Evaluating the effectiveness of a biologically inspired energy-harvesting concept

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An experimental and numerical study was performed to evaluate the effectiveness of a biologically inspired energy-harvesting concept. A scale model, based on the undulating fins of cuttlefish, was tested in the exhaust region of the Clarkson University wind tunnel from speeds of 3.5 to 8.8 m/s. The resulting power and efficiency curves indicate this design may not be a viable alternative to conventional rotary turbines. The test data could also be used to create a computational model to describe the motion and power output of the generator and this model will be used to optimize the design.

I. Nomenclature

V = velocity of oncoming wind (m/s)
A = cross-sectional area (m)
ω = angular velocity (rad/s)
τ = Torque (Nm)
P = power generated (watts)
ρ = density of air (kg/m^3)
RH = relative humidity (%)
T = temperature (C)
v = voltage (from torque sensor) (volts)

I. Introduction

With climate change becoming an evermore-looming threat to global quality of life, it is becoming more critical that alternatives to fossil fuel, based power production, are found, implemented, and utilized. Forms of renewable energy like wind turbines and solar panels will have to be more heavily utilized, and making them more affordable and accessible is critical to these types of alternative energy being widely adopted over fossil fuels.

This paper details the first experimental testing of a new sustainable energy-harvesting concept inspired by the fins of cuttlefish, a marine invertebrate related to squid and octopus. A proof of concept model was built, without optimization, data was taken of its performance in the Clarkson University Wind Tunnel. The following paper will detail the concept itself, the experimental procedure and set up used in testing, and an analysis of the test results.

II. Background

The present paper details the computational and experimental results of a biologically inspired energy harvesting concept (BIEHC) with the aim of determining whether this concept warranted further research and development Inspired by the undulating fins of cuttlefish, the generator was built and tested in order to determine the design's efficiency under varying air flow conditions. However, this design may also prove to be effective in harvesting the energy in other flowing mediums such as water in rivers and tidal flow, but this is yet to be tested.

A proof-of-concept model was made of the generator, however, this design was too large to fit in a traditional wind tunnel testing space, and therefore the area behind the wind tunnel's exhaust fan was used as the testing space. Wind velocity data was taken from the wind tunnel in order to calibrate and understand the testing space, and a stable analysis point was found. Data acquisition code for the virtual instrument program LabView was written in order to take wind velocity (V), Angular Velocity (ω), Torque (τ), and Power data (P). Where power is equivalent to:

$$P = \tau\omega \tag{1}$$

This data was then used to create power and efficiency curves for the generator and was compared to a theoretical limit of efficiency - Betz's Limit. Betz's Limit or Betz's Law states that the theoretical maximum efficiency a wind turbine can have is 0.593. Meaning that only 59.3% of the kinetic energy in the wind can be used to generate power [1]. Betz's law can be expressed by the coefficient of power (Cp) where Cp equals:

$$C_p = \frac{P_{turbine}}{P_{wind}} \tag{2}$$

where P_{wind} is expressed as:

$$P_{wind} = \frac{1}{2}\rho A V^3 \tag{3}$$

such that C_p equals:

$$C_p = \frac{P_{turbine}}{\frac{1}{2}\rho A V^3} \tag{4}$$

where P is the power output of the turbine, ρ is the density of the air, A is the cross-sectional area of the turbine and V is the velocity of the wind.

Larger turbines come closer to reaching Betz's limit, achieving power coefficients of 0.45-0.5, while smaller turbines perform at lower efficiencies of 10-35% [2][3].

From a commercial view, however, pure efficiency is less important than cost per kilowatt hour. Meaning that even if a larger turbine is more mechanically efficient but very costly, it is a less viable product. Currently, even small residentially marketed 10kw turbines range from $40,000 to $60,000 [4] with more powerful turbines in higher ranges. These costs put residential wind turbines out of the financial reach of many consumers, meaning that the spread of renewable energy is slow. However, new designs in wind technology may help lower the cost and make sustainable energy solutions more accessible to the wider public.

The emerging field of biomimicry, the process by which nature is used as inspiration for design and engineering by shed light on new wind turbine designs. Taking inspiration from the natural world to solve design and engineering problems is not new, but the idea of applying nature-inspired designs to wind energy harvesting devices is more recent. The ridges on humpback whale flippers have been found to delay stall around the fin, allowing for a more hydrodynamic design – a feature that translates well into traditional rotary turbine blades [5]

The present paper focuses on the design elements of oceanic invertebrates, mainly cuttlefish. Cuttlefish, like octopus and squid, propel themselves through a process of jet propulsion by ejecting water through a funnel-like organ or siphon. Cuttlefish, as illustrated in Figure 1, also propel themselves using a thin fin of muscle along their mantle.

Fig. 1 Cuttlefish Fin

The most important innovation in the BIEHC is that it is "towerless" meaning it could be installed and used in many more applications than traditional turbines. The roofs of buildings, homes, medians of highways, or even flowing water could be used to generate power. The towerless design could also potentially be a more cost-effective alternative to traditional rotary turbines. The present paper details the experimentation of this design to gauge its viability as an addition to alternative energy options, and it's efficiency and output.

III. Experimental Procedure:

The purpose of testing the BIEHC was to determine its viability as a proof of concept model for this type of energy harvesting device. A test apparatus was constructed, which is detailed below, along with the other testing equipment and procedure that was used.

A. Test Device:

As can be seen in Figure 2 a test apparatus was constructed. The device features two main components: the wind capturing sail and its supports, and the internal mechanical mechanism. The sail was made out of a durable non-rip nylon, cut and sewn into a 30.5in by 15in rectangle with slots sewn into so it could be pulled over the supporting ribs. The device features six vertical ribs, all secured on one end to a single axis. They are free to pivot about the axis but the axis itself is immobile. The vertical ribs are spaced 6in, apart, and 5.07in, up the ribs a pivoting coupler was attached; this coupler was then attached to the crankshaft that translates the oscillatory motion of the ribs into rotational motion. Each crank arm is displaced 60º from the previous position, so that as the ribs oscillate, coupled together by the sail, they cause the crankshaft to rotate. The radius of the crankshaft, from the center of rotation to the connection point with the coupler is 1.5in. The device as a whole is 30.5in long, and 36.5 in tall.

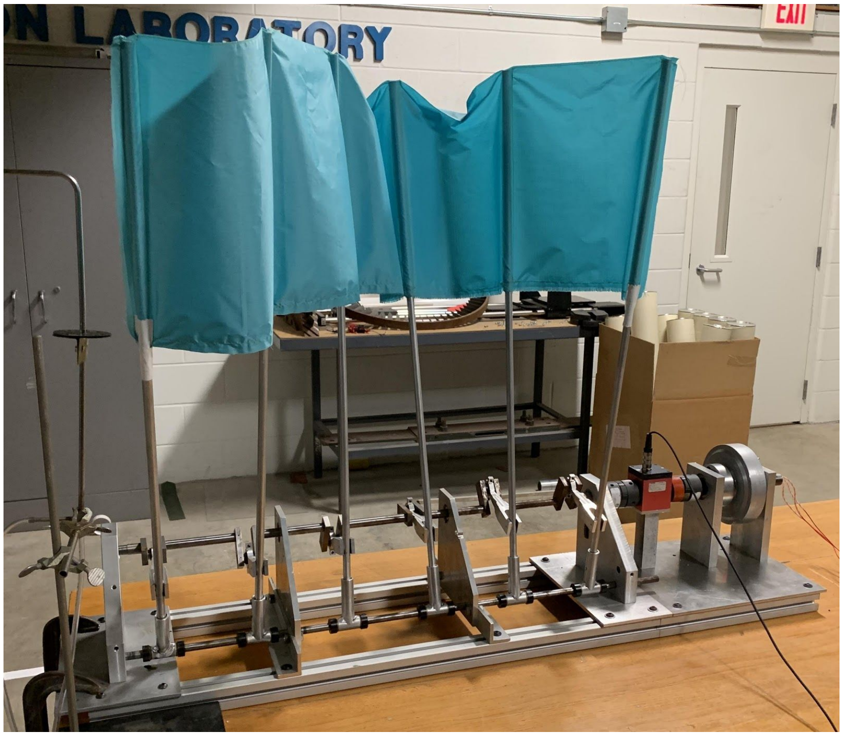

Fig. 2 Energy-Harvesting Concept Proof of Concept Model

B. Preliminary Experimental Procedure:

In order to run tests on the energy harvesting concept, a variety of equipment was used to measure its outputs. The measurements included output torque, upstream wind velocity, the angular velocity of the device, the watts produced, the voltage produced by the torque sensor, along with more constant measurements like the ambient temperature, the relative humidity, and the air pressure. The last three were used to calculate the air density at the time experimentation took place.

The tests were performed in the Clarkson University Wind Tunnel. The tunnel has the capability of producing wind speeds of 60 m/s, but only wind speeds between 3-10 m/s were used for this experiment. The height of the device meant that it could not be placed inside the testing chamber of the Clarkson University wind tunnel and therefore was set up in the wind tunnel exhaust stream.

In this new testing area, the relationship between wind tunnel settings (in RPMs of the motor) and the wind velocity of the air out of the exhaust was not known. A grid was made extending across the width of the wind tunnel exhaust – approximately 2 meters across – and extending 5m outward. The grid was marked at meter increments outward and 0.25m increments across the exhaust with the midline of the exhaust being the zero point for the grid.

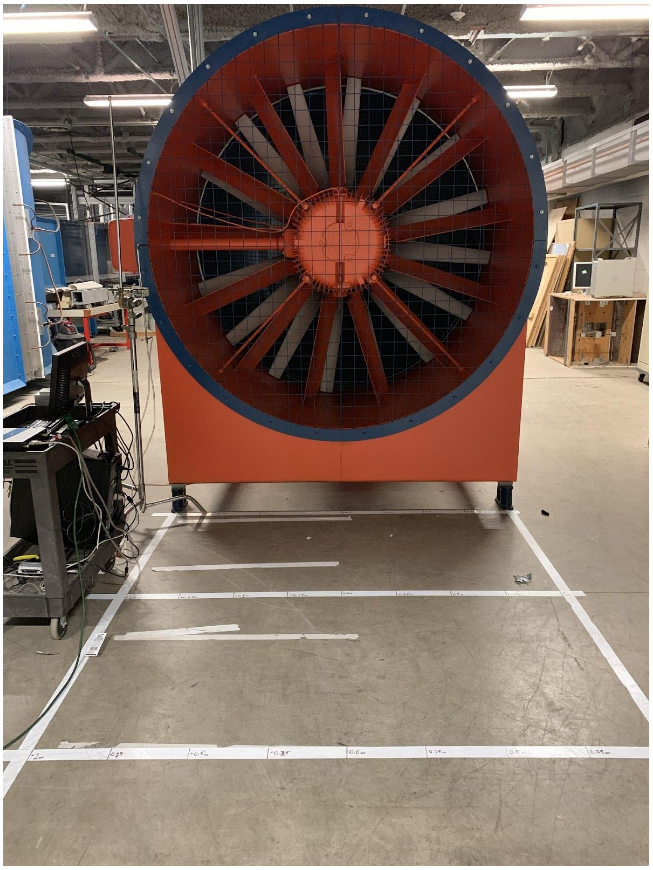

Fig. 3 Wind Tunnel Exhaust and Grid

To create a plot of the wind speeds corresponding with different positions across the exhaust, and at different distances away, a pitot static tube was mounted on a movable stand so that the static and dynamic pressure of the air could be measured and the up-stream wind velocity could be calculated. The whole set up consisted of a National Instruments USB-6211 multifunction DAQ, Omega HX93B Series Relative Humidity and Temperature Transmitter**.** The pitot-static tube was connected to a GPG 2500 series mensor gauge, which read out the static and dynamic pressures in Pascals. The GPG 2500 series mensor gauge data was fed into Labview was used to calculate the upstream wind velocity by taking in the mensor gauge data and temperature and relative humidity data from Omega HX93B Series Relative Humidity and Temperature Transmitter which was wired into a NI USB 6211 DAQ device. This device transferred the sensor data and relayed it to the Labview Program. Using this setup it was possible to set the pitot static tube at each mark on the grid, run the Labview code, and take wind velocity data for each grid point at different wind tunnel settings. First, data was taken at intervals of 0m to 5m away, and from left-hand edge of the exhaust fan to the other in 0.25m increments only with the tunnel set to 250 RPM. This was to gauge where the wind field across the exhaust became relatively uniform.

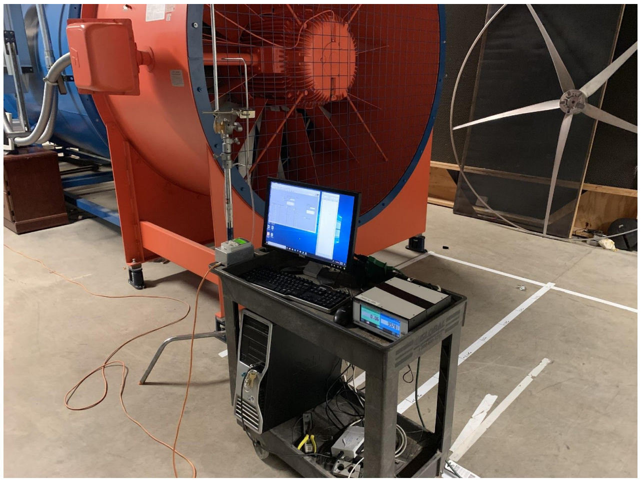

Fig. 4 Wind Tunnel Exhaust Setup

This process was repeated for wind tunnel settings of 250 RPM to 550 RPM. The result of this preliminary work was that a point of wind velocity uniformity was found. Meaning that from one edge of the exhaust fan to the other, the wind speed did not very much. This point was where the test apparatus and equipment would be set up. The point of uniformity was determined to be 4 meters from the face of the exhaust fan, and 0.5m from the midline of the exhaust.

Figure 6 displays the wind velocity measured across the exhaust at different distances away with the wind tunnel set to run at 250RPM. The wind tunnel exhaust, as seen in Figures 3 and 4, is a large fan. It can be expected that the center of the fan leaves a wake in the air as it is running, but that at a certain point away from the face of the exhaust the air flow across the width of the exhaust becomes relatively uniform. The tests showed that after 3 m away the wind speeds across the exhaust fan leveled out as expected.

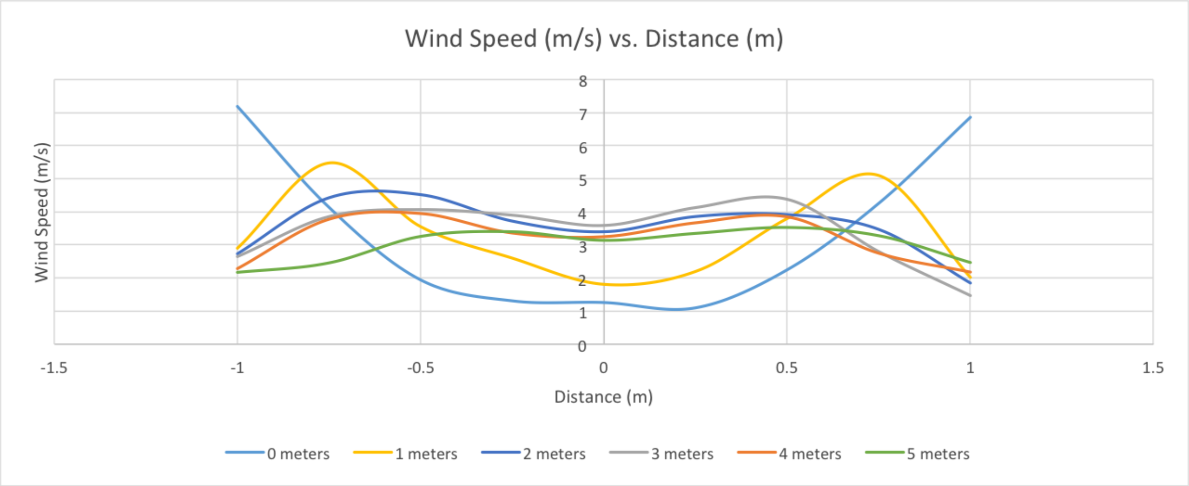

Fig. 6 Wind Speed vs. Distance Away from Exhaust at 250 RPM Fan Speed

Figure 7 shows the recorded wind speeds at the 4m mark along the exhaust face at various tunnel settings. This test was done in order to see if different wind speeds drastically changed the shape of the curve and if it higher wind speeds reintroduced the wake effect from the center of the exhaust fan. As can be seen in Figure 7 this did not happen, and the 4m mark at 0.5m from the left-hand edge of exhaust fan was chosen as the testing point for the BIEHC

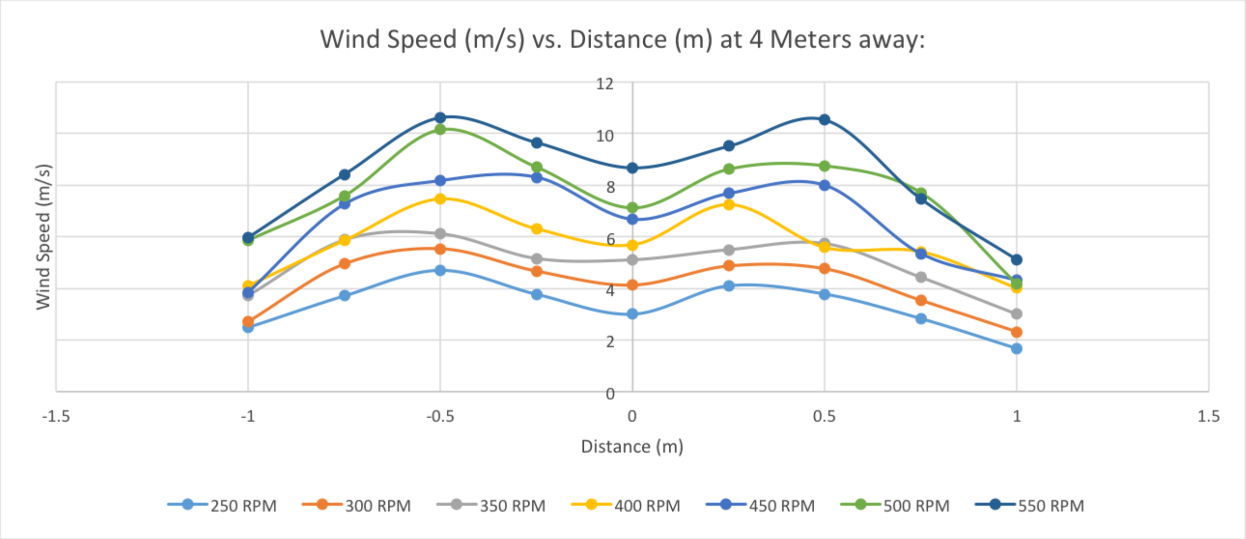

Fig. 7 Wind Speed vs. Distance Across Exhaust at 4 Meters

C. Experimental Set up:

Once the testing point was found, the experimental set up for the energy-harvesting concept could be put in place. As seen in Figure 8, the set up comprised: the energy harvesting concept, a TRS605 Futek Torque Sensor, a 50W 250 RPM Permanent Magnet Generator, a BK Precision 8522 2400W Programmable Electric Load Bank a National Instruments USB-6211 multifunction DAQ, a dual voltage DC power supply**,** Omega HX93B Series Relative Humidity and Temperature Transmitter**,** and GPG 2500 series mensor gauge.

Fig. 8 Experimental Set up (1)

The torque sensor utilizes a 12 pin connector for different measurements types, however for the purposes of this experiment, only six were used. According to the manufacturer the sensor requires an excitation voltage of 11-26 VDC for torque measurements and an excitation voltage of 5VDC for rpm measurements. A dual voltage DC power supply was used to supply the excitation voltage to the torque sensor. The red wire was connected to the +15V terminal, orange wire to the +5V terminal, and the black wire to the GND terminal of the DC power supply. The green and white torque signal carrying wires were then connected to the NI USB-2611’ s +A/2 and –A/2 analog inputs respectively. The blue angle signal wire was connected to the first digital I/O terminal, while the black ground wire was connected to the fifth. A close up of this setup can be seen in Figure 9.

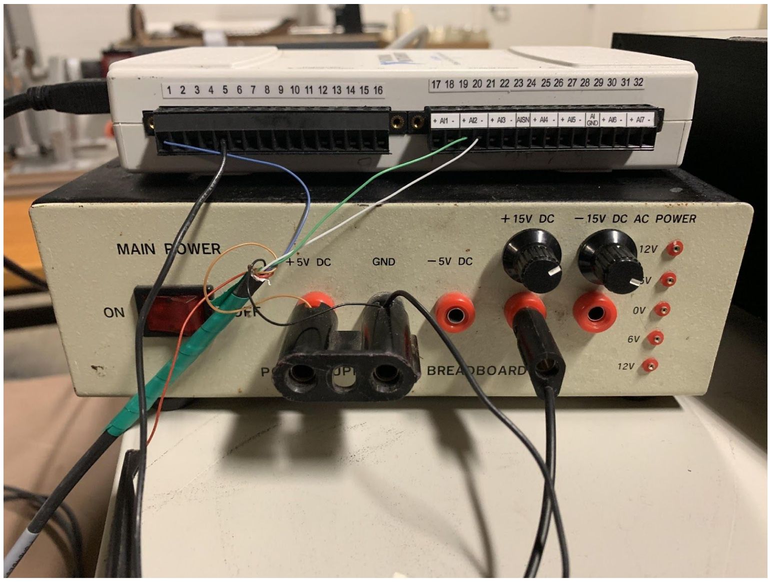

Fig. 9 Experimental Set up (2) – Power Supply and NI USB 3622

An Omega HX93B Series Relative Humidity and Temperature Transmitter was also connected to the NI USB-2611, however the measurements and data being read off the device were incorrect, and the temperature of the testing space from a thermometer in the room, and the relative humidity of the area at that day and time of testing were determined to be adequate approximations for the purposes of this test.

A pitot static tube was mounted alongside the device in order to measure the wind velocity and a Mensor Digital Pressure Gauge 2500 was used to measure the static and dynamic pressure. This data was used to calculate the wind velocity during testing to see how it compared with the original wind velocity mapping data. A BK Precision 8522 2400W Programmable Electric Load Bank was used to apply load to the generator. A three-phase transducer was used to connect the three-phase generator to the two terminated load bank.

D. Experimental Procedure:

With all the equipment in place, the energy-harvesting concept was mounted and placed 4 meters away from the exhaust face, and 0.5 meters from the left-hand edge of the exhaust fan. The wind tunnel was run at speeds of 250, 300, 350, 400, 450, and 500 RPM which corresponded with wind speeds of 4.7, 5.54, 6.12, 7.47, 8.18, and 10.15 m/s. In the first, control trial the machine was set to run at each wind speed and the resistance applied to the generator by the load bank was increased at set increments of 4,000, 2,000, 1,000, 500, 250, 100, 50, 25, 10, 5, and 0.1 ohms in order to observe at what resistances the device produced maximum power. Once that maximum point was found for each wind speed, data was recorded for a total of five minutes at a sample rate of 10 samples per second. This sample rate and time of recording was chosen for this first control trial to ensure that the proper resistance and maximum power point was found.

For the next three trials the sample rate was changed, and the device was only run at the critical resistance found in the control trial. At each wind speed the load bank was set to the critical resistance and data was taken for a total of two minutes at a rate of 1,000 samples at 200 samples a second, producing a data point every 5 seconds. This procedure was repeated for a total of three critical resistance trials.

IV. Results and Analysis

The data from the wind tunnel tests is shown in Figure 10. As can be seen, the BIEHC's power curve falls far below that of Betz's projected limit. This difference is to be expected, as Betz's limit is theoretically unattainable.

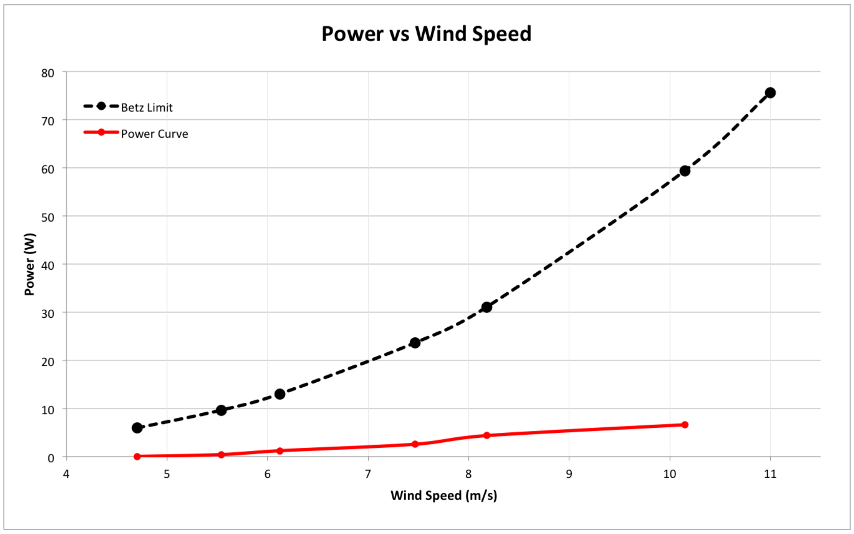

Fig 10. Energy Harvesting Concept Power vs. Wind Speed Data

Figure 11 shows the corresponding coefficient of power generated by the BIEHC. As can be seen, the BIEHC maximum coefficient of power was 0.082, meaning that it was able to extract 8.8% of the energy from the oncoming wind. This is far lower than the theoretical Betz coefficient of power, 59.3%. The Coefficient of power was calculated using Eq. (4).

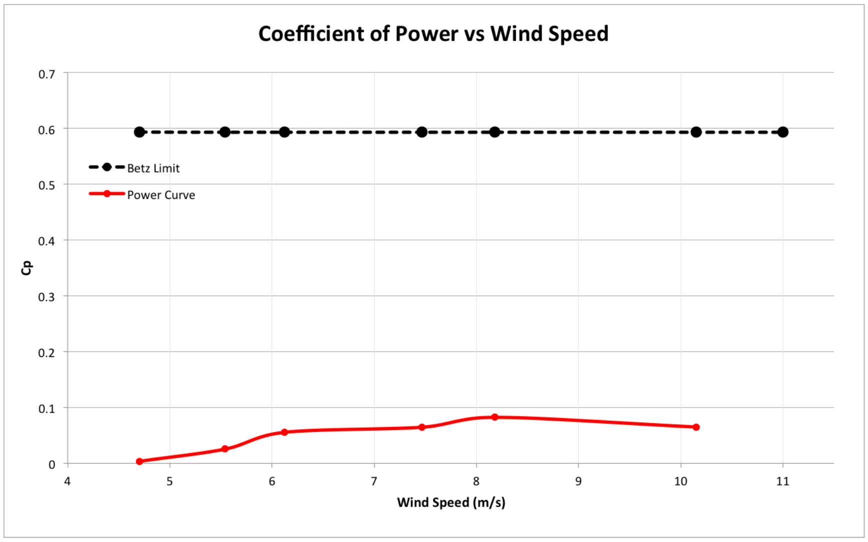

Fig 11. Energy Harvesting Concept Power Coefficient vs. Wind Speed Data

From this experiment, it can be concluded that the Proof-of-Concept model for the BIEHC concept does have an energy-harvesting capacity and will require research and optimization in order to understand it's merits compared with those of traditional wind turbines.From the results, it can be seen that the Cp of the device was at a maximum of 0.08, far below the Cp value of Betz's Limit (0.593), and far below that of a comparable traditional turbine. However, this is only a proof of concept model and has gone through no optimization or improvements. It is possible that another configuration of a similar device might yield better results and understanding.

However, it is also very important to note that the cost per kilowatt hour is more commercially important than efficiency alone. Cost per kilowatt-hour can be calculated by [6]:

$$cost/kwh = \frac{kW \times 24hr \times 30days \times lifespan\ in\ months \times C_p}{cost} \tag{5}$$

In the case of the BIEHC, the lifespan is unknown, however, for the sake of this calculation, the estimate of 10 years will be used. The cost of the machine so far has been $5000. If this calculation in Eq. (5) is done the final cost/kWh is $0.0100, or a cent. Despite this being an optimistic estimate, this is a very interesting data point, even though the BIEHC performs at very low efficiency, the cost per kilowatt hour is also very low. Meaning that despite its low output it may still be a viable addition to current wind turbines due to its low cost.

V. Conclusion & Future Steps

It was observed that the proof of concept model of the BIEHC performs at a far lower efficiency than Betz's Limit and traditional rotary turbines, but its optimization needs further research. However, because of it's very low cost/kWh it may still have room to be a viable, low-cost addition to current traditional turbines.

There are also aspects of the design and experimentation that can be looked into in the future. The results from this test could be used to create a computational model to describe the motion and power output of the generator. This computational model can later be used in aiding optimization of the design. The design could also be tested under different conditions, in various flowing mediums besides wind, or the mechanics of the design could be altered to improve it's output. The findings offer an insight into how the current design can be optimized to improve it's output and efficiency, and it's potential for commercial use.

VI. Acknowledgments

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