UNIVERSITY OF CALIFORNIA, BERKELEY
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MASTER OF ENGINEERING

Wind Power
Final Report

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Executive Summary

The goal for this project is to determine a solution for extracting wind power in a way that is less intrusive to wildlife and less visually and audibly disturbing to nearby residents, issues that are typically not addressed in traditional wind turbines. Through our competitive research and literature survey, we found that a small scale, vertical axis, Savonius type wind turbine can be a potential solution to harvesting wind energy in communities like Marin County. Our work was dedicated to enhancing this design with wildlife safety features, improving its aesthetics, and optimizing performance through an iterative process involving computational fluid dynamics simulations and the design-by-morphing methodology.

While Marin County is planning to transition to 100% renewable energy sources by the the year 2025, many community members have expressed their concerns that wind turbines would pose a threat to wildlife, negatively impact the visual landscape, and be audibly disruptive. The human-centered design process allowed us to identify these concerns and develop a solution to harvesting wind in Marin. The small size of our design naturally lessens the visual impact it would have on the landscape. As for wildlife safety, traditional wind turbines have been criticized for the many bird fatalities associated with them; our small scale turbine has the advantage of operating at heights that are lower than the flight paths of birds of prey, thus reducing the possibilities of collisions with them. Also, the concentrator feature on the design shields the blades from birds approaching in the direction of the wind and allows the birds to better perceive the turbine as a stationary object that they can avoid, as opposed to the blurred blades of a traditional design that can be very confusing for the birds. Lastly, unlike traditional turbines which are very loud due to their high tip speed ratios, our drag based design has much lower tip speed ratios and is consequently much quieter. However, the regulations present technical obstacles for the design of a wind turbine; the main problem being the height. The 40 foot height restriction for wind turbines in Marin subjects the turbine to much lower wind speeds and more turbulent winds, which greatly reduces the turbine's available power. Since our design is drag-based, it is better able to extract the energy from the low speed, turbulent winds than the lift-based traditional turbines are.

The other aspect of this project involved the optimization of an existing design, the California Energy and Power (CE&P) turbine. New designs were generated using a process called design-by-morphing: a computational method that allows us to combine any number of shapes to produce a final combined geometry. Our team focused on generating new designs for the concentrator that were then tested for performance using computational fluid dynamics. Five new concentrator shapes were generated and then simulated with a 24 mph wind speed and two different rotational speeds, 4RPM and 40RPM, along with the original design. At 4RPM, which is the operating condition recommended by CE&P, the original design performed the best with a power output of 2.82 kW. When the operating speed was increased to 40 RPM, all five new geometries performed much better than the original, with the best design producing 8.85 kW while the original produced only 6.90 kW. However, these results have some uncertainties from the lack of better computational equipment.

Through many interviews with community members and field experts, as well as attending community events, we were able to gain a much better understanding of what it takes to site wind power in Marin County. Eventually, the goal is to site a small scale prototype of this design in Marin to hopefully increase the acceptance of wind turbines in the area and encourage more wind turbines to be sited in the region. While exploring California Energy and Power's turbine, our team was able to find improvements in bird safety, aesthetics, and performance. The initial tests show power improvements of about 250% by operating at 40 RPM instead of 4 RPM, suggesting that greater power output is possible at higher operating speeds. Future teams could benefit from exploring more designs and optimizing the operational speeds and tip speed ratios. The wildlife and structural implications of increasing the operational speed are something that should also be investigated.

Contents

1 Developing small scale wind energy solutions

1.1 Our approach

The Wind Power capstone project is an effort to bring innovative small scale wind energy solutions to communities with niche environmental needs that are otherwise not met by traditional wind turbines or other energy sources. Namely, the focus is to design a wind turbine that is bird-safe, quiet, and attractive, which are design targets that are generally overlooked in traditional wind energy devices.

To address these needs, we have selected a small scale vertical axis wind turbine design with a concentrator feature, allowing us to operate within the Marin County regulations for wind energy conversion systems (WECS), and decrease the obtrusiveness of the wind turbine. It should also be noted that decreasing the elevation at which the turbine operates introduces more turbulent flow regimes to the turbine blades, which was a key motivator to proceed with a vertical-axis, savonius-type wind turbine. Over the course of the project, we have worked on enhancing the wind turbine design by incorporating wildlife safety devices, and improving its aesthetics and performance through an iterative process involving computational fluid dynamic simulations and the design-by-morphing design methodology.

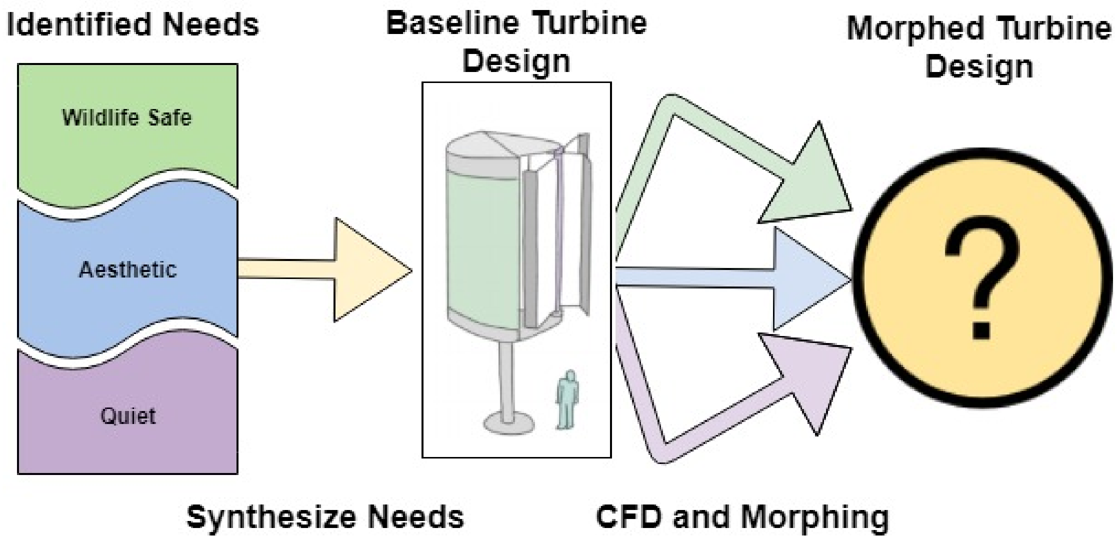


Figure 1: Project flow, starting with the identification of needs and finishing with a morphed turbine design

1.2 Rapidly growing industry

Industry-wise, this project fits broadly into the energy generation and utilities industries and more specifically in the renewable energy sector. This is a field that has experienced accelerating growth in recent decades, primarily because of rising social awareness of climate change but also because of decreasing prices of renewable energy devices like solar panels.

Where our specific design point fits into the industry as a whole becomes apparent when other competitors in the renewable energy sector are analyzed. Solar energy, for example, whether in the form of photovoltaic (PV) cells or concentrator mirror arrays, is a common and available source of renewable energy but is plagued by being effective for only a fraction of each day and having its output severely diminished by weather or even seasonal changes (Williard, T., 2017). Wind energy is not affected by these shortcomings and hence can act as a nice complement to solar, but current traditional wind farms feature extremely large turbines that are visually and audibly disruptive. Not to mention they pose a real risk to avian life in communities where they are installed, resulting in restrictive regulations on their placement.

2 Understanding contextual obstacles in the establishment of wind power

Before delving into the technical details of the turbine design, it is important to understand the various social, regulatory and economic aspects of establishing wind power and how they are realized in Marin County.

2.1 Social trends

Our main point of contact for learning the social trends in Marin is Tom Flynn, an environmental management consultant based in the county. He has helped us to navigate to solutions that are within the community's requirements and has connected us with many community leaders and field experts. For example, through Tom we have been able to contact supervisors in Marin as well as attend green energy conferences in the county to gain insight on their political climate. With these interactions, we were able to witness the community's enthusiasm for green energy firsthand and were able to speak with them directly to better understand their needs and concerns.

Through these activities, we learned that Marin County is positioning itself to remain as one of the leading communities in the United States to reduce carbon emissions (Connolly, D., 2017), with its community planning to transition to 100% renewable energy sources in the coming decades. The people of Marin enjoy a median household income of $100,662 and wish to preserve the natural beauty of the region, while harvesting the energy from the abundant wind resource in the area (Connolly, D., 2017), ("Data USA," 2017). They are hence more willing to pay a premium for locally sourced power.

2.2 Regulatory trends

The primary issue with meeting this demand locally is Marin County's regulatory environment. The county has published regulations concerning wind energy conversion systems (WECS) that outline permissible height (40 ft.) and proximity to prominent ridgelines (300 ft.). There are also restrictions on diameter, noise level, and proximity to structures and property lines (Marin County Code Title 22, 2010).

A pre-build study must verify that the completion of the project will pose no threat to any local, migratory, or endangered species of wildlife. This concern is due to known negative interactions between wind farms and species of birds and bats. If a development is approved and completed, a post-build study must then be done to report on whether or not the project is adhering to the pre-build study's estimates.

2.3 Economic trends

Meeting these regulations and maintaining the economic viability of a wind power system is a challenge. The traditional option for efficient wind energy is large scale wind farms. They are able to access better wind resource at higher elevations. Building turbines at lower heights and near structures (trees, houses etc.) subjects them to "lower quality" air, resulting in less energy generated and thus longer payback periods. A way to partially mitigate this is to site smaller turbines in large, windy clearings. Unfortunately, constructing turbines in these large fields increases the cost of transmitting any power that is generated to the grid. This issue is pertinent in Marin, where the county's best wind resources are located in its western area. This is a significant distance from the nearest interconnection station, which is owned by Pacific Gas and Electric Company (Warner, D., 2017).

Current manufacturers of small scale turbines try to get around economic issues by saving costs and sacrificing structural integrity to improve their turbines' payback period. This means these small scale turbines suffer more mechanical damage than the large-scale ones and sometimes they wear-out in only a couple of years. Several experts have stated in interviews with us that their opposition against small scale wind turbines is because of their short-lived nature.

Our economic challenge is to achieve an acceptable payback period (7-10 years) with a product life time of at least double that amount. This target was chosen as it is an ambitious goal to work with, given the fact that most small scale wind turbines in the market pay themselves back in more than 15 years (if they survive that long). Subsidies and tax credits can make this option even more lucrative once the technology is in place and proven.

The primary buyer of the power generated by our turbine would be Marin Clean Energy (MCE). MCE is the local community choice aggregation program and provides residents the opportunity to incorporate varying levels of renewable energy into their electric service. MCE is looking to diversify its energy sources and offer its customers more locally sourced wind energy (Saxby, L., 2017). This makes it a direct contributor to the large demand for local renewable energy mentioned earlier. If a local wind power development is able to produce electricity on the order of kilowatts or more, then MCE would be interested in purchasing energy from it at a premium (Saxby, L., 2017).

3 Addressing the needs of communities like Marin County

By taking a human-centered design approach and spending several months interviewing a variety of stakeholders, like community members, wildlife experts, and renewable energy project managers, we were able to uncover a number of community concerns and concentrate our energy on tackling core issues, like wildlife safety, noise, and appearance. Along with gaining a better understanding of the political-social-regulatory situation in Marin County, we were able to engage the community and realize that there is a very large population in Marin County who supports the establishment of local wind power generation. A summary of the interviews and literature review that was conducted this year can be seen in the appendix.

As a result of our human-centered research and analysis, our wind turbine design has two overarching objectives: To deliver a wildlife safe, aesthetic, and quiet wind turbine to communities like Marin County, while producing sufficient power to make the device economically viable. The following sections outline how our design will go about doing so.

3.1 Bird safety

Small scale wind turbines have the advantages of being less threatening to protected birds of prey, being less obtrusive to viewscapes, and adhering to the existing WECS regulations in Marin County.

To begin, when turbines operate at elevations that birds of prey often hunt, there is higher likelihood that bird strikes will occur. For example, the 90 foot tall turbines in the Altamont Pass Wind Resource Area (APWRA) have recorded killing 4700 birds in a single year, including endangered varieties like Bald Eagles (BioResource Consultants, 2004). Due to the large number of recorded bird fatalities, The Endangered Species Act has been the primary legal counter-argument to the installation of wind turbine projects (Williard, T., 2017). By specifying that our wind turbine design have a shorter tower and operate at a lower height, the design will implicitly avoid encroaching on the flight regimes of protected birds and drastically reduce the number of interactions between birds of prey and wind turbines.

Another technique to increase the wildlife safety of the small scale wind turbine is to adopt a stationary design, or at least a design that is perceived as being stationary, allowing birds to identify and evade the wind turbine. Only appearing stationary without attention to color and material is insufficient though, as it has been observed for example that stationary transparent windows are difficult for birds to perceive; and collisions between the two are responsible for 100 million to 1 billion bird deaths each year (Klem Jr., 2010). To tackle this, our design will incorporate a concentrator that shields the blades from birds approaching the turbine from the direction of the prevailing wind.

Figure 2: Blade exposure of horizontal axis wind turbine (left) and vertical axis wind turbine design (right)

Although large wind turbine farms have been shown to divert birds' migration patterns by approximately 500 meters (Masden et al., 2009), a study conducted by Minderman et al. has shown that the presence of small scale wind turbines does not change bird activity (2012). With this in mind, we are still taking steps to maximize the birds' ability to perceive the turbine design. When flying near the turbine, the opaque nature of the concentrator creates a solid profile, offering no gaps for birds to attempt to pass through, thus lowering the likelihood that birds will interact with the turbine (Howell, J., 2017). When it comes to perching or nesting behaviors, the top and interior cavity of the concentrator will undoubtedly attract birds and increase the potential risk of avian fatalities (Nelson & Curry, 1995). Anti-perching coils can be deployed on top of the concentrator to discourage birds from perching on the turbine, while a finely spaced mist net can close off the internal cavity of the concentrator to prevent birds from nesting in the turbine.

The wind currents that flow downstream of traditional horizontal axis wind turbines are similar to the currents of tall trees, where bats often look to roost and hunt (Cryan et al., 2014). As bats hunt, they use echolocation to identify and track their prey. Two studies found that bats are better able to detect surface-based prey with echolocation when the surface is smooth, such as water (Siemers et al., 2005, Clare & Holderied, 2015). One hypothesis for the attraction that bats have with wind turbines is that the smooth surface of the towers facilitate better hunting. In a study conducted by Bennett & Hale, bat activity was significantly lowered at textured surfaces, when compared to smooth surfaces (2015). In the case that the sandpaper finish does not sufficiently deter bats, an ultrasonic acoustic emitter can be implemented. These devices have been shown to decrease bat fatalities by approximately 10% (Arnett & Hein, 2013). To aid in bat perception and discourage bat-turbine interactions, the final turbine design can have a sandpaper-like surface treatment. With these wildlife safety measures in place, we can now focus on creating an aesthetically pleasing wind turbine.

3.2 Community perception and aesthetics

In a national survey conducted by Lawrence Berkeley National Lab aimed to understand the attitudes of individuals who live within 5 miles of wind turbines exceeding 364 feet in height, preliminary results show 57% of respondents were positive and 34% of respondents identified as having a neutral attitude towards wind turbines (Rand & Hoen, 2017). At a local level, Marin is a split community. On one side of the spectrum, the community demands renewable energy, which has culminated into a pledge by the county supervisors to transition to 100% renewable energy sources by the the year 2025 ("Go 100% Renewable Energy," 2017). On the other hand, community members of Marin have expressed concern that, in addition to posing a threat to protected species of birds and bats, the presence of wind turbines will negatively impact the natural viewscape. These concerns are also reasons as to why we are proceeding with a small scale turbine that incorporates a concentrator. Operating at lower elevations allows the wind turbines to be located near prominent ridgelines without being obtrusive, and the concentrator shields the moving components from the observer, presenting less of a distraction.

Additional efforts that were focused on improving the appearance of the wind turbine were incorporating camouflage and biomimicry into the turbine design. Camouflage is the application of colors and patterns to the surface of an object in an attempt to make the object less perceiveable, while the incorporation of biomimetic design is the act of looking to nature for inspiration or features which can be emulated.

When discussing the act of applying camouflage to wind turbines, it should be noted that traditional horizontal axis wind turbines cannot be camouflaged because of the necessity that the turbines be easily perceived by aircraft flying overhead (Pattison, C., 2018). Since this design operates at a much smaller scale than traditional wind turbines and does not have to worry about interfering with aircraft, it can leverage the concealment benefits of camouflage. The current camouflage is a patchwork of large squares, with each square taking a shade of color that is common in the landscape, which in this case, is Marin County. For other locations, it would be necessary to survey the turbine site and select colors that are appropriate for that particular location. The patchwork camouflage designed for Marin is shown in Figure 3.

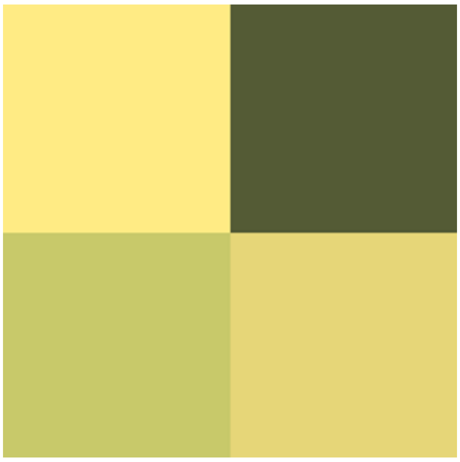


Figure 3: Patchwork camouflage developed for Marin County

At short distances, these solid squares of color present themselves as a collection of opaque panes, which gives the turbine an appearance similar to a large painted building and should be easily perceived and avoided by birds. Figure 4 shows the 40 foot tall turbine at a short distance, set in a potential site in Marin County.

Figure 4: Camouflaged turbine at short distance

The true concealment benefits of the camouflage are realized most at further distances. The patchwork camouflage is designed to reduce the rigidity and definition of the turbine's silhouette, as well as incorporate natural and non-uniform coloring on the surface of the structure. Figures 5 and 6 demonstrate how the turbine blends into the landscape of Marin County as the distance between the viewer and the turbine increases.

Figure 5: Camouflaged turbine at middle distance

Figure 6: Camouflaged turbine at long distance

It can be seen that incorporating camouflage is able to reduce the perception of wind turbines, but does not address the industrial appearance of traditional wind turbines. In an attempt to inspire viewers to consider the small scale wind turbines more natural looking, we sought help to incorporate biomimetic design. This help to incorporate geometry inspired by biology was received from Bruce Webster of PAX Scientific, a fluid dynamics research and design firm based in Marin County. After communicating with Bruce about the turbine's needs for improved appearance and efficiency, he encouraged us to explore the incorporation of natural logarithmic curves into the turbine's concentrator design. Combining Bruces's guidance with the design-by-morphing methodology, resulted in the geometry shown in Figures 7 and 8, which exhibit more smooth, flowing curves when compared to traditional wind turbines.

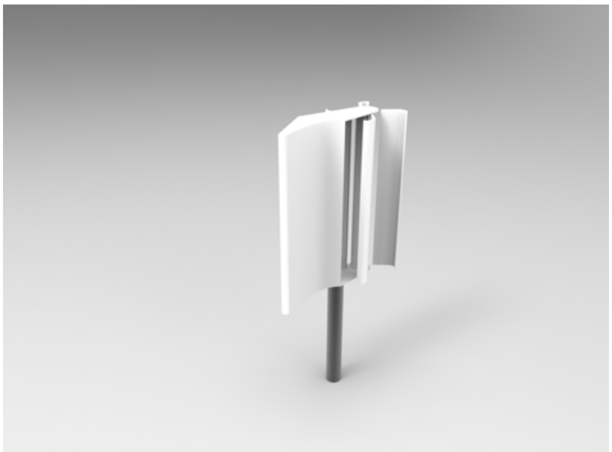


Figure 7: Turbine concentrator based on natural logarithm, view 1

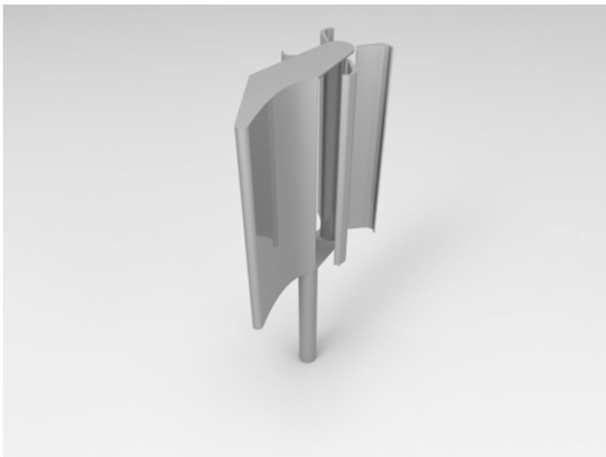


Figure 8: Turbine concentrator based on natural logarithm, view 2

To ensure that the appearance of the turbine and wildlife safety was improving, images of the turbine camouflaging schemes and concentrator geometry, as seen in Figures 5, 6, 7, and 8, were used to elicit feedback from stakeholders living in Marin, as well as wildlife experts from H.T. Harvey & Associates, National Wind Institute, American Wind Wildlife Institute, and Bat Conservation International.

3.3 Regulatory environment

Finally, to better facilitate harvesting wind energy, Marin County took steps to write a regulatory document that outlines the permitting process for WECS. To further elaborate on the regulations mentioned previously, for a prospective wind energy project to avoid time intensive and costly wildlife studies, wind turbines can be no taller than 40 feet tall and their proximity to prominent ridgelines no closer than 300 feet, while diameter and noise level are also regulated (Marin County Code Title 22, 2010). To address the mandate that noise levels are to be less than 45 dBA at any property line, we have elected to use a drag based system, which, by design, does not allow the blade tip speed to exceed the speed of the wind. With this tip speed ratio being the main contributor to noise generation, we thus address the audible pollution issue.

4 Operating at small scale presents technical obstacles

Our small scale vertical axis wind turbine with a concentrator addresses the community's concerns regarding bird safety, turbine aesthetics, and conforms to Marin County's WECS regulations. These design decisions do however have technical implications on power production, due to the fact that wind speeds are dramatically decreased at lower elevations as well as being far more turbulent.

4.1 Wind power availability and altitude

When wind flows over a surface, it exerts a horizontal force on the surface in the direction of the wind, which can be defined as shear stress when calculated per unit area. In turn, the surface exerts an equal and opposite force on the wind which causes friction, reduces speed, and adds turbulence to the flow near the surface. The result is that wind velocity at the surface is zero and increases with height until it reaches the free stream velocity layer, which is a smooth layer that is virtually unaffected by the stresses close to the surface. This free stream velocity layer is an ideal place for lift based devices to harvest energy, and is part of the reason traditional wind turbines tend to be very tall.

Since we are restricted to the relatively low height of 40 feet, it follows that we are operating in comparatively low-speed and turbulent conditions. This significantly hurts power generation since the amount of power available in the wind is proportional to the cube of the wind velocity. Power density of the wind is given by the following equation, where v is equal to the velocity of the wind and ρ is equal to the density of the air:

$$P_w = \frac{1}{2}\rho v^3 \tag{1}$$

Power density of the wind is the total amount of energy transported across a unit area per unit time. From this equation, it is evident that just a 10% decrease in wind velocity leaves us with 27.1% less power.

Note that power density in the wind is not to be confused with the available power density, which is the theoretical maximum amount of power that can be extracted, represented by the following equation:

$$P_A = \frac{16}{27}\frac{1}{2}\rho v^3 \tag{2}$$

The factor in this equation is $\frac{16}{27}$ (Betz limit) which shows that at best, 59.3% of the power in the wind is available for extraction, and again reinforces that wind velocity is one of the most important factors in maximizing power production.

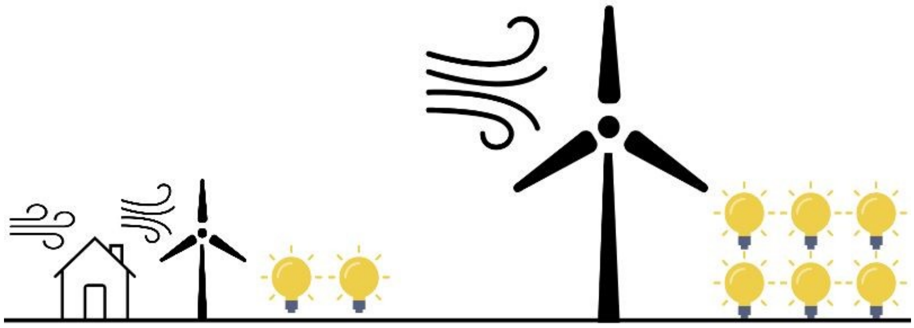


Figure 9: Power density of wind increases with the cube of wind velocity

The reality of our low altitude operation regime must then be made up for by ensuring our turbine is located in an area with already higher than average wind speeds, and with minimal nearby structural obstructions like tall trees or buildings. Additionally, the incorporation of a wind concentrator facing the incoming air flow allows our drag based design to harness wind energy more effectively by shielding the return side of the turbine from incoming wind. This is outlined in the figure below.

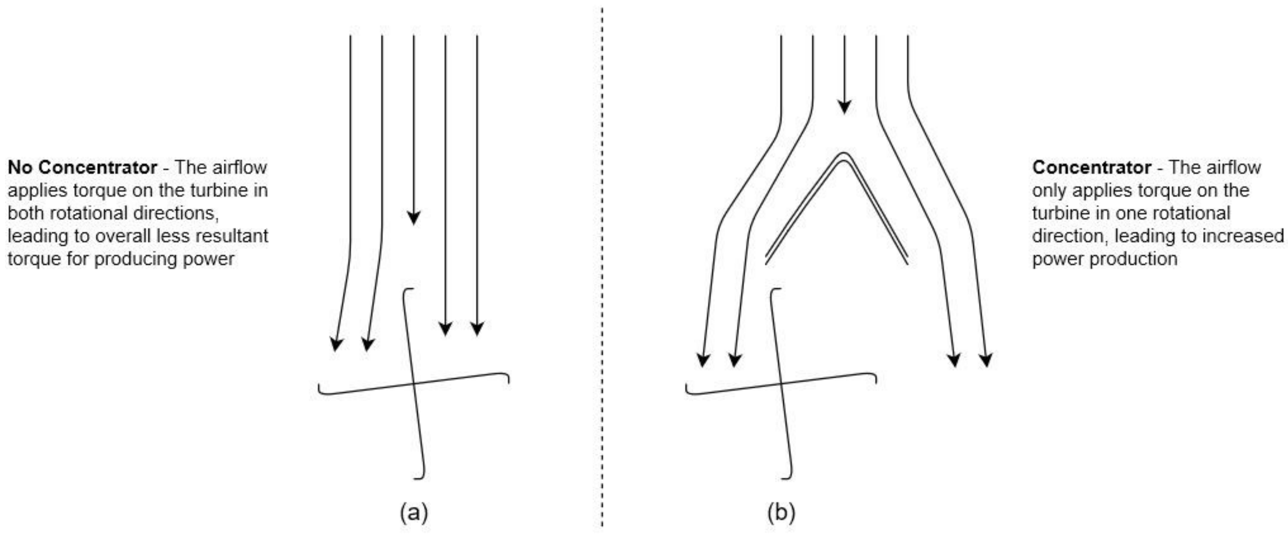


Figure 10: Vertical axis wind turbine torque without (a) and with (b) concentrator

4.2 Turbulence and altitude

Turbulence relates to altitude in much the same way that wind speed does, as explained earlier. Traditional horizontal axis wind turbines (HAWTs) operate based on lift characteristics similar to an airplane wing, meaning the wind generates a force perpendicular to the direction that it is blowing due to pressure differences on the two sides of the blades. This process is effective but requires laminar (i.e. non-turbulent) flow in order to operate efficiently, which is an additional reason HAWTs tend to be extremely tall (∼450 feet). Given that the flow at 40 feet will be fairly turbulent, the lift based HAWT is suboptimal. A better method in these conditions would be to employ a drag based vertical axis wind turbine (VAWT). In drag-based turbines, the wind exerts a force in the direction that it is blowing. Since it is simply a matter of wind impinging on the surface, a VAWT can withstand turbulent flows much better than the laminarity-dependent lift based design and has the added advantage of being able to take wind from any direction.

Combining these advantageous operating characteristics at low speeds and turbulent flows with the aforementioned noise production advantages due to lower tip speed ratios, we can conclude that given the height restrictions, a drag-based VAWT with a concentrator is an optimal option.

5 Optimizing an existing design to improve performance

Through our competitive research and literature survey we found a viable existing design for a small scale VAWT with a concentrator: The California Energy and Power (CE&P) Turbine. We decided to pursue optimization of an existing design solution instead of starting from scratch because of the time constraint of the project and also to avoid 'reinventing the wheel'.

5.1 Design-by-morphing

Our optimization of power generation, noise levels and avian-safety utilizes a novel design process called design-by-morphing. This is a computational method that allows us to generate novel shapes by combining any number of base shapes, with variable weights to each, to produce a final combined shape with characteristics from each base geometry. This is especially relevant as many characteristics of the design (e.g. aerodynamics, aesthetics) are shape dependent (Oh, Chung-Hsiang, Jiang & Marcus, 2017). We then test the performance of the morphed shape via computational fluid dynamics (CFD) and use the results to improve the next morphed iterations. In simple terms, a geometry with bad performance will weigh less in the next iteration of morphing and a geometry with better performance will weigh more. This allows us to retain all of the 'good' features of a design while knocking out the features which contribute to a decrease in performance.

As a starting point for the optimization process we chose concentrator optimization. We constraint the two end points of the concentrator to keep the positioning relative to turbine blades the same across morphed designs. Concentrator positioning, angle, gap and blade optimization will follow this study. We also limited our analysis to two dimension in order to iterate faster. Besides this, variation between 2D and 3D performance is within acceptable limits for the current design (Kendall, G., 2017).

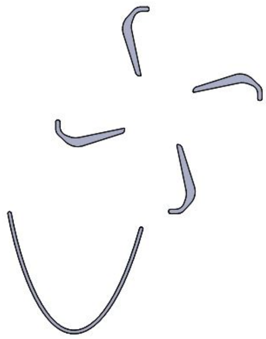


Figure 11: Vertical Cross-section of Current Design

In order to morph 2D shapes we developed an algorithm that could take geometries with their corresponding weights as input and output a new morphed shape. The algorithm is described below.

1. Constructing a baseline design in Solidworks
   The concentrator design is visualized and constructed in Solidworks. The 2d sketch of the concentrator is then converted into a set of finite points along the curve. Number of points along the curve decide the resolution. X and Y coordinates of these points are then stored in an Excel worksheet.

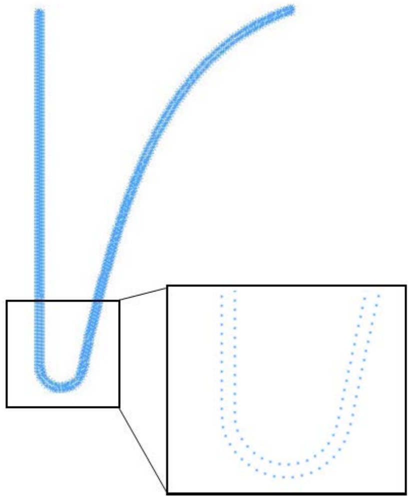


Figure 12: Discretization of concentrator into points in Solidworks

2. Importing the points in MatLab and selection of control points
   The coordinates for the two baseline shapes are imported in MatLab. Control points are selected on both shapes to match similar features, for instance head to head and tail to tail.

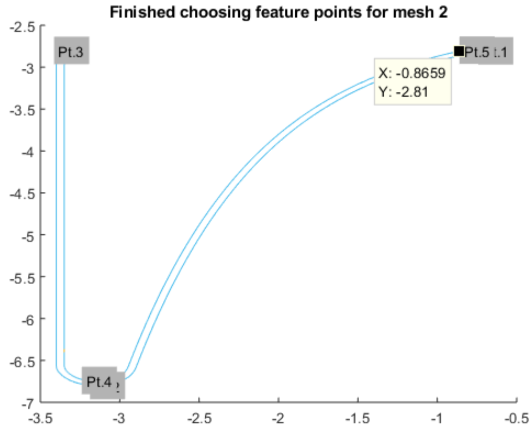


Figure 13: Selection of control points

3. Breaking shapes into parts
   Following selection of control points each shape is broken into multiple curves at these points.

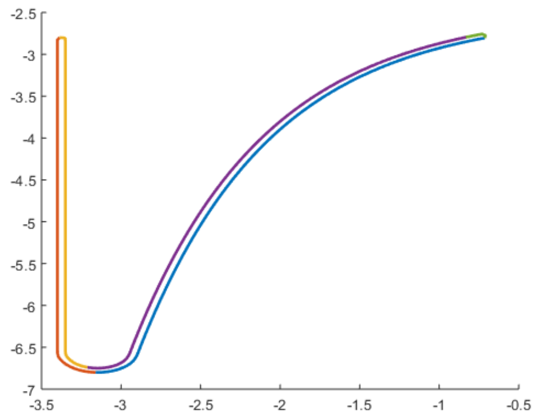


Figure 14: Parts of curve depicted with colors

4. Morphing individual parts
   A weighted sum of coordinates of points on corresponding parts is then carried out to come up with morphed part. So a part between control point 1 and control point 2 on shape 1 will be morphed with a part between control point 1 and control point 2 on shape 2. This is done for all parts.

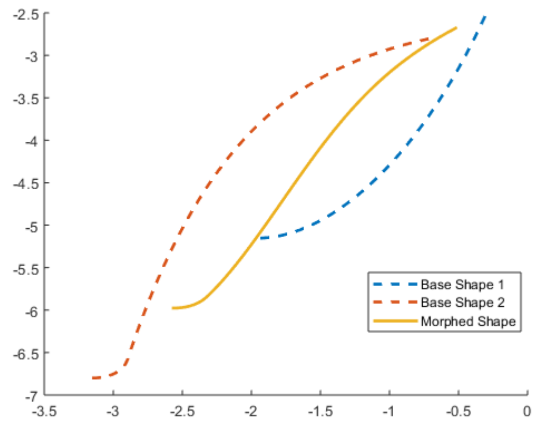


Figure 15: Weighted average (morphing) of one part

5. Recombining morphed parts
   Finally, the morphed parts are then appended together to get back the morphed shape.

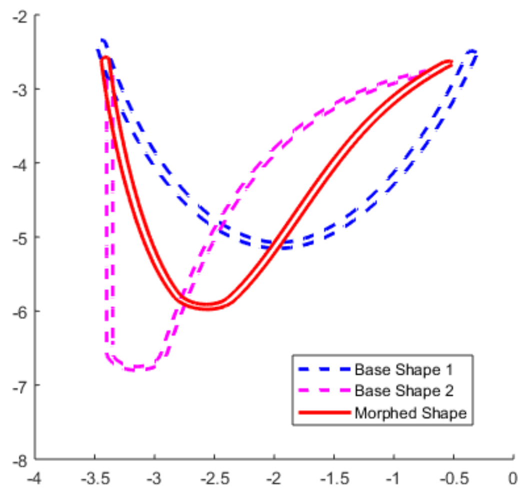
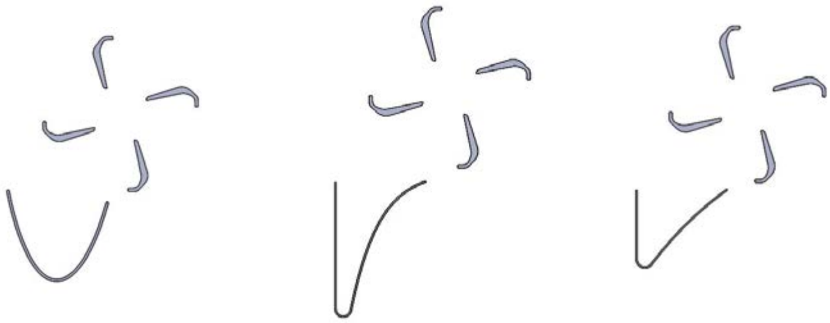


Figure 16: Morphed shape after assembly of morphed parts

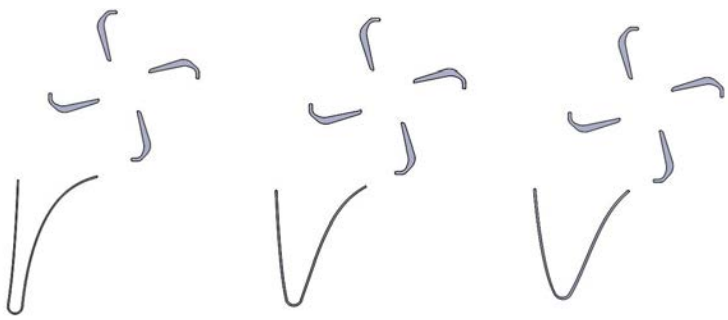
Using this tool we are able to morph two baseline shapes at a time and create a new shape. We carried out CFD simulations on the following six designs. Three of these are baseline shapes and three are morphed, based on the weights indicated in Tables 1 and 2.

Table 1: Baseline concentrator designs



Baseline 1	Baseline 2	Baseline 3
Current Concentrator design	Logarithmic concept 1	Logarithmic concept 2
(1,0,0)	(0,1,0)	(0,0,1)

Table 2: Morphed Concentrator designs using first two baseline designs



Morphed 1	Morphed 2	Morphed 3
(-0.25,1.25,0)	(0.25,0.75,0)	(0.5,0.5,0)

5.2 Computational Fluid Dynamics (CFD)

5.2.1 Purpose

The primary purpose of carrying out CFD simulations was to compare the effectiveness of the different concentrator geometries obtained from morphing in improving the power output of the wind turbine.

This was done by evaluating the different torques exerted by the same wind flow on the blades of the turbine for the different concentrator geometries. Due to mechanical and electrical losses, torque is not a direct measure of the electrical power output of the turbine. The two values are correlated however via equation 3 in the Analysis section, hence evaluating the torque can give insight into which concentrator will theoretically yield the best performance.

5.2.2 Methodology

The CFD simulations were carried out in two dimensions (2D) in the student version of ANSYS Fluent, using the sliding mesh method. The choice of 2D for the simulations was primarily motivated by the desire to run calculations quickly enough to get torque results for as many concentrator geometries as possible; simulating all three spacial dimensions would have taken a substantially longer amount of time.

While omitting the third dimension is not an entirely accurate representation of the real flow conditions on the turbine, we concluded that it would be acceptable for our purposes since the 3D geometry of the turbine is a direct linear extrusion of the 2D cross section. Additionally, since the target is simply to compare the concentrators' performance relative to each other, the relative value of the torques is more important than the absolute accuracy of values.

5.2.3 Procedure

The first step in carrying out the CFD calculations was to create the 2D geometries of the fluid domain and the turbine that would be input into ANSYS Fluent. The geometries were created in Solidworks, with an added body-of-influence region to aid in improving mesh refinement around the turbine and in its wake region. An illustration of the domain dimensions and the relevant positioning of the turbine in the fluid domain is shown in Figure 17 below.

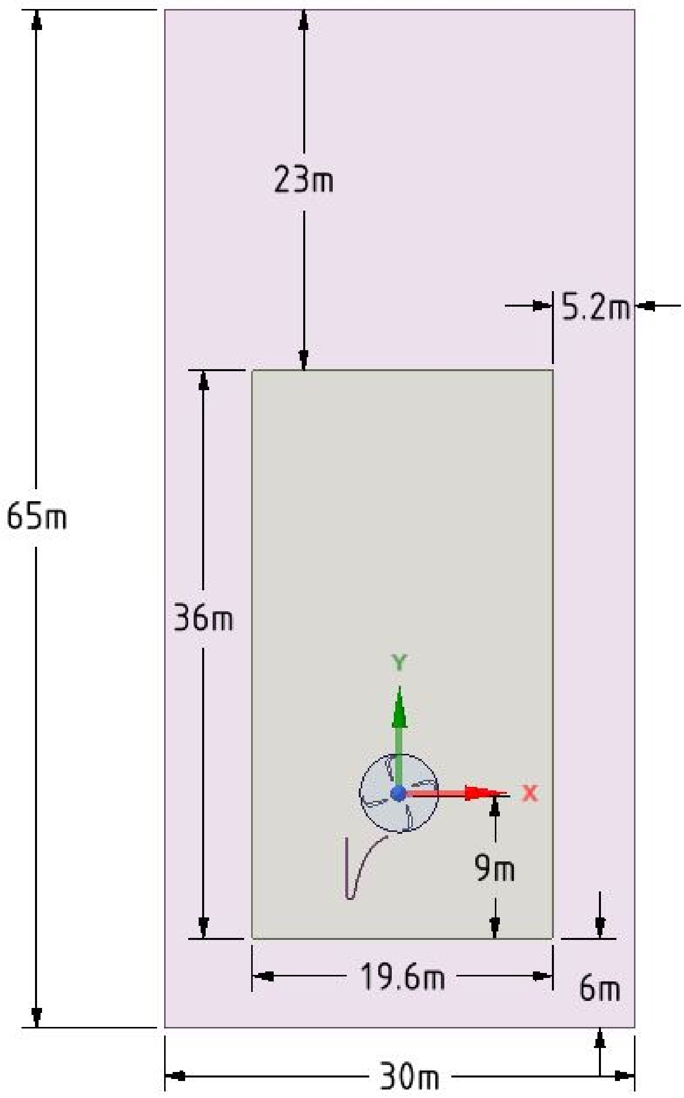


Figure 17: Illustration of the domain dimensions and turbine position

The geometry was imported into the ANSYS Fluent meshing module, where the discretization of the fluid domain into finite elements was carried out. The fluid elements were set to be triangular, and 5 inflation layers were created on the boundaries between the solid turbine and concentrator geometries and the fluid domain, to better capture boundary layer effects.

The mesh resolution was set to be finest near the turbine blades and within the rotating mesh region, with the element sizing set to 3mm directly adjacent to the blades. It then got coarser as the distance from the turbine increased, with element sizing increasing to a maximum of 8mm within the body-of-influence region. Having this region set up to primarily capture the area of the domain downstream from the turbine meant the simulation would be able to better capture flow changes in the wake region, thus making for more accurate flow calculations. Outside the body-of-influence region, the maximum element size was set to 3m, with a growth rate of 1.2 from the 8mm boundary. This aided in staying within the 512k element count limit that is imposed on the student version of ANSYS: In general, all simulations had a fluid element count of 480k-510k. An illustration of the final mesh used in a sample simulation is shown below in figures 18 and 19

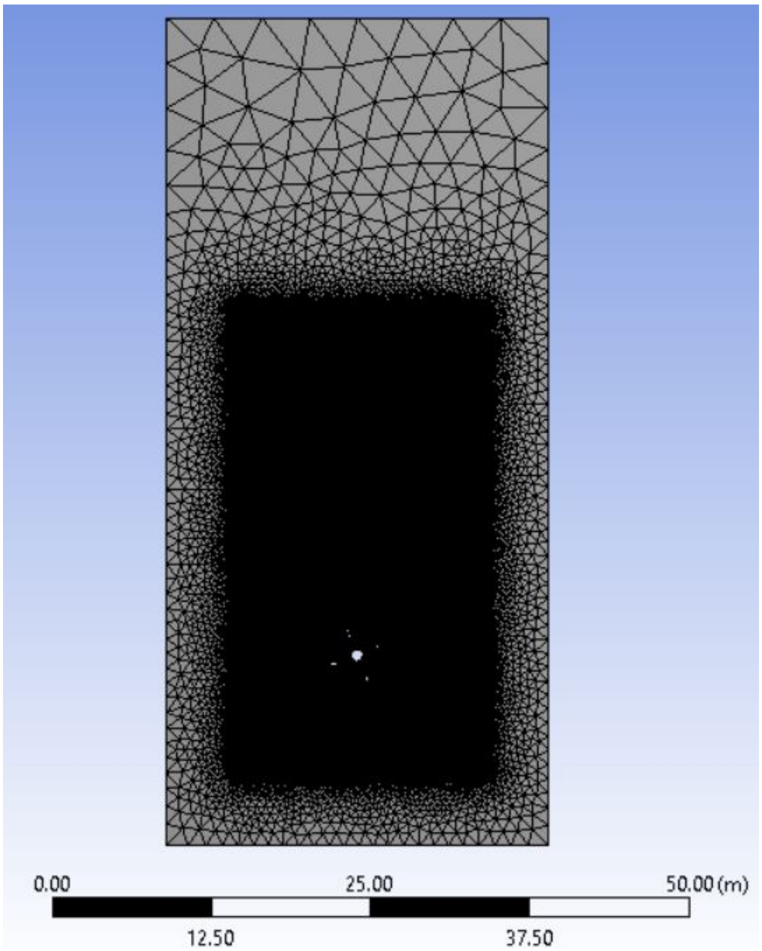


Figure 18: Illustration of the overall fluid domain meshing

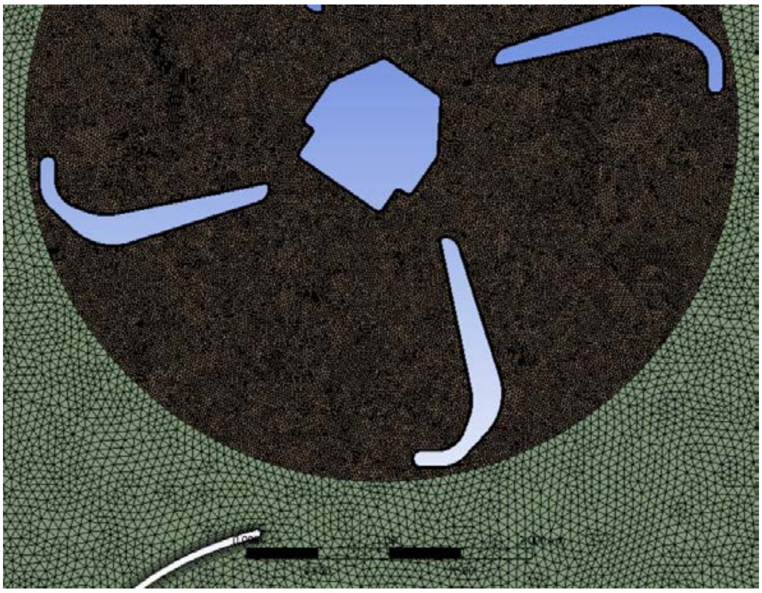


Figure 19: Illustration of the fluid domain meshing near the blades and concentrator

The completed mesh was imported into the ANSYS Fluent solver. The simulation was transient (i.e. time dependent) due to the continuously rotating nature of the turbine, and a pressure based solver was used because of the relatively low flow speeds involved. A realizable k-epsilon turbulence model was employed, as it is usually recommended for rotating bodies (Mohamed, 2010).

The sliding mesh method entails setting a constant rotational speed on the turbine blades and the circular mesh region directly surrounding them, and subsequently calculating the flow around the blades resulting from this constant rotation and the free stream air flow. Two rotation speeds were chosen to be simulated for each of the first four concentrator geometries: 4RPM and 40RPM. The 4RPM value was chosen as it was the operational rotation speed communicated by our industry partner. Additional simulations at 40RPM were done as this value is more in line with optimal operating characteristics for similar vertical-axis wind turbines. Subsequent to obtaining results comparing turbine performance at these two rotational speeds, the last two simulations were only carried out at 40RPM, as performance at this faster speed greatly surpassed that of the lower speed for all previous geometries. Further detailing on the results is presented in section 5.2.5.

With the geometry and rotation speeds set up, the boundary conditions were set on the simulation as follows:

Table 3: CFD boundary conditions

Inlet	10.7 m/s inwards flow velocity (24 mph)
Turbine and Concentrator	walls
Domain sides	symmetry
Downstream outlet	0 gauge pressure outlet

Finally, a constant time step size of 0.01s was set for the 4RPM simulations, while a time step value of 0.001s was set for the 40RPM simulations. The smaller time step choice for the faster rotation speed is due to the fact that at 40RPM, the turbine blade tips move too large of a distance over 0.01s for the simulation to maintain acceptable continuity, preventing the simulation from converging. At 4RPM, the displacement of the blade tips over 0.01 is substantially smaller, and allows for the simulation to converge. For both rotation speeds, a maximum value of 50 iterations per time step was set.

In determining the duration of the simulation, the goal was to get at least 3 full rotations of the turbine calculated (1 to initialize the flow and 2 to evaluate the torque on the turbine). For the 4RPM rotation speed, this meant a full flow time of 45s. For the 40RPM calculations, 3 full rotations would be completed in just under 5s, but the simulation was set to run for 15s to allow the flow in the turbine wake region to stabilize.

5.2.4 Analysis

For the purpose of evaluating the torque on the turbine, the simulation was set to record the torque value on the blades every time step in an external file. The torque values from the first of the three rotations were ignored as the flow was still initializing, and only the values from the last two rotations were averaged into the final torque value τ. From this, the power produced can be calculated using equation 3, where h is the turbine height and ω is the turbine rotation speed in rad/s. This power value is one parameter for indicating the performance of each concentrator:

$$P = \omega \tau h \tag{3}$$

The averaging of the torque values to calculate τ was carried out via a MatLab script that imported the raw torque data from the torque output file and calculated the mean torque over the final two rotations of the calculation.

The second parameter used to evaluate concentrator performance was C_p, which is an indicator of concentrator the turbine efficiency, as it shows the ratio of power output to the overall available power in the wind. C_p was calculated via equation 4, where P is the power output calculated from equation 3, ρ is the air density in $\frac{kg}{m^3}$, and v is the air flow velocity in $\frac{m}{s}$:

$$C_p = \frac{P}{\frac{1}{2}\rho v^3} \tag{4}$$

5.2.5 Results

Running the aforementioned analysis on the CFD results from each concentrator yielded the following results.

Table 4: Concentrators' Performance at 4RPM

Concentrator	Torque (N.m)	Power (kW)	Cp
Baseline 1	748	2.82	10.44%
Baseline 2	713	2.69	9.95%
Baseline 3	736	2.77	10.27%
Morphed 1	-	-	-
Morphed 2	-	-	-
Morphed 3	681	2.57	9.50%

Table 5: Concentrators' Performance at 40RPM

Concentrator	Torque (Nm)	Power kW	Cp
Baseline 1	183	6.90	25.54%
Baseline 2	202	7.61	28.19%
Baseline 3	208	7.84	29.03%
Morphed 1	235	8.85	32.80%
Morphed 2	204	7.69	28.47%
Morphed 3	197	7.42	27.49%

As can be seen, the baseline concentrator provided by our industry partner (baseline 1) performed best at its set operating condition of a 4RPM rotation speed and a 24 mph wind speed, producing a power output of 2.82 kW, at an efficiency of 10.44%. Our concentrators are not far behind however, with the worst performing one being the morphed 3 concentrator, producing approximately 9% less power at 2.57kW, with an efficiency value of 9.50%.

At an operating condition of 40RPM however, and maintaining the same wind speed of 24mph, all geometries perform substantially better, with all efficiencies increasing by a factor of 2.5-3. Additionally, it can be seen that the default concentrator (baseline 1) relative performance drops to where it is the worst performing concentrator. The best performing geometry at 40RPM was morphed 1, producing 8.85 kW, approximately 7% better than the default concentrator.

Two main insights can be garnered from the geometry performance results. Firstly, that increasing the rotation speed of the turbine to where its tip speed ratio is in accordance with the generally accepted optimum for this kind of turbine (0.8-1.2) has the potential to greatly improve the performance of the baseline design provided by CEP. Secondly, morphing does in fact have the potential to produce novel shapes that outperform the its baseline source geometries.

The ability to extrapolate between geometries shows particular promise: When looking at the results in table 5 it can be seen that negatively weighting a worse performing shape (baseline 1), and going beyond a 1.0 weight for a better performing shape (baseline 2) yields our best performing concentrator (morphed 1), with its performance outdoing either of the two other interpolated geometries (morphed 2 morphed 3).

5.2.6 Limitations

While the results shown above are useful for guidance on what concentrator geometry is the most effective, the procedure and results are not without limitations. The two root issues with the way the calculations were carried out were the fact that the student version of ANSYS was used and that all of the calculations were carried out on personal laptops with limited computing power.

The student version of ANSYS limits the element number in a mesh to 512k. Given the large domain size in this study, this limitation meant that the smallest elements closest to the turbine had to be set at a relatively large 3mm. A more appropriate sizing for fluid elements near the turbine blades and within the rotating region would be around 0.1mm, and such a setting would have yielded more accurate results.

The ability to work with different mesh sizing would have also enabled the carrying out of a mesh convergence study, which would have been effective in showing how reliant the calculations' results were on the mesh sizing.

Since the primary purpose of the CFD portion of the project was to evaluate the performance of different morphed geometries, it would have been valuable to carry out simulations on a larger number of shapes. Given the limited computational power at our disposal however, each simulation would take approximately 2-3 days to complete, and the short duration of the project meant we had to settle for the relatively small number of 6 geometries. Additionally, evaluating the performance of each concentrator under different turbine RPM values would have yielded insight into the relation between tip speed ratio and performance, but such tests were not possible to carry out due to the fact that higher RPMs would have required smaller time steps, which in turn would increase the simulation time well beyond the already long 2-3 days.

Finally, throughout the simulations, no specific initial conditions were set, meaning that the data from the first rotation was not representative of the actual flow around the turbine as the flow was still initializing. Being able to import the final flow conditions from previous simulations as the initial conditions for subsequent ones would have enabled us to use our limited resources more effectively.

6 Looking ahead

6.1 The bigger picture

The results of this study serve an intriguing case for the viability of morphing as a method to generate aerodynamically optimized geometries for a concentrator on a single drag based VAWT. Ultimately however, the goal of this and other renewable energy studies is to further the development of economically sustainable and environmentally friendly energy sources. It thus becomes important to consider the context in which the proposed design would operate and its relative effectiveness when compared to other established renewable energy sources like photovoltaics (PV) and traditional HAWTs.

A first step towards evaluating the contextual viability of this design would be to compare its performance and environmental impact over its life cycle to the aforementioned energy sources. It has been shown for example (Sherwani Usmani, 2010) that a typical mono-crystalline PV system operating at 11% efficiency will produce about 165g of green house gas (GHG) emissions per kWh of energy produced. This figure includes all of the processes needed for its functioning, including silicone production and PV cell manufacturing. At this production rate, an environmental payback period is estimated to be 4.47 years. That is to say, after this period is over the PV system will have produced enough clean electricity to offset the GHG emissions that went into its production. There is also potential for furthering a system's environmental case by recycling its components after its functional life, but the availability of such a process is fairly limited at the moment (Müller et al., 2005). On the other hand, a traditional 3MW HAWT has been shown to require only 12 months to produce enough energy to pay back the energy costs of producing it (Crawford, 2009). These figures are not meant to show the advantages of one energy production method over another, but rather to highlight the kinds of analysis necessary to make an informed decision on the viability of a design such as the one proposed in this study.

In carrying out a similar life cycle analysis (LCA) on our design, it would be useful to draw from HAWT LCA data, since both kinds of turbines will for example need similar raw material extraction and manufacturing processes. Given the novel geometry of the design however, further analysis on the effects of economies of scale (or lack thereof) on the LCA is needed. Better insight can also be gained from investigating how the combination of the device's small scale with advancements in new manufacturing methods like 3D printing can impact the pre-siting aspect of the LCA (Dabiri et al., 2015).

Another important consideration to be made in a potential LCA of our design would be to take into account novel siting methods and new geometry configurations when estimating its energy production. The power values shown in the results section of this study can serve as a starting point, but solely focusing on them would be too narrow of an outlook.

It has been shown for example that VAWTs have an advantage over traditional HAWTs in their ability to be densely clustered over similarly sized plots of land (Brownstein et al., 2016). In fact; doing so has the potential to allow VAWTs to produce orders of magnitude more power per unit area when compared to HAWTs: Figures indicate up to 30 W/m^2 for clustered VAWTs, as opposed to 2.5 W/m^2 for HAWTs and 20 W/m^2 for concentrating solar power (Dabiri, 2011). Investigating optimal placement of VAWTs in such an arrangement would be needed, since their relative positioning will impact the overall power production (Stevens et al., 2014).

It is worth noting that exploration of dense packing will require departing from the 2D analysis because variations in the vertical component of wind flow become increasingly important. However, studying flow of more than one turbine in 3D may get limited by computational capability and scaling would need consideration (Stevens et al., 2014).

Geometry wise, the work of this study can be expanded to optimizing not just concentrators but also blades and the overall rotor configuration. For example, hybrid rotor geometries featuring blends of darrieus and savonius type characteristics have been shown to have the potential for larger energy production over a single configuration rotor (Marinić-Kragić et al., 2018).

6.2 Project specific recommendations

As a recommendation for future teams, we suggest carrying out a more rigorous study including variable tip speeds and more degrees of freedom (baseline shapes) which could point to more optimal designs and optimal tip speed ratio to achieve best performance for the present case. Along with this, understanding wildlife and structural implications due to operation at higher speeds could also be one of the primary efforts.

In parallel to our morphing efforts, we also looked at siting a small scale prototype of the CE&P design in Marin County with some added exterior modifications to improve bird safety and aesthetics. Namely, we investigated adding camouflage to the structure to make it less visually obtrusive to residents, and anti-perching devices to make the structure less attractive to birds. The prototype siting is being carried out in close cooperation with local developer David Warner, who has expressed great enthusiasm and interest in the potential for harvesting wind energy along Marin's coastline. As part of this effort, David Warner has provided the team with wind data from studies carried out in the time period between 2004 and 2015, indicating the mean and maximum wind speeds in certain potential siting candidates in Marin. The data is shown in Appendix 8.1.

Since this siting process involves working with the County council and other stakeholders like David Warner, the process may have to be carried out next year as well. This will familiarize the team first-hand with the permitting process and enable us to incorporate community feedback in future designs, in addition to providing helpful data on community acceptance of the design and bird interactions with our modifications. Eventually, we anticipate that this siting will increase the acceptance of wind turbines in the community and perhaps ease out the permitting process for future turbines. This siting will also help demonstrate to the world that small scale wind turbines are a legitimate method of safely harvesting renewable energy. With the successful establishment of small scale wind turbines in Marin, efforts would be made to site the design along the coasts of developed and developing countries, alike.

6.3 Conclusion

This year's progress has been instrumental in understanding the underlying issues against wind power generation in Marin County. Through our human-centered approach we found that solutions such as financial incentives, have worked in other places in containing apprehensions against wind turbines, but may not necessarily apply to a wealthy community like Marin County where maintaining landscape takes precedence over any (reasonable) monetary benefit. Consequently, it became apparent that we needed a new design to advance and satisfy regulations.

We explored improvements in California Energy and Power's vertical axis wind turbine because it had features that directly addressed the concerns of Marin's community. Since it was already in production, our ideas could reach the ground much faster. We explored improvements in both, camouflaging and bird-safety measures and also improvements in performance of this turbine. Through the preliminary CFD work and literature review, we have concluded that the turbine should run at higher speeds than it is being currently operated in order to extract more power. We have seen improvements in power output of approximately 250% through the CFD simulations by operating at 40 RPM as opposed to 4 RPM. Furthermore, CFD results indicate better performance can also be achieved by modifying the design of the concentrator.

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8 Appendix

8.1 Marin county wind data

Wind data for Marin county (San Rafael Hills) – mean speed

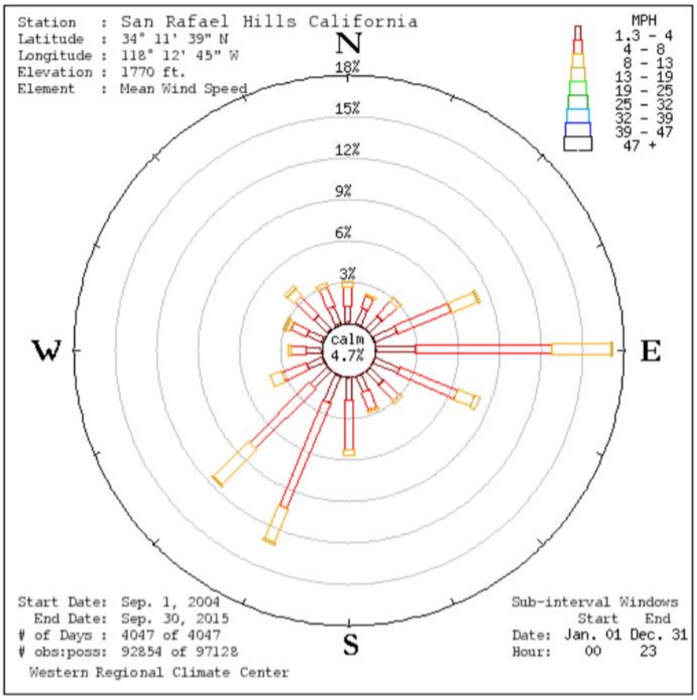

Figure 20: Mean wind speeds in San Rafael Hills

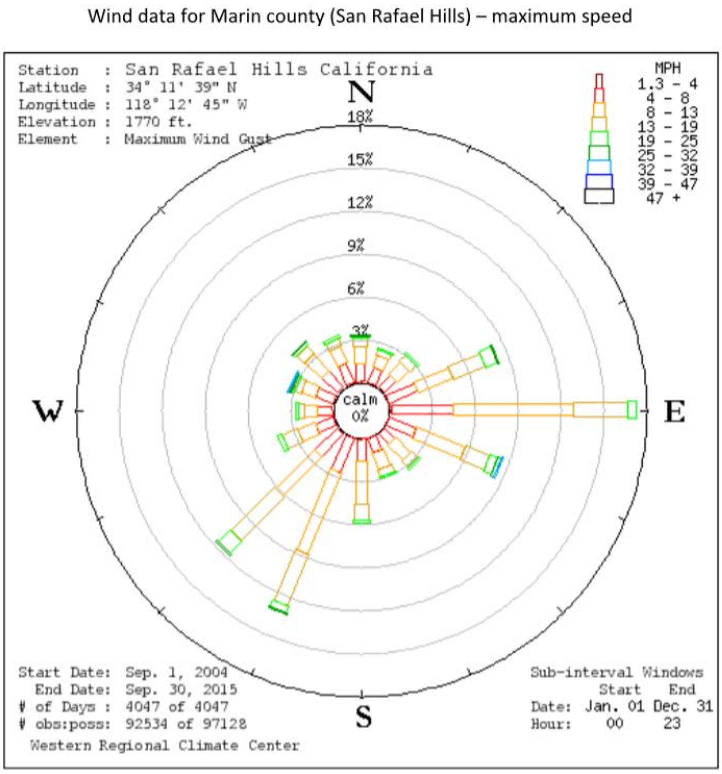

Figure 21: Maximum wind speeds in San Rafael Hills

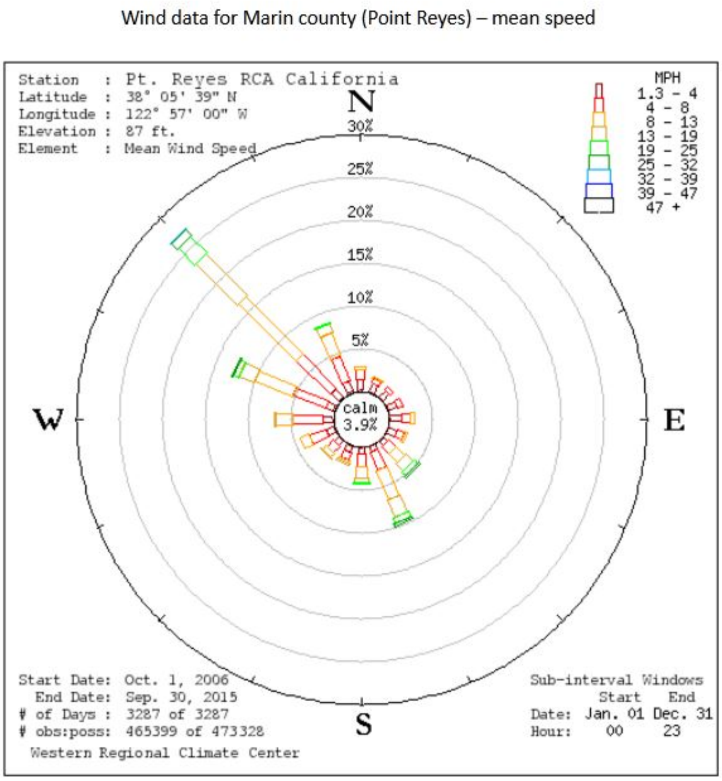

Figure 22: Mean wind speeds in Point Reyes

8.2 Summary of interviews and literature review

The following tables summarize the major insights gained from the interviews and literature review conducted throughout the 2017-2018 academic year. For interviews, the month and year that the interview was conducted. as well as the interviewee's full name are listed. For literature reviewed, only the year the document was published and the author's last name are listed. The insights are also categorized by the topics they pertain to: birds, bats, or Marin County.

Interview/Publish Date	Interviewee/Author Name	Topic	Summary of Insights Gained
October, 2017	Barbara Salzman	Birds	-Wind turbines seem quite dangerous when comparing a field full of wind turbines to a field without wind turbines. -Siting solar projects in developed areas is less problematic than siting projects in undeveloped areas, which are likely habitats for wildlife. The nature of wind turbines causes birds to change their behavior, which is a problem.
September, 2017	Judd Howell	Birds	-Painting one of 3 blades of HAWT uniform black reduces motion smear and allows birds to perceive the turbines $\sim$50% sooner. -Birds are looking to fly through gaps. If a bird sees a regular pattern that looks too small for them to fly through, they won't try. This is why windows are such a problem for birds. -Birds of prey can be struck by turbine blades when they are hunting. They are focused on what's happening on the ground, rather than what's in the sky around them. -Bald and Golden Eagle Protection Act is major legal leverage to shut down wind projects. -Most bird strikes occur as the bird is taking off and landing near turbines. -Comparing a few large turbines vs a large number of small turbines (but same total amount of swept rotor area), there was no difference in number of fatalities. -Small VAWTs have had similar mortality rates, due to guy wires. -Lattice poles on turbines are essentially perches for birds, which is why turbines have gone towards solid towers.
1995	Nelson & Curry	Birds	-High incidence of raptor mortality generally is attributed to perching and foraging behavior, and the presence of small mammals in grassland sites.
1997	Howell	Birds	-There is no support to say that larger rotor swept area of turbines contributes proportionally to avian mortality (larger area does not necessarily lead to more mortalities). It has been found that avian fatalities involving turbines may be simply linked to the number of turbines, rather than their sizes.
December, 2017	Judd Howell	Birds	-Incorporating mesh/net on concentrator to prevent birds from nesting in cavities. -Anti-perching coils can be placed on flat surfaces that may be suitable for perching. -Camouflaging the turbine imitates dense cover, which birds don't necessarily like to fly through. -Closer spacing of the turbines will deter birds from foraging among them.
January, 2018	Chris Pattison	Birds	-Lidar is effective at detecting birds and curtailing wind turbine operation. -Want to avoid camouflaging the turbines as trees, as that will make the turbine attractive to nesting. -Some successful wind projects in Kansas and Nebraska got wildlife group members on the board, allowing them to select the types of bird protection measures taken.
February, 2018	Matt Saldana	Birds	-Need to present the financial argument to have the turbine projects proceed. -Money earned by turbines can be put back into schools, police, and fire departments.
February, 2018	Stu Webster	Birds	-Eagles and bats are the major concern, not songbirds or migrating birds. -AWWI has a website that contains a library of research organized by region, year, and subject.

Interview/Publish Date	Interviewee/Author Name	Topic	Summary of Insights Gained
September, 2017	Judd Howell	Bats	-Raising cut-in speed of turbines can greatly reduce bat fatalities. -Barotrauma could be a concern when dealing with bats around large turbines.
February, 2018	Cris Hein	Bats	-Bats are very lightweight, so high wind speeds deter them from flying. -Anything closer to the ground is likely to interact with more bats, but not necessarily increase fatalities. -Most fatalities late summer and early autumn, which is when these species mate. Turbines could be a meeting area.
March, 2018	TETHYS Webinar	Bats	-Detection of surface-based prey using echolocation is facilitated by smooth backgrounds such as water surfaces and smooth leaves. -Bat activity was significantly lower at texture-treated surfaces compared to smooth vertical surfaces in a bat flight facility. -Bats approach turbines from leeward side (fly upwind to the turbine). -Ultrasonic bat deterrents have not been successful at significantly decreasing bat fatalities. -Ultrasound has deterred some types of bats, while attracting others. -The researchers have found more success with 'clicking' or pulsing the ultrasound signals.
2014	Cryan	Bats	-Bats avoid blades that spin quickly, because the blades cause chaotic downwind turbulence that are dissimilar to the oscillating vortices shed by tall trees.
September, 2017	David Warner	Marin	-MCE was going to buy all the power generated by the Marin Agricultural Wind Co-op. -Wind assets were analyzed on private land in Marin and 6 commercial grade locations were found (30-40 MW).
2010	WECS Document	Marin	-Water pumping turbines have height relaxation up to 100 feet from ground. -Grid tied turbines are restricted to 40 feet.
September, 2017	Leslie Alden	Marin	-WECS document was an effort to get turbines into Marin. Audubon Society was major opponent of this effort. -Northwest corner of Marin would be best for turbines. -Marin County gets ~70% of its renewable energy from the wind farms in Solano, CA.
October, 2017	Tom Williard	Marin	-McEvoy Ranch was first and last utility scale turbine in Marin, and it took 4 years to permit. -Avian and visual studies required for WECS in Marin make the turbines cost prohibitive. -Conducted wind studies across Marin and the resource isn't great. Possibly along the ridgelines, but the WECS regulations prohibit building up there.You need a lot of wind to make turbines make sense. When you have that much wind, small turbines fall apart quickly, when turbines need a lifespan of 20-30 years. -When selecting a site, it is important to consider the interconnection with PG&E, which the turbine owner will have to pay for. Unless working on a microgrid, there needs to be a connection to the transmission lines.
2018	MCE 2018 Open Season	Marin	-MCE offers a competitive, objectively administered opportunity for qualified suppliers of various energy products to fulfill certain portions of MCE's future resource requirements. -In the case that an economically viable project can be established, MCE is willing to purchase some of the power produced.