vertical, and thus, the same principles governing the lift and drag forces generated by airfoils apply to the shape of the oscillating device's sail. This is the standard, regardless of the sail's angle of attack, with the lift component parallel to the direction of oscillation, and the drag component in the direction of the wind, as shown in Figure 9. The lift and drag forces are dictated by the equations also shown above, demonstrating the linear

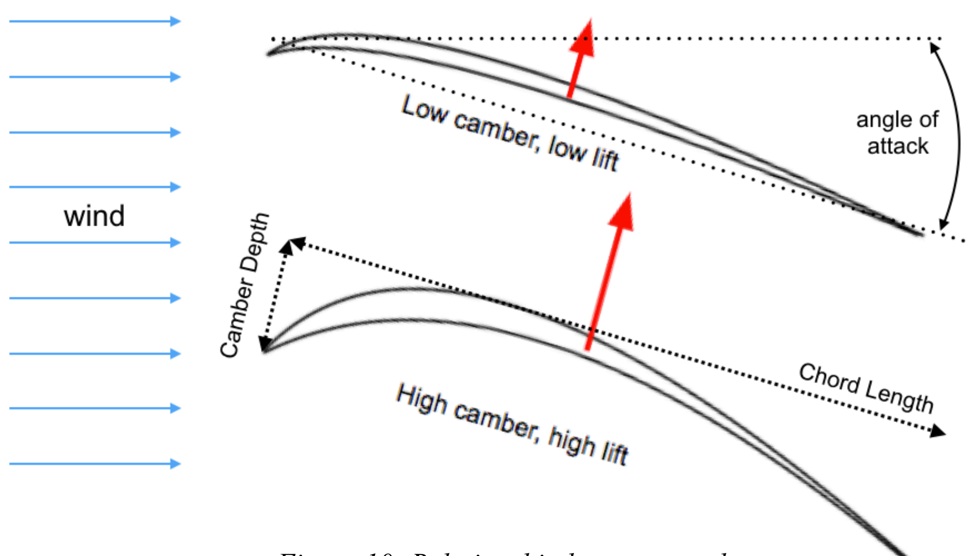

Figure 10: Relationship between camber depth and lift force

dependence of lift force on sail area (not cubic!) (Garrett & Wilkie, 2005).

The CFD simulations performed by last year's team also do not identify a crucial aspect of the sail design that greatly affects performance: 3D shape, or 'camber.' The camber of a sail, be it on a boat or windsurfing rig, is a description of how curved the sail is in cross section and, besides the sail's 2D profile and angle of attack, is the most significant factor in determining coefficients of lift and drag which characterize the sail (Garrett & Wilkie, 2005). In constant wind speeds, and across varying angles of attack, as the camber depth is increased, the pressure differential between the fluid passing over the top versus the bottom of the foil becomes greater, resulting in greater lift (Larsson, Eliasson, & Orych, 2014). Last year's prototype leaf-shaped sail, though aesthetically pleasing and approximately rectangular, lacked camber due to its being constructed from a laser-cut sheet of wood. The rigid, flat shape resulted in very low lift, which disadvantaged the device.

Optimal camber depth is usually described as a fraction of the sail's chord length, varying from ~1/20 of the chord length at minimum to maximum ~1/5 of the chord length, with the maximum camber depth located at approximately a quarter of the chord length from the leading edge in order to optimize the coefficient of lift (Larsson, Eliasson, & Orych, 2014). The lift and drag coefficients are also highly dependent on the sail's angle of attack—the lift coefficient is commonly maximized at ~1.5 between 20-30˚ of attack angle, and typically requires experimental determination, varying depending on the sail profile and camber shape (Garrett & Wilkie, 2005). For the OWP device, the lift force is responsible the sail torque about the oscillatory rotation axis (x-axis), and the sail design should thus be optimized for lift.

A fundamental difference between the design requirements of airplane wings and sails (though both are cambered airfoils) is that airplane wings only need to provide lift in one direction: up. Thus, they can be constructed rigidly, as they only need to hold one shape. Sails, on the other hand, need to provide a cambered shape that provides lift in two directions—from the airplane wing model above, up and down. As shown in Figure 11, a sailboat turns its hull to move across the wind in a new direction (changing 'tack,' to and from either 'port tack,' which

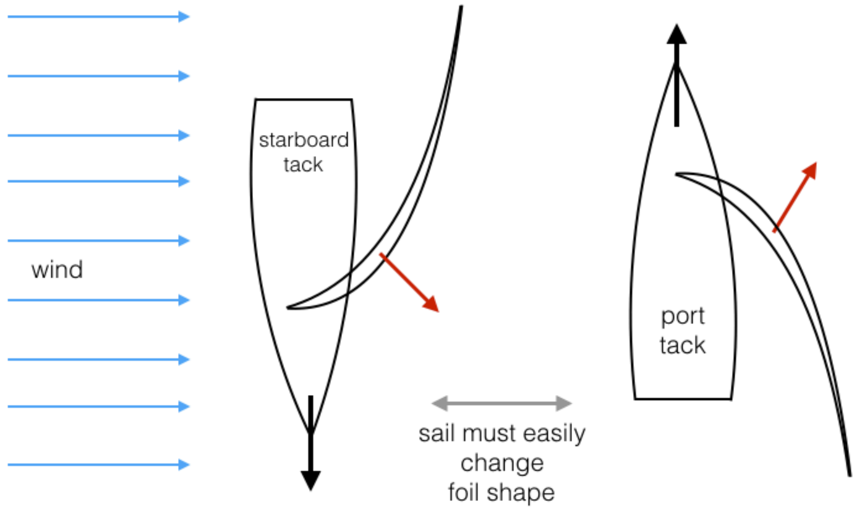

Figure 11: Camber orientation change with boat direction change (same as oscillatory 'flip')

the wind hits the left side of the sail to 'starboard tack,' where the wind hits the right side) the sail needs to switch its camber orientation to provide lift in the new direction of motion. This 'tacking' phenomenon is identical to the flipping of the sail during oscillatory motion, and thus necessitates a sail that can morph, while remaining lightweight. As a result, sails are usually constructed of soft materials to facilitate the switching between two cambered foil shapes (Larsson, Eliasson, & Orych, 2014). The benefits of such construction are clear whenever a sailboat or windsurfer turns around—the sails fill with wind on the new side in once the boat has turned, recreating the cambered foil shape and maintaining forward motion in the new direction. There is also great potential for adjusting the performance of the sail for different wind speeds by changing the camber depth with adjustments of sail tension: the 'tighter' the sail is tensioned along the length of the boom, the less sail material available to luff out into 3D shape (Larsson, Eliasson, & Orych, 2014; Fincham & Friswell, 2015).

5.3 Characterization of Sail Forces

There are a number of different methods of measuring the forces acting upon a sail of a given area, cross sectional shape, and 3-D camber (foil shape) in the literature, almost all of which require either numerical CFD methods, wind tunnel testing, or experimental measurement of pressure differentials across the windward and leeward (facing towards and away from the wind, respectively) surfaces of the sail (Morris, "Derivation of Forces on a Sail Using Pressure and Shape Measurements at Full Scale," 2011). For OWP, determining the actual torque input of the test sails was vital to characterizing the efficiency of the device as a whole, and to specifically get an idea of which parts of the device following the sail contributed most to power losses. Developing an understanding for how the sail torque scales with the device's size was also significant in determining the viability of the oscillating concept at larger scale. To that end, it was in this year's team's interest to identify a reliable method of determining the sail's mechanical power input and scaling effects. It was determined that CFD would not provide accurate results because of the difficulty associated with accurately reproducing the prototype sail's 3-D shape in CAD software. Experimental measurement of the pressure differentials across the sail would have required an array of pressure taps to be installed on both sides of the sail, which would have been difficult to construct and analyze to create an accurate picture of total sail torque for varying wind speeds and angles of attack. As a result of these challenges, the test method that was adapted from the research was direct experimental measurement of aerodynamic forces experienced by the sail, in a similar fashion to the Sail Force Dynamometer developed at MIT by James Stackpole Herman ("A Sail Force Dynamometer: Design, Implementation, and Data Handling, 1989). In his research, Herman created a test rig to directly measure sail forces and moments about the x, y, and z coordinates for varying angles of attack in different wind conditions (z coordinate in the vertical direction of the mast, x coordinate along the length of the boom, and y perpendicular to the plane of the sail area). Herman's experimental method maps well to the OWP device, because, unlike a boat, which can freely move in all directions, the OWP sail's motion is constrained in every direction except for rotation about the x-axis, about which the entire sail and flipping assembly oscillate, and the z-axis (about which the sail flips, and the angle of attack is changed). Because the sail can only rotate around the x-axis, the only sail force acting to create motion in the oscillating device is the lift force, as shown in Figure 9 in section 5.2. The sail's total lift force is concentrated at a center of effort located approximately half way up the height of each sail, and thus creates a torque about the axis of rotation. Thus, the most direct method of determining OWP's sail force (and, subsequently, torque and mechanical power input) was to experimentally determine the torque developed by the sail around the axis of oscillation for varying wind speeds and angles of attack. The sail torque was measured statically by determining the angle at which a known counterweight can be supported in a given wind speed. This method also allowed for direct performance comparisons to be made between the small and large prototype sails, which helped to clarify (and, unfortunately, experimentally disprove) the previous year's CFD results in accordance with the existing theoretical understanding of sail forces.

5.4 Experimental Methods

Because our team was neither able to find a wind tunnel large enough, nor wind

Figure 12: Experimental setup in truck bed

conditions consistent enough to conduct accurate testing, experimental testing was conducted by strapping the device into the bed of a pickup truck and driving at different speeds to simulate constant wind conditions. Important considerations in the design of this test were to ensure the device was properly secured, and that the sail was clear of the roofline of the truck, so as to provide the least turbulent airflow. As previously mentioned, the purpose of the test was to determine the torque contribution of both the $0.5m^2$ and $1m^2$ prototype sails about the horizontal (x) axis at different angles of attack for different wind speeds, as shown in Figure 12. This was

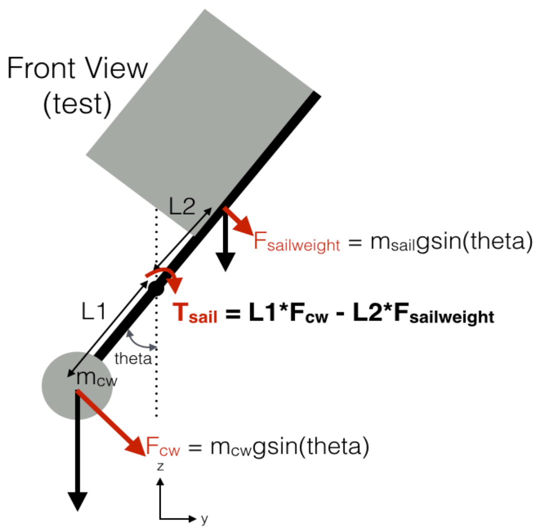

Figure 13: Stationary displacement angle measurement setup

Figure 14: Stationary torque test setup

accomplished by constraining the motion of the flipping mechanism's inverted pendulum and adjusting the teeth of the flipping mechanism's bevel gears tooth by tooth to change the sail angle by discrete amounts (approximately 20˚ per tooth). By examining how high of an angle the sail was able to lift the lower counterweight arm, to which a known amount of weight was added, the team was able to determine what device configuration resulted in the greatest torque production, and would thus result in the highest power output during normal operation without over rotating (past horizontal, or 90 degrees). Figure 13 shows a free body diagram of the sail and counterweight torque calculations, and Figure 14 shows the actual test setup. Considering the average wind range of 4.5 - 15.7 mph determined by the 2015-16 OWP team in the Marin County region where the device is most likely to be sited, the torque experiment was conducted at wind speeds (truck speeds) of 5, 10, and 15mph, though the majority of data was collected at 10mph (Koh, 2016: 19). The plot in Figure 15 compares the torque generation performance of both the $0.5m^2$ and $1m^2$ sails tested at varying angles of attack in the average wind speed of 10 mph. The test clearly demonstrated the linear dependence of sail force on area, and also demonstrated that the device performs best when the sail lift force is maximized, which surprisingly corresponded to much higher angles of attack than initially expected.

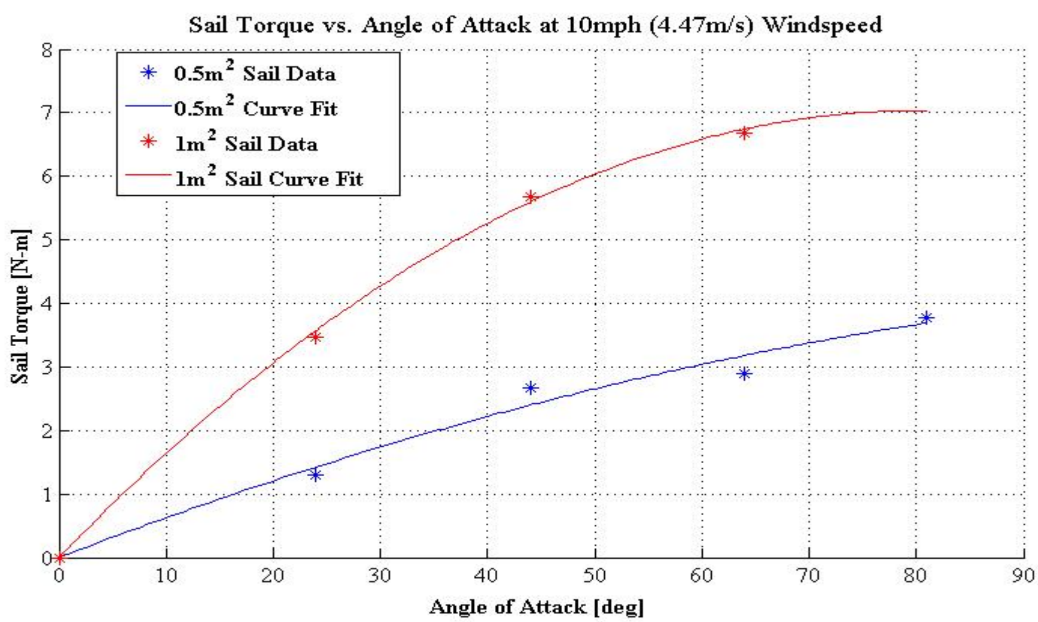

Figure 15: Sail Torque vs. angle of attack at 10mph (4.47m/s), with both $0.5m^2$ sail and $1m^2$

Somewhat surprisingly, angles of attack significantly higher than the 20-30˚ optimal range identified in improved the sail's torque generation. The likely explanation for the lift generating success of very high (44-81˚) angles of attack for the oscillating wind power device is that as the sail rotates through each oscillation, the wind direction relative to the sail's forward velocity creates a less extreme apparent wind angle, effectively reducing the sail's angle of attack relative to the wind (Larsson, Eliasson, & Orych, 2014). The results are presented in Table 1, with the most significant torque and power outputs for each sail highlighted in red. Data for the large sail at 81˚ angle of attack was not collected at either 10 or 15 mph wind speed, and thus, the small sail's torque and power production at 64˚ angle of attack in 10 mph wind is also highlighted for comparison's sake. The team also found during testing that the flipping mechanism is not capable of maintaining an 81˚ angle of attack, because the pendulum hangs too close to 90˚ to flip easily once the sail oscillates, thus, the 44˚ and 64˚ angle of attack settings are of greater relevance to the device.

Truck Speed	Angle of Attack	$0.5m^2$ Sail Torque (Nm)	Coefficient of Lift	$0.5m^2$ Sail Power (W)	$1m^2$ Sail Torque	Coefficient of Lift	$1m^2$ Sail Power (W)
10 mph	24˚	1.292	0.42	2.71	3.461	0.38	7.25
10 mph	44˚	2.67	0.87	5.59	5.67	0.62	11.87
10 mph	64˚	**2.89**	**0.94**	**6.05**	**6.68**	**0.73**	**13.99**
10 mph	81˚	**3.78**	**1.24**	**7.92**	-	-	-
15 mph	44˚	2.89	0.95	6.05	6.27	0.68	13.13
15 mph	64˚	3.77	1.23	7.89	6.89	0.75	14.43

Figure 16: Stationary torque testing results

5.5 Discussion of Results and Future Sail Recommendations

Though there was a high potential for error in the test setup (on the truck), the measurement of the displacement angle, and the apparent wind angle relative to the sail, the results in Table 1 demonstrate trends that can influence the design of further iterations of the oscillating device. The coefficients of lift for each sail orientation were determined by solving the lift force equation listed in Figure 9 in section 5.1 using the experimentally determined sail torque to approximate an average sail lift force (by simply dividing the sail torque by moment arm to each sail's center of effort), using 1.225 kg/m^3 as the density of air. Maximizing the coefficient of lift for any sail size is of utmost importance in optimizing the power potential of the device, as lift forces are almost entirely responsible for powering the oscillatory motion. The power from the sail is calculated as the device's average angular speed of oscillation multiplied by the experimentally determined sail torque, for both sails. Based on observations during power testing, the OWP device oscillates at a frequency of approximately 20rpm (0.333Hz), resulting in an average angular speed of 2.09 rad/s. This method of determining power is useful because it enables the power output of a scaled version of the sail design with similar aspect ratio and camber depth to be extrapolated from a linear regression of the torque data presented above: if the area of the sail is increased to 10m^2, it can be predicted that the large sail will produce ~10x the 1m^2 sail's measured torque, or around 70Nm. If the scaled up device oscillates at the same frequency (though it is likely to oscillate much slower), it would be capable of producing approximately 150W. This scale-up analysis is completed in greater detail in section 6.2, and is the basis upon which the team has evaluated the potential commercial viability of the oscillating device, especially as compared to continuously rotating horizontal or vertical axis wind turbines of similar size.

In order to further improve the sail's lift generation capabilities, future teams would be advised to add more skeletal support to the soft sail design in order to help it create a more idealized foil shape in each orientation. Such internal support structures are referred to as 'battens,' and, when placed and tensioned properly, can cause the sail to consistently pop between idealized camber shapes as it switches direction. Some racing sails for windsurfing and sailing also utilize 'camber inducers' (also known as 'cams'), which sit on the mast to further aid the formation of idealized camber shapes, though they require a much more complicated sail design that creates room in the sail for the camber inducers to sit on the mast (Ezzy). Unfortunately, the manufacturing complexity of adding camber inducers would likely drive the sail's cost too high, and prove not worthwhile, as the cost of racing windsurf sails with cams *and* battens is usually at least 1.5x the cost normal sails with only battens. Thus, implementing a simple fabric sail cut to luff into an idealized cambered foil shape with simple battens is likely more economical and beneficial to the oscillating design. Future teams would also be recommended to spend time co-developing a highly detailed CAD model of a constructed sail to analyze in CFD, and to compare the results of that CFD to experimental tests like the static torque test outlined in this section. Doing so would verify the validity of the scaling model, and help sail designs iterate more quickly.

6 Conclusion

6.1 Summary of Results for Final Prototype

Using Eq. (1) combined with results from static torque testing measurements and dynamic power measurements, the team has determined the power generation potential of the device, as well as where power is being lost to inefficiencies. For the power calculations, the torque delivered by the sail is assumed to be constant. In fact, the torque will vary over the operating range and decrease to zero when changing direction. Thus, this analysis can be considered a rough approximation. From Eq. (1), at a wind speed of 10 mph (the wind speed that testing was completed at) and not considering the efficiency of the turbine, there is 139 W of power in the wind. Considering the Betz limit, it is possible for a wind turbine to capture 82 W of that power. However, the swept area in the power equation is for a multi blade wind turbine rotating at very fast speeds and therefore assumes the full swept area is being fully utilized. Since the OWP device moves very slowly, only a portion of the wind in the swept area is actually captured by the device. This portion is assumed to be equal to the ratio of the projected area of the sail to the swept area, or 80 percent of the remaining power. Therefore, of the 82 W of possible wind power only 16.4 W can actually be captured by the sail. The maximum torque created by the small prototype sail was 2.89 N-m as measured during static torque testing at 10 mph wind speed and the observed frequency of rotation during dynamic testing was 20 rpm. Therefore, the sail outputs 6.05 W of power. The maximum torque measured during static torque testing at the output shaft was 1 N-m. At 20 rpm, this translates to 2 W of power. Thus, there are about 4 W of power lost when transferring the power from bidirectional to one direction through the 90-degree bevel gears. Finally, the measured electric peak power was 1 W. Power is lost between the output shaft and the final output because the generator is operating at a low rotational speed leading to a low efficiency (Hartmann, 2017). These inefficiencies and power losses are summarized in Figure 17 below.

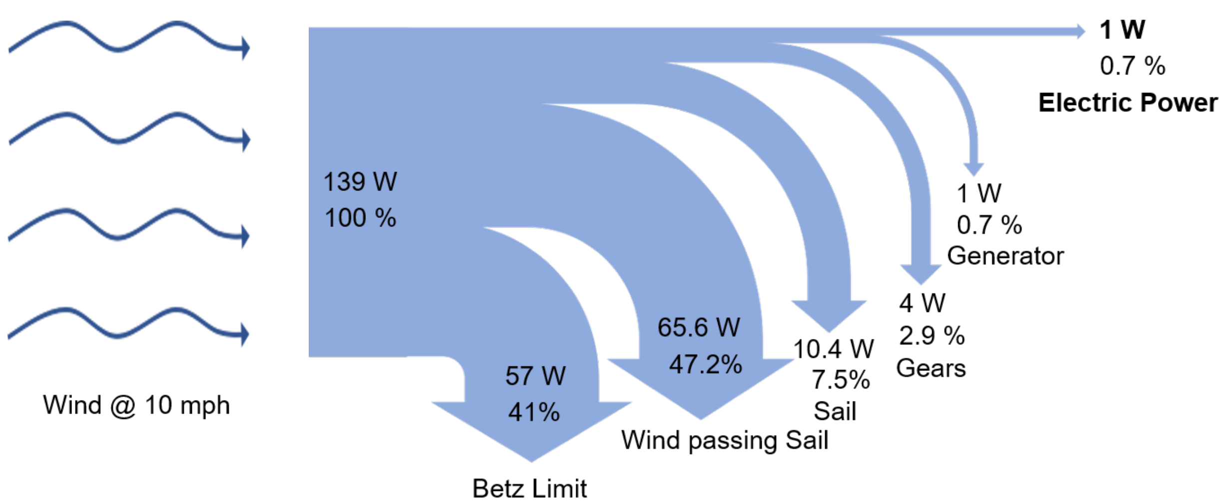

Figure 17: OWP's Power Losses

The team has identified opportunities for improvement in the current prototype that are expected to reduce the losses and increase the output power. First, the sail can be optimized, using CAE tools and simulations, such as CFD. Second, the structure should be improved so that the bevel gears no longer misalign. Finally, the power conversion system's efficiency can be improved by operating the generator at a higher rotational speed to increase efficiency. However, the power analysis from the previous paragraph reveals that even with an optimal drivetrain and power conversion system, the output power cannot exceed 6.05 W with the current sail design and is not expected to exceed 16.4 W with any sail design at 10 mph wind speed. A commercially available horizontal axis wind turbine of a similar swept area of 2.4 m^2 (vs. 2.5 m^2 OWP) in comparison has an electrical power output of approximately 50 W at the same wind speed ("HY-600", n.d.). The difference is assumed to be caused by the higher operating speed of the horizontal axis wind turbine. It allows for a higher utilization of the wind power available in the swept area - there is less wind "passing the blades". Additionally, it requires less moving parts and the electric generator operates at a higher efficiency. The expected power output is further decreased because OWP's sail needs to change direction frequently, making high speed operation challenging. For these reasons, the oscillating operating principle of OWP is not efficient enough to be competitive with wind power designs that use a continuous circular motion operating principle.

6.2 Assessment of Full Scale Design

Not only is the OWP device not competitive with traditional turbines, the device itself is not financially viable. Because the team built and tested a scaled-up version of the initial sail prototype, and verified a linear relationship between the torque generation potential of the sail and its surface area, it is possible to extrapolate the scaling effects of operating within the height limits determined by our industry sponsors. Assuming that the device will be operated at an average wind speed of 10mph (within the range of 4.5 to 15.7 mph described in section 4.3), with a sail of nearly identical aspect ratio and camber depth to the tested 0.5 m^2 and 1 m^2 prototypes (and thus similar coefficients of lift and drag), it is safe to assume that the torque produced scales linearly with area. Thus, assuming the sail height will be 4 m, and the sail area will be approximately 10 m^2, at 10 mph wind speed, and an assumed 64° angle of attack (to maximize torque, as determined experimentally), our model would predict the large sail to produce 74.9 N-m of torque. Optimistically assuming the device still oscillates at 20 rpm at this scale, the power produced by the sail would be 157 W. Assuming a constant torque, no losses in the gear train, *and* a perfectly efficient electric generator, this large scale device would need to cost $700 or less (see Figure 1) to pay for itself within seven years. Considering the complexity of the design, and the resulting number of components, this price point is unfeasible.

Our team recommends that future parties interested in pursuing the oscillating wind power concept do not constrain themselves to oscillating concepts and focus on addressing the issues of aesthetics, wildlife safety, and noise through additions or modifications to proven methods of harnessing wind energy. To that end, a few promising future design directions are presented in Chapter II, Section 5. Doing so would reduce the cost of production, decrease the likelihood of component failure, and improve the device's likelihood of success, especially considering the unique marketing opportunity for such a device, which is described in detail in the following chapter.

Chapter II: Engineering Leadership

1 Introduction

The purpose of this chapter is to situate the oscillating wind power device within the wind power marketplace by analyzing the current market, examining public perceptions, ethical challenges, and the regulatory landscape surrounding wind power to inform the oscillating technology's design and marketing strategy. An analysis of the renewable energy marketplace and competitive wind power industry affirms that there is opportunity for small wind power devices that can serve residential and farming applications. The Oscillating Wind Power concept has potential to succeed in this sector, due to its avoidance of the common visual and sonic concerns of traditional horizontal axis wind turbines, as well as its ability to operate within regulatory boundaries.

2 Wind Power Market Analysis

The share of renewable energy production relative to total energy production in the United States is growing, and will continue to grow due to increased statewide government renewable standards. In 2014, the US used 3,903 Terawatt hours (TWh) of electricity mostly in three sectors – residential, commercial, and industrial (US Energy Information Administration, 2016). As shown below in Figure 18, about 13% of the US's electricity generation is currently from renewable sources (including 6% from hydroelectric, 4.7% from wind power, and 2.3% from other renewable sources such as solar) with the remaining 87% of the generation coming from fossil fuels and nuclear (Ulama, 2016b: 4).

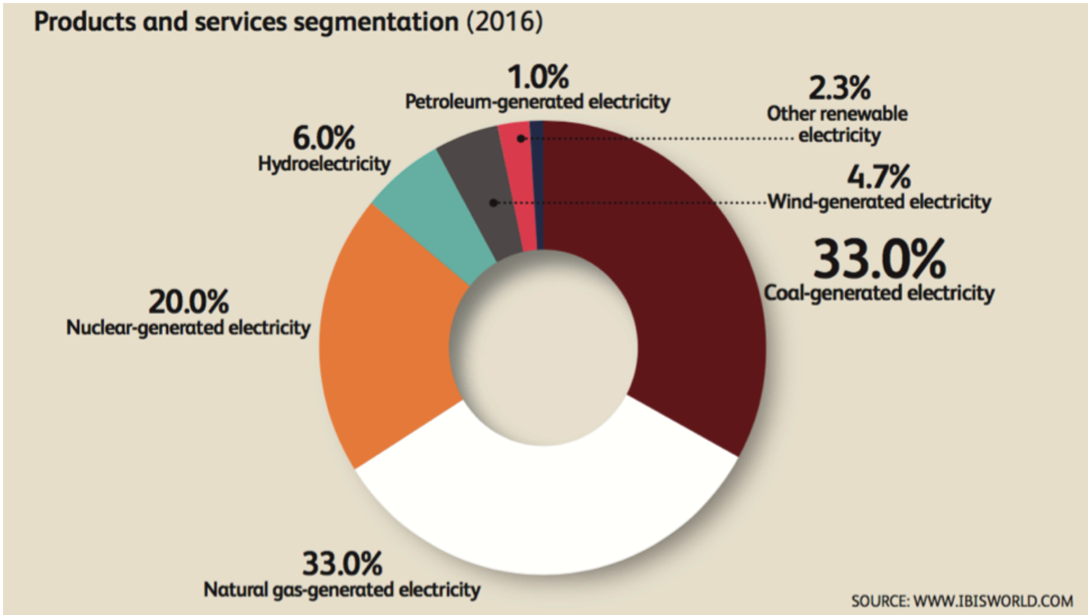

Figure 18: Electricity Generation Mix (Ulama, 2016b: 4)

Twenty-nine states have renewable portfolio standards (RPS) in place that require electricity suppliers to focus on the growth of renewable energy generation (Ulama, 2016a: 7). California's RPS requires 50% of electricity sales to be from renewable sources by 2030 (American Wind Energy Association [AWEA], n.d.). Hawaii's RPS requires that 100% of its electricity be from renewable sources by 2045 (Ulama, 2016a: 7). There will need to be significant growth of the renewable energy sources to meet these goals, and wind energy is one of the most promising opportunities. Wind power has great potential due to the abundance of wind energy resources in North America, which the Wind Resource Map in Figure 19 shows clearly.

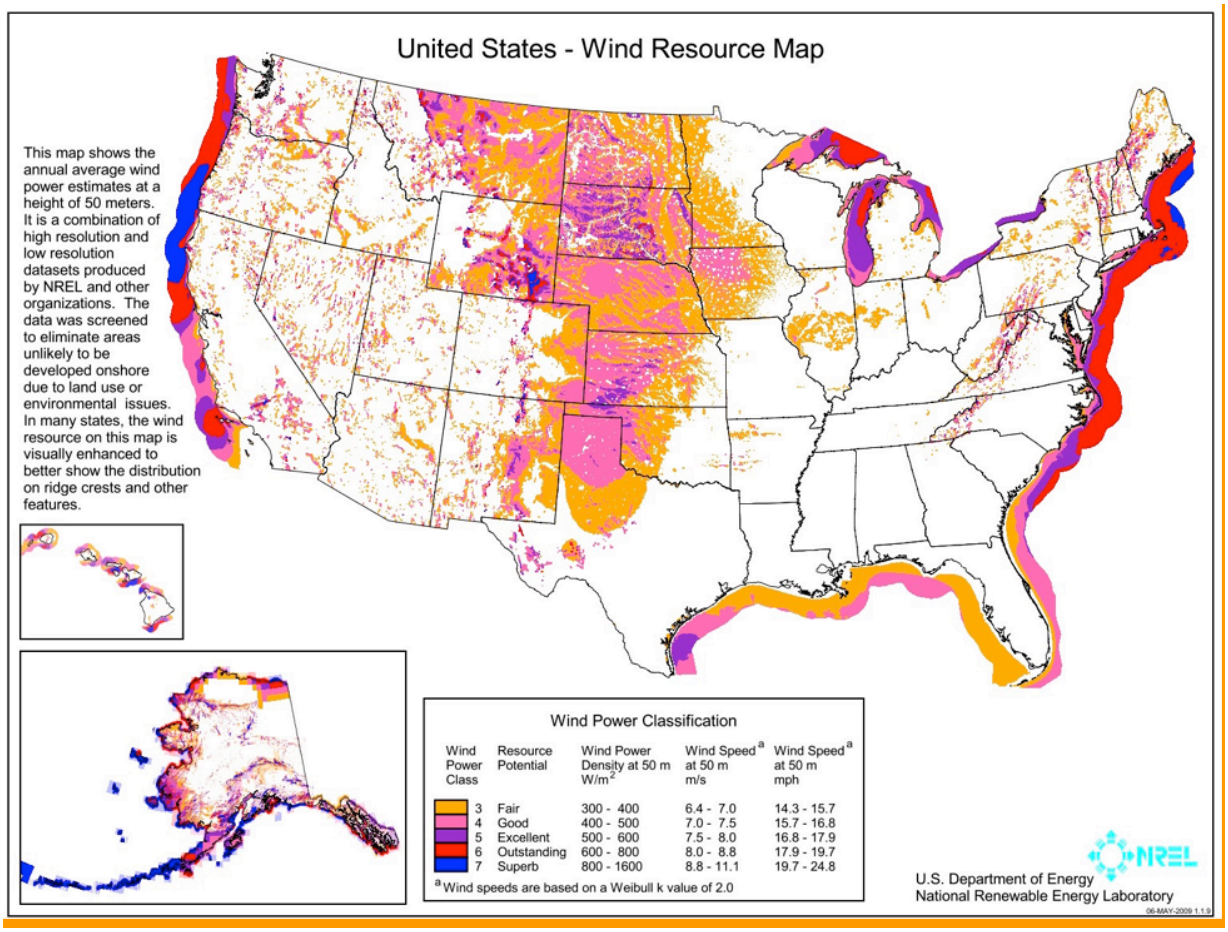

Figure 19: Wind Resource Map (NREL 2009)

There is high wind capacity through the middle of the US, as well as along coastlines and lakes (NREL 2009). It is estimated that the US wind energy potential is about 15,000 gigawatts (GW) – 11,000 GW for onshore wind and 4,200 GW for offshore wind (US Department of Energy 2015: 60). This potential is estimated to be able to produce 49,700 TWh per year, about 13 times the current US electricity demand (US Department of Energy 2015: 60). As of 2013, the installed wind capacity in the US was 61 GW across 39 states (US Department of Energy 2015: 5), less than 1 percent of the 15,000 GW of wind energy potential. Figure 20 shows the locations of where the wind capacity is installed. Comparing Figures 19 and 20 shows that wind capacity has been installed through the middle of the US, but very little has been installed along the coastlines, leaving a region with underutilized wind potential.

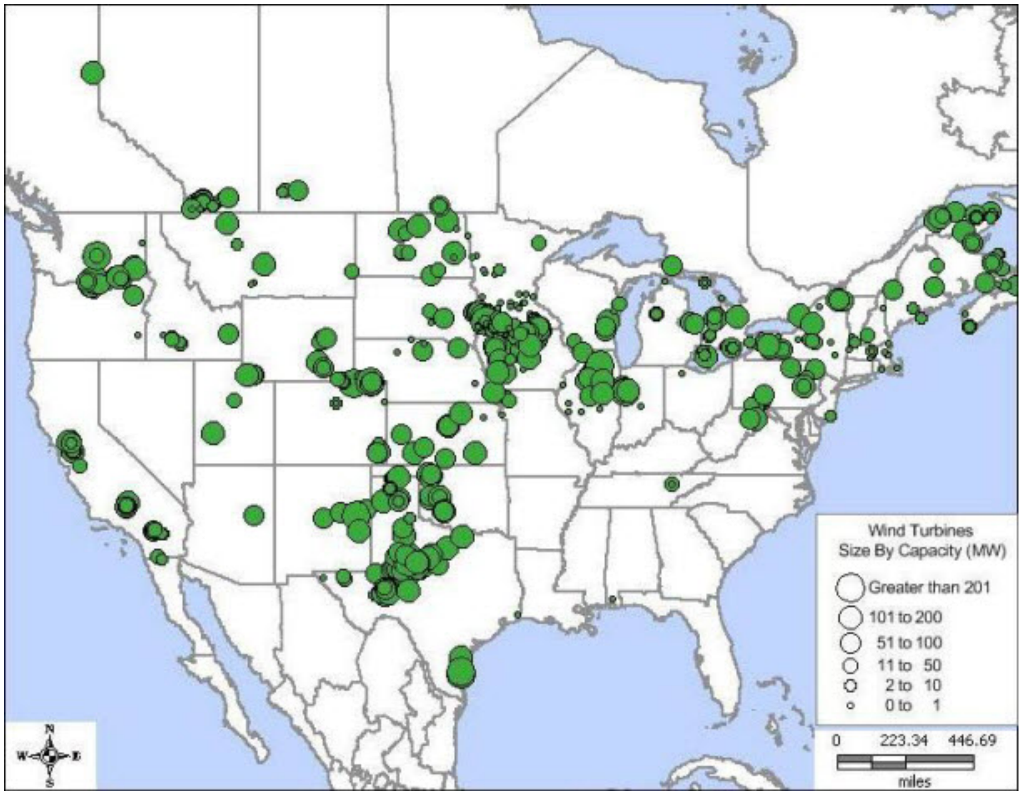

Figure 20: Wind Generating Capacity (US Energy Information Administration, 2011)

The wind energy industry is broken down into two major categories: utility scale wind, which are wind farms that generate greater than one megawatt (MW), and distributed generation, which produce less than one MW. The vast majority of the devices in use are horizontal axis wind turbines (HAWT) (Ulama, 2016a: 26), which are categorized depending on their output power level: those that produce less than 100 kW are categorized as small, those between 101 kW to 1 MW are mid-sized, and any greater are considered large wind turbines (Orell & Foster, 2016: 1). 'Small,' in the dimensions of the wind power world, means turbines ranging from 30-40 meters (~120 ft) in height, with rotor diameters of approximately sixteen meters (52 ft) (AWEA, 2009). Utility scale wind requires a large financial investment, and thus, only major energy producers or larger organizations can afford to install such devices. Despite the inaccessibility of large scale wind power, there are many landowners that live in wind resource dense areas and want to take advantage of this, driving the demand for small scale wind turbines (Ulama, 2016a: 13). With 65.6 percent of wind turbines installed between 2003 and 2015 being small distributed wind turbines, the market for small turbines is large (Orell & Foster, 2016: 38). OWP falls into the small distributed wind category, and thus, the potential for commercial success is high if it performs comparably to other small wind turbines.

3 Public Perception and Ethical Challenges

The team's industry advisor Tom Flynn, who is connected with landowners in Marin County that are looking to utilize wind power on their land. Marin County is an especially difficult location to site wind power devices because of strict regulations and local opposition to the visual disruption of such devices (Flynn, 2016; "*Ordinance No. 3548",* 2010). In an interview with Dave Warner, founder of the Marin Agricultural Wind Co-Op, it was established that potential OWP stakeholders in Marin include small-scale ranchers who are looking to capture the abundant wind resource on their coastal land to pump water for livestock and operate off-the-grid (Warner, 2016). These users would greatly benefit from the oscillating solution—they have a desire to be energy sustainable, but have difficulty employing turbine-based small-scale wind power due to the strict height and sound restrictions in Marin County. Marin County's stringent regulatory landscape is indicative of the unique challenges faced by wind power in areas of the U.S. with high wind energy potential, and demonstrates a reluctance to adopt wind power, despite its potential sustainability benefits.

While, according to public opinion polls, a significant portion of Americans support wind energy expansion, there is often a high level of rejection when new wind turbine sites are established near populated areas (Krause, Pierce, & Steel, 2016). This effect is described as "NIMBYism" by Maria A. Petrova (2013), where NIMBY stands for 'Not-In-My-Back-Yard'

(Petrova, 2013). NIMBYism is a distinctly human problem, stemming from negatively perceived visual and sonic impacts, and resulting in a fear of decreased property value (Petrova, 2013). Large wind turbines create low frequency infrasound that stimulates human brain areas responsible for mental activity and anxiety (Ambrose & Rand, 2011), as well as disturbing shadow flickering effects due to the turbine's blade motion (Bishop & Miller, 2007). Health issues caused by noise pollution have been reported for people living in the immediate vicinity of large wind turbines (Ambrose & Rand, 2011), and while such negative health effects have only been proven to apply to large wind turbines, small wind energy devices deal with noise and visual disruption as well (Van Bussel & Mertens, 2005). This is primarily because smaller wind turbines are typically installed closer to residential areas and buildings. Marin County regulations dictate the maximum allowable noise level of wind energy devices to be 50 dB during the day and 45 dB at night, measured *at any location* within a neighboring property (*"Ordinance No. 3548",* n.d.). The regulations also state that wind energy devices "shall be designed and located to minimize adverse visual impacts from public viewing places, such as roads, trails, scenic vistas, or parklands and from adjacent properties" (*"Ordinance No. 3548",* n.d.). Such stringent visual and sound regulations directly reflect public displeasure with the aesthetics of traditional wind turbines.

Another issue with significant impact on the public perception of wind power devices comes in the form of an ethical dilemma: the threat to bats, birds, and other wildlife. Studies have shown that some wind power turbine sites cause bird mortalities with concerning frequency (Smallwood K. S., 2007). Large scale turbines in California's Altamont Pass, for example, "kill relatively large numbers of raptors and other birds protected by the MBTA [Migratory Bird Treaty Act]" (Smallwood & Thelander, 2008). While the cited sources focus on large wind turbines, small scale devices could still be a potential threat to wildlife according to wildlife ecologist Judd Howell, who met with the OWP team to discuss the animal safety of the oscillating design (Howell, 2016). Mr. Howell recommended a few things that could be done to decrease bird and bat fatalities: colorful, reflective tape or fabric on the moving portions of the device, as well as a relatively slow, predictable motion.

The issues of noise, visual disruption, and wildlife safety must be addressed in the design and implementation of the OWP device, especially considering the negative public perception that already surrounds traditional wind power devices. By designing the device to comply with Marin County regulations as well as Judd Howell's recommendations, OWP will position itself to enter an unserved market for small wind power devices, uncovering greater aesthetic value in clean energy and helping homeowners navigate regulation that does not necessarily align with their sustainability goals.

4 Marketing and Sustainability Challenges

Based on the information presented in previous sections of this chapter, it is clear that there exists a uniquely defined, uninhabited design space within the wind power market that the OWP device has great potential to fill: small scale, non-turbine-based wind power that is quiet, aesthetically appealing, and safe to surrounding wildlife. The device's greatest challenge, then, is to meet these constraints while producing enough power to both be economically attractive and to ultimately pay back the energy used to produce it.

According to a 2014 Mintel report, the desire to be sustainable is on the rise amongst younger generations (Mitchell, 2014). The fact that over half of the millennials surveyed in the report demonstrated a commitment to purchasing environmentally friendly commercial goods indicates that sustainability and 'greenness' are likely to become increasingly valued in society

(Mitchell, 2014). Thus, communicating the device's 'sustainability' is key to successfully marketing it as a viable energy solution, and the most logical language to communicate this is its energy generation potential, or power rating, similar to almost all existing wind power solutions. For wind power, and thus OWP, sustainability means both being able to pay back its monetary cost within a reasonable timeline (seven years, as mentioned in Chapter 1.2) as well as to offset the energetic costs of sourcing, producing, assembling, shipping, and installing its constituent materials within its lifetime. A life cycle assessment (LCA) of large scale 2-megawatt (MW) horizontal axis wind turbines carried out in 2014 found that the devices were able to produce enough power to pay back the energy used throughout the course of their 20+ year anticipated lifetimes (from material sourcing through production, maintenance, and recycling/disposal) within at most one year (Haapala & Prempreeda, 2014). This means that for the remaining 19+ years of the devices' lifetimes, they produce truly 'clean' power, and have a net positive energetic impact. The oscillating device also needs to be capable of extracting enough wind energy to offset the energy requirements of its own production, and can only be marketed as a sustainable solution if it can operate long enough with minimal repairs.

Unfortunately, the mechanical complexity of the current oscillating device, especially as compared to both horizontal and vertical axis turbines, which require less components and undergo fewer, less extreme loading cycles, implies that repairs are likely to occur with greater frequency than for traditional turbines. This is primarily due to the fact that each oscillation fatigues the sail, the flipping mechanism, the gearing, and the surrounding support structure much more than continuous rotation would, due to the acceleration and resulting forces from the stopping and starting of the device's rotation. For future iterations, reduction of the total number of parts and selection of materials with low embodied energy could help reduce wear and decrease the amount of time the device would have to be operated before producing enough energy to offset its own energetic costs. The relatively low power generation potential determined by the results of this year's testing further suggest that the oscillatory concept carries with it greater efficiency setbacks than aesthetic benefits, and that marketing such a comparably inefficient device alongside traditional turbine based wind power would be difficult.

5 Conclusions and Future Design Directives

Based on extrapolation of experimental results from this year's testing and iteration of the oscillating wind power concept, the team has determined that scaling the device to operate within the specified height limits would not produce enough energy to justify both the monetary and environmental costs of production, as mentioned in section 6.2 of Chapter I. Nevertheless, there still exists a uniquely uninhabited design space for low height, aesthetically pleasing, wildlife safe, and quiet wind power, especially in coastal regions. Thus, the team recommends future groups work directly with members of the Marin Wind Co-Op to explore alternative designs that could meet the constraints of this design space, while maintaining a level of power conversion efficiency great enough to justify commercialization. Based on this year's findings around oscillating wind power, the team recommends pursuing a design trajectory that builds on the verified efficiency of continuously rotating turbines (horizontal or vertical) to achieve the aforementioned design constraints. The team sees potential in a vertical axis turbine which use soft sails rather than rigid blades, similar to Nils Ferber's micro wind turbine, which was developed as a lightweight solution for collecting power when backpacking in remote areas (Ferber, n.d.). The use of soft sail-like materials ensures the device is not harmful to wildlife and makes the turbine lighter (thus extending the life of its support structure). Additionally, the team envisions creating a cowling that could surround turbines to protect birds from reaching the blades and also allows for more aesthetically appealing design options. The shield could also take inspiration from the wind concentrator developed by California Energy & Power, which serves to funnel wind into an external converging nozzle to increase the fluid velocity before jetting it over the rotating blades of a vertical axis wind turbine ("Evolution of Design", n.d.). This design addition was proven to increase the efficiency of the vertical axis turbine by a factor of two, and could be incorporated into an aesthetically appealing covering ("Evolution of Design", n.d.). The team believes these ideas have potential for higher efficiency than the oscillating design, but can still meet the aesthetic and regulatory requirements in markets like Marin County.

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