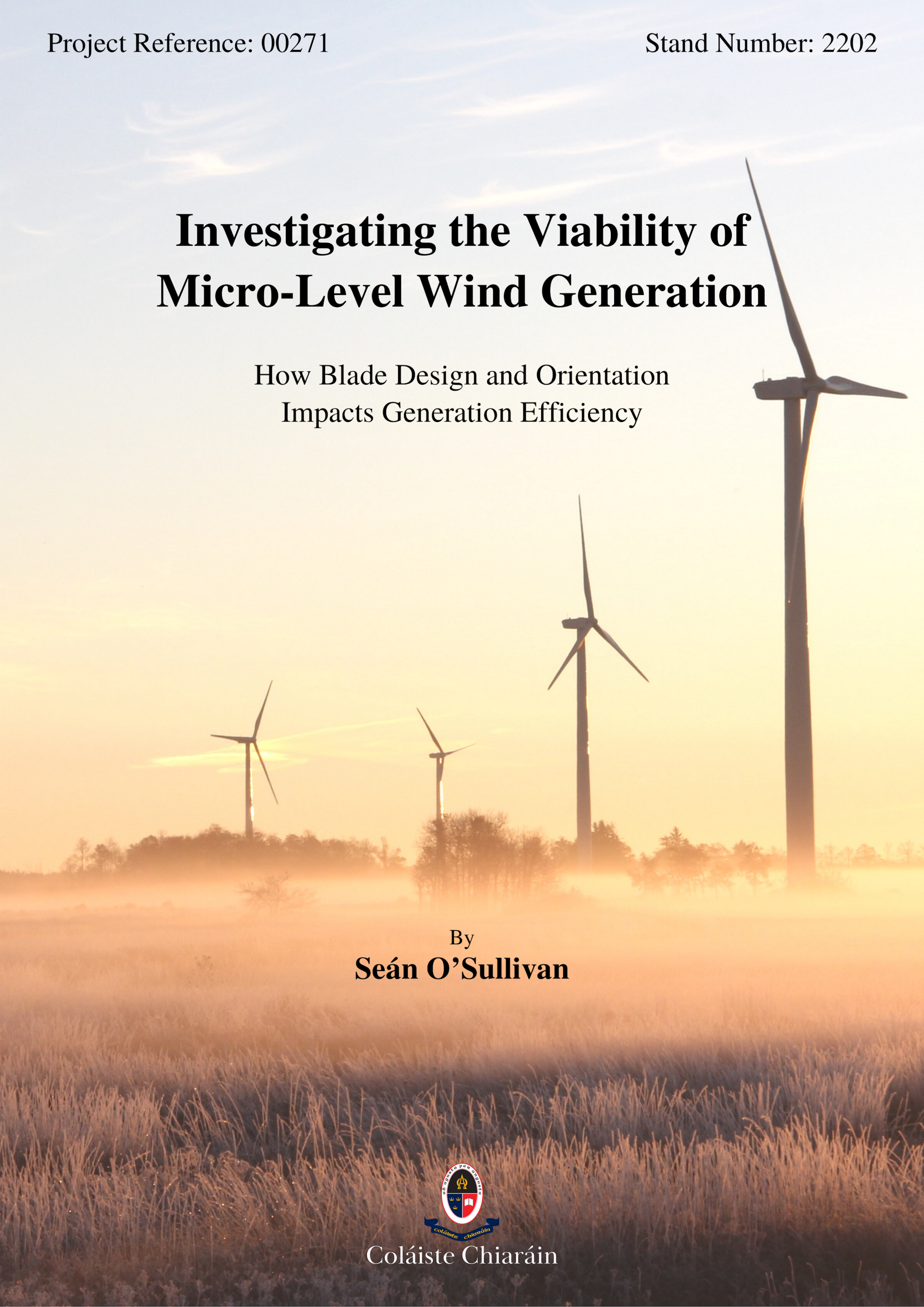
Project Reference: 00271 Stand Number: 2202



Investigating the Viability of Micro-Level Wind Generation

How Blade Design and Orientation
Impacts Generation Efficiency

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Summary/Abstract

In my project, I aimed to investigate the viability of Micro-level wind generation and conduct an experimental investigation into how turbine rotor design and orientation affect generation in light of the current cost of living and energy crisis.

I began by surveying parents, staff and students at my school to investigate their opinions on climate change, the cost of the electricity crisis and micro-level wind generation in particular. From the survey, the main findings were that people are concerned about climate change and the rising cost of electricity.

A significant point of concern as to why respondents said that they would not consider investing in micro-level wind energy generation was the initial cost. A large percentage of respondents said that they would consider installing a wind turbine in their homes, with this number rising if a government grant was made available.

I researched, designed, and 3D Printed 16 wind turbine rotors, 4 Motor Housing Assemblies, and 2 Arduino Data Capture Boards, carrying out a total of seven experiments. Two of these tests were in the wind tunnel, in laminar airflow conditions at the University of Limerick and 5 in outdoor, turbulent airflow conditions; I collected the energy generation data from each experiment using an Arduino Uno, converted to mV using an ADC (Analog to Digital Converter), and then saved to file. I recorded this data from each rotor with the corresponding wind speeds in each experiment for accurate analysis. This data collection allowed me to compare the performances of all the testing wind turbines in all conditions, ultimately indicating which rotor design could generate the highest energy output (in mV). Then I compared this performance to the most commonly used wind turbine rotor design, calculating an overall performance increase.

Finally, I tested a commercially available 500W wind turbine, estimated how much it would generate annually, and applied my findings from the experimental investigations to understand how these designs could affect total efficiency and translate this to money saved.

This study used a mixed methods approach, firstly conducting a survey (with a total population of 169 respondents) to understand public opinion towards the topic at hand, next I conducted an experimental investigation into the effectiveness of each wind turbine rotor design. I then applied my findings to the potential energy generation of a 500w commercially available wind turbine and translated my findings into money saved. Lastly, I drew and found direct comparisons between the results of other studies investigating how blade design and orientation affect generation and mine.

Key Findings

- The best turbine rotor category was the Scimitar "Convex Curved" Shape HAWT. On average, generating 11.04% more energy than the Traditional Straight Bladed HAWT outdoors in turbulent airflow and 27.34% better in the laminar wind flow tests, with an **average overall performance improvement of ~19%**. The best design from this category generated 32% more than the "Small" Straight Bladed HAWT rotor, 450% better than the "Small" Helical VAWT rotor and 726% better than the "6 Bladed" Helicoid VAWT rotor.
- At an annual average wind speed of 6 m/s, a 500w wind turbine would generate approximately 1138.8kW/h in one year.
- Replacing the 500w Turbine's Traditional Blades with Scimitar "Convex Curved" Blades and applying the average potential performance improvement of ~ 19%, could generate 1355.172 kW/h annually. This finding could reduce payback time by approximately 19%. A possible up to ~19% reduction in rotor size while maintaining the same electricity production. Or the possibility of generating higher levels of electricity in regions with lower average wind speeds.
- I calculated that the 500w Wind Turbine could produce ~€493 worth of electricity annually. Applying this higher-performing HAWT rotor variation, you could see a potential increase of approximately €93 up to €586 saved each year.
- Pre-current electricity pricing, the base model above would have generated just €228 worth of electricity (at a unit rate of around 20 c / kW/h, April 2020).
- This study confirms that at a micro-scale, HAWTs consistently outperform VAWTs. On average, the HAWTs performed 7.7 times better than the VAWTs.
- HAWT performance saw a 34% average recorded mV generation improvement in the wind tunnel, and laminar airflow conditions than outdoors.
- VAWT performance saw an 80% average recorded mV generation in the outdoor, turbulent airflow conditions compared to in the wind tunnel.
- I found that scaling the turbine designs by 1.5 led to a 27.1% decrease in peak HAWT performance and a 47.8% decrease in peak VAWT performance.
- I found that doubling the number of blades on the turbine led to a 14.9% decrease in HAWT performance and a 38.5% decrease in VAWT performance. Although I wasn't measuring torque, I observed a much higher force behind this and the "Large" design.

Comparing my findings and observations to other studies' conclusions.

I analysed my main findings and researched similar studies online and found that my results were consistent with other studies.

- Peak HAWT generation in my project was at 4.34V, and VAWT peak generation was at 0.76V. In a similar study, using larger motors I found their HAWT peak generation was at 8.99V, and VAWT peak generation was at 1.4V. This is almost exactly double my experimental results, showing that the ratio between peak voltage generation from my HAWTs and VAWTs is consistent with the commercial models.

- My testing showed HAWTs generate significantly higher RPM but low torque. The VAWTs ran at a significantly lower RPM, but higher torque, and more consistent rotation speed regardless of wind speed. This is consistent with studies involving commercial models.

Background Research

In my initial background research for this project, I researched the cost of electricity production and how much electricity prices increased in light of the current cost of living crisis. I wanted to learn about the electricity consumption needs of the average Irish household and investigate the possibility of renewable energy-based solutions for offsetting these observed electricity cost hikes in this current cost of living crisis. After learning about Ireland's potential wind energy output, I found that Ireland was one of the best locations in all of Europe for wind energy-based load hours, alongside the UK and Denmark.

Leading me to question whether wind energy was a viable option for helping offset the current cost of living crisis energy needs alongside the possibility of it being an effective solution to deal with the current price of the electricity crisis. In researching domestic/Micro-level wind generation, apart from the unchangeable variables such as location and potential wind capacity, I came across an extensive discussion regarding how wind turbine rotor design and orientation affected the electricity generated by wind turbines.

Key areas of my background research include:

- Fossil Fuel Companies made €4Bn In Profits as the European Energy Crisis Began
- Electricity Price Inflation in Europe in the First Half of 2022
- EU Approves Emergency Measures To Tackle Energy Costs
- Breakdown of Ireland's Electricity Production by Sources
- What is Currently the Safest Source of Energy
- Average Cost per Mw Produced for all Energy Sources
- Average Irish Household Electricity Consumption and Bill
- Ireland's Potential Wind Energy Output
- Pros and Cons to Wind Energy Generation
- Horizontal Axis Wind Turbines
- Vertical Axis Wind Turbines
- General Overview of Micro-Wind Generation

This process was fascinating, providing me with an extensive understanding of the climate surrounding the viability of Micro-level wind generation, not all of which I would expect anyone to read.

My full background research can be found in **Appendix A**

Public Opinion Towards Micro-Wind Generation Survey

Introduction:

After conducting my background research, in which I looked to understand and learn about the climate surrounding the topic of micro-wind generation, I decided that an element of my project would have to be investigating the opinions of adults towards climate change, renewable energy, the current cost of living crisis, and the option of domestic micro-wind generation. To do this, I created a sixteen-question-long survey using Google Forms and sent it to all staff, parents, and students involved in my school. I left the form open to receiving responses for two weeks. In the end, I received a total of 169 responses.

On the next page is a comprehensive list of the core conclusions gathered from the survey.

All survey questions and their respective graphs can be found in **Appendix B**

Survey Results Summary

To conclude here are the main findings of the survey:

- Total Survey Population = 169
- Out of all of the respondents: 82.8% were over 20 years old, 60.9% were over 40 years old, 21.9% over 20 and less than 40 years old, 13% less than 20 years old.
- 80.5% of respondents think about climate change and its impact on their future.
- 41.4% say that they consistently make climate-positive decisions in their day-to-day life.
- 95.9% believed that in light of the current rises in electricity prices, their behaviours towards conserving electricity had shifted towards maximising energy saved.
- In light of these cost rises 67.5% have thought of investigating renewable energy sources for home electricity generation.
- Only 16% of respondents' houses had a form of renewable energy supply such as solar PV or wind contributing to powering their home, 97% of these had solar panels, and one respondent had a micro-wind turbine.
- A majority of 71.1% of respondents had very little to no knowledge about micro wind generation.
- 86% of people surveyed see it as a viable option for home energy generation.
- 72.2% wouldn't object to someone mounting a turbine in their garden, bearing in mind the maximum allowed height without planning permission in Ireland is 13m.
- When provided information about payback times, 78.7% said that in response they would consider installing a wind turbine in their home.
- Initial cost was the highest concern held by the respondents as a possible reason why they would not consider getting a micro wind turbine unit (41.4%).
- When asked, 55% of respondents said that they would be willing to pay between €1000-€2499 for a wind turbine.
- When shown a map and explanation showing how Ireland is one of the best places in Europe for wind generation, and then informed about how the Irish government currently does not offer any grants or incentives for micro wind turbines; when asked if government incentives should be put in place for home micro energy generation 94.1% responded with yes.
- Finally when they were asked if the government grants were put in place, would they be more likely to consider buying a Micro-wind generation unit for their home, 90.5% responded yes.

Introduction

We are in the middle of a climate, energy, and cost of living crisis. Within the last six months, we have witnessed an exponential increase in electricity prices, and the worst may still be yet to come. In 2022 Energia increased electricity costs by 33.5%, Electric Ireland by 38.24%, and Bord Gais Energy by 48.6%. Ireland is now already 23% above the EU average and the fourth most expensive in the 27-nation EU, recent figures from Eurostat show. Indeed, solar is now proven to be a viable option for home-scale renewable energy, but installation entails a standing charge upwards of €7,500.

As shown from my initial survey, the majority of respondents have expressed concern about climate change and the recent rise in electricity prices. A small percentage of respondents reported having a renewable energy source in their homes. Seven out of ten respondents said they had little knowledge regarding micro-wind generation. A majority of respondents 71% of respondents said that they had very little to no knowledge regarding micro-wind generation, yet when shown a map illustrating how Ireland is one of the best places in Europe for wind energy production, 94% of respondents were in favour of the Irish government introducing grants and incentives towards micro-wind energy generation. Half of the respondents said that they were willing to pay between €1000-€2500 for a domestic wind turbine, and when provided with the hypothetical scenario of the Irish Government did introduce grants supporting micro-wind generation, 90.5% of respondents responded saying yes they would be more likely to consider micro-wind energy to power their homes.

In my project, I will investigate the viability of affordable, home micro-wind energy generation, specifically an experimental investigation into the viability and effectiveness of various Horizontal and Vertical Axis Wind Turbines at a micro-scale. For each rotor design I will investigate how scaling and doubling the number of blades on the turbine rotor affects the energy generated, after this, I plan on applying my findings to a commercially available domestic turbine to understand whether current blade designs and orientations in use in micro-level turbines could be altered to increase potential energy output, or reduce blade diameter.

I will design and 3D Print all of my models based directly on and adhering to the core design principles of each turbine rotor variation, I will also design and assemble four motor housing assemblies for four small 3V DC motors, two for horizontal axis wind turbines and two for vertical axis wind turbines. Finally, I will make two Arduino boards that can measure the energy generated by the four turbines, the wind speed measured by an anemometer, and the electricity generated by a 500w 24v turbine which was sponsored to me by CarbonFreeHeat.ie, after contacting 15 Irish-owned renewable energy companies.

I have contacted Dr Ronan O'Higgins, Aeronautical School of Engineering, and Dr Joe Leen, Chief Technical Officer from the Aeronautical Engineering School at the University of Limerick. I have received access to one of their wind tunnels for testing my wind turbine rotor designs. I aim to test all of my turbines outdoors, in turbulent wind flow and the laminar flow of a wind tunnel.

Using the data acquired and conclusions drawn from these experiments, I aim to create a final optimised 3D Printed wind turbine rotor, which I will compare to commercially available models by conducting a cost analysis. Considering energy generated, costs involved, and how long it would take to pay itself back. Through my research, I intend to provide a definitive answer as to whether micro-level wind generation is a viable solution for offsetting the current energy crisis and helping fight climate change.

Design Procedures

Essential information:

VAWT: Vertical Axis Wind Turbine.

HAWT: Horizontal Axis Wind Turbine.

Rotor: The complete unit consisted of the blades and the hub of the wind turbine.

Blade: An airfoil that is angled to increase or decrease the wind resistance of the rotor. Standard turbines have either two or three blades.

Hub: The assembly that connects the blades to the main shaft and drivetrain.

Nacelle: The housing on the uppermost tower section that contains the power generation components of the turbine such as the generator, main shaft, and drivetrain.

Tower: The structure that supports a wind turbine's rotor and other assemblies. Can be constructed of tubular steel, concrete, or lattice. Colloquially, individual wind turbines within a site are often referred to as "towers".

Swept Area: The area of the circle defined by rotating turbine blades.

Micro-Wind / Small Wind: Another name for distributed wind. This encompasses wind energy used for generating power for homes, farms, and other sites requiring relatively less energy than utility-scale wind generation.

Applications and Tools Required

Fusion 360 - Student Licence - 3D Modeling Software
Arduino IDE - Arduino Programming Environment
Ultimaker Cura 4.2 - 3D Printer Slicer
3X Ender 3 Pro - 3D Printer
  PLA Filament, 2Kgs, 1.75mm
Soldering Iron
Two Part Epoxy Resin

To make all of the models in this project I used Fusion 360 on a student licence, and then 3D Printed them using my Ender 3 Pro.

Model ID Legend:

ID	Orientation	Type	Variation	Test 1 - Outdoor	Test 2 - UL 1	Test 3 - UL 2	Test 4 - Outdoor 2	Test 5 - Outdoor 3	Test 6 - Outdoor 4
1.1	HAWT	Sraight Bladed Rotor	Small	n/a		n/a	n/a	n/a	
1.2	HAWT	Sraight Bladed Rotor	6 Bladed	n/a		n/a	n/a	n/a	
1.3	HAWT	Sraight Bladed Rotor	Large			n/a	n/a	n/a	
2.1	HAWT	Curved Bladed Rotor	Small	n/a		n/a	n/a	n/a	
2.2	HAWT	Curved Bladed Rotor	6 Bladed	n/a		n/a	n/a	n/a	
2.3	HAWT	Curved Bladed Rotor	Large			n/a	n/a	n/a	
3.1	VAWT	Helicoid Rotor Turbine	Small	n/a		n/a		n/a	
3.2	VAWT	Helicoid Rotor Turbine	6 Bladed	n/a		n/a		n/a	
3.3	VAWT	Helicoid Rotor Turbine	Large			n/a		n/a	
4.1	VAWT	Darrieus Rotor Turbine	Small	n/a		n/a		n/a	
4.2	VAWT	Darrieus Rotor Turbine	6 Bladed	n/a		n/a		n/a	
4.3	VAWT	Darrieus Rotor Turbine	Large			n/a		n/a	
5.1	VAWT	Alternative Helical Rotor Turbine	Small	n/a	n/a			n/a	
5.2	VAWT	Alternative Helical Rotor Turbine	6 Bladed	n/a	n/a			n/a	
5.3	VAWT	Alternative Helical Rotor Turbine	Large	n/a	n/a			n/a	
6	VAWT	Symmetrical Airfoil Helical Rotor	Small	n/a	n/a			n/a	

n/a	
	Successful
	Unsuccessful

Fig 1, 2.

Designing and 3D Printing Turbine Rotor Variations

Initial Prototypes

Introduction

At the very beginning of my project when I was figuring out exactly what I was going to do with my project. I spent a considerable amount of time looking into various ways of manufacturing the turbine rotors and how I would test them. Below is a list and explanation of the various iterations my project went through before finalising.

- Rotors large enough to drive a commercial 500w turbine.
- Printing small, medium and large rotor sizes.
- Printing the blades of the HAWTs in two halves.
- Printing blades, horizontal or vertical (going with or against the 3D Printed grain).
- First iterations of VAWTs, and HAWTs.
- Ideas of points of comparison → double the number of blades, what turbine variations to use?

Summary and Reflection

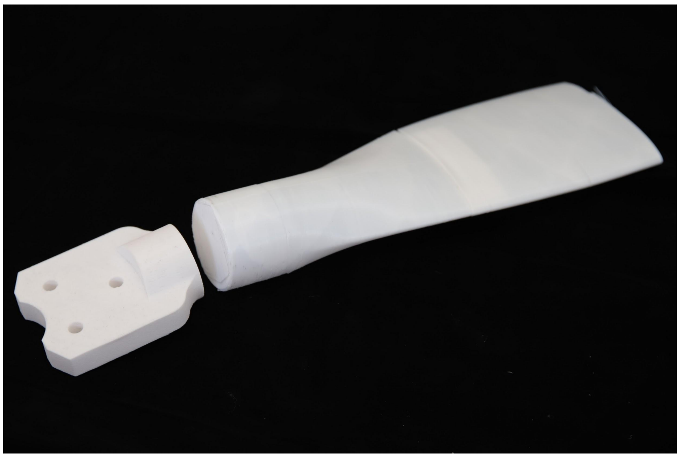
When I started working on this project, I had intended on designing 3D Printing and fiberglassing turbine rotors big enough to power the 500w motor that "CarbonFreeHeat.ie" had sponsored me, but I quickly realised that trying to create the blades at this scale was undoable, far too time and material consuming and fragile. To test both design categories, my first intention was to manufacture two HAWT and two VAWT blade types that would link to the 500w turbine's central hub. From there, I could incorporate gearboxes and make two independent motor housings for the turbine.

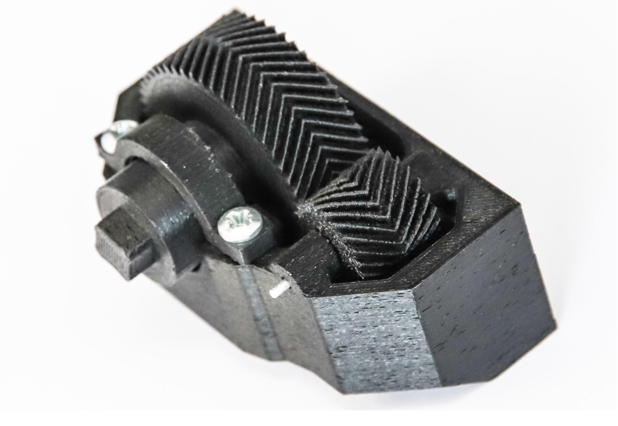
As soon as I started designing the blades, I ran into a brick wall. I discovered that 3D printing the rotor blades was just too slow, the quality it was providing even then was too poor to use and couldn't hold itself together. Almost directly after starting, I had to reassess my goals for this project from scratch. These were my thoughts: As my project examines the viability of micro-level wind generation, I cannot produce at the scale of a 500w turbine. However, I had intended to research the best rotor design for this scale of wind generation and apply that to the energy produced by a 500w domestic wind turbine to understand potential performance and efficiency improvements.

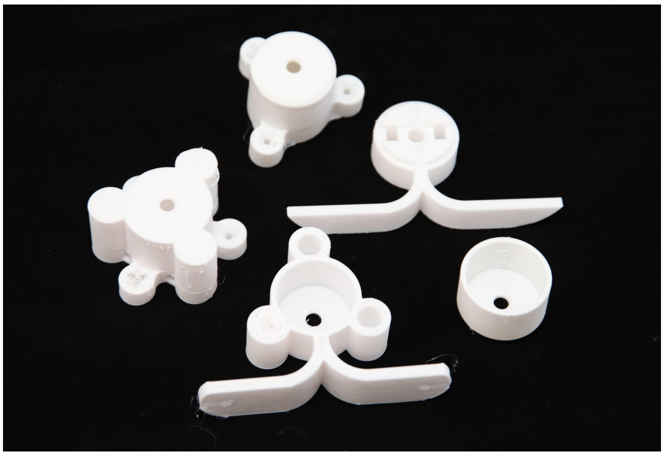
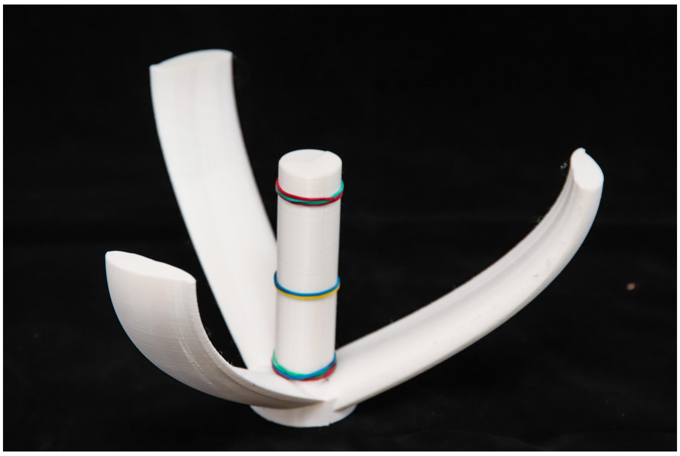
I thus concluded that all of the models I create and 3D-print must be scaled-down versions of the turbine rotor models to compare them equally both outside and in the University of Limerick's wind tunnel, treating their experimental data as direct comparisons.

I still made sure to perform tests, collect data, and use the 500w wind turbine as a practical illustration of micro-wind energy generation. Additionally, I experimented with many prototype concepts when I began designing the standard turbine rotor designs that I intended to compare with one another. For example, at one point, I considered using gearboxes for the VAWTS and tried to make rotors in small, medium (base size uniformly scaled by 1.5), and large sizes (base size uniformly scaled by 2) before concluding that the largest sizes were too big for the motors I intended to use. In this phase, I designed many different iterations of each turbine rotor before deciding on the final rotors.

Initial prototype photographs Fig 3-13.





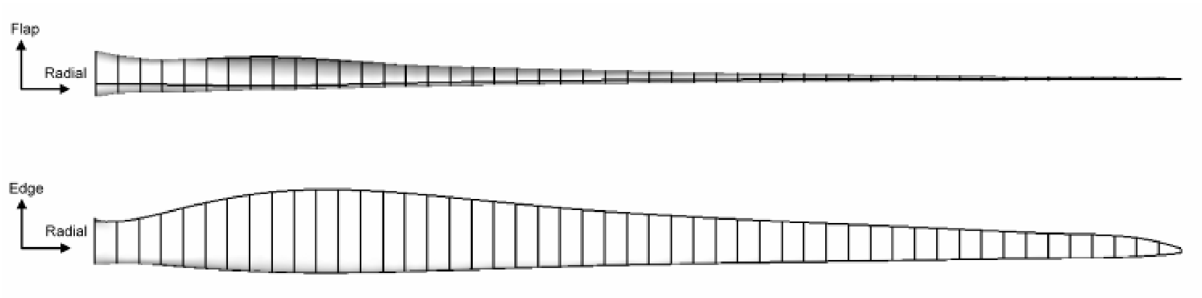
Designing Rotor Category 1 - Traditional (Straight) Bladed HAWT

Introduction:

In comparing the efficiencies of HAWT rotor designs, informed from my background research and previous knowledge regarding wind rotors, I thought that it was necessary to compare the most popular HAWT blade design, used in commercial and domestic wind turbine rotors, to all other variations that I will test. From this rotor design I, as you will see, was able to directly compare its performance to others and from there roughly estimate potential percentage performance increases on the 500w Turbine that was sponsored to me, if alternative variations were used.

When discussing this turbine blade category or any of its respective variations, as a form of shorthand I referred to it as the "Straight Bladed HAWT".

Example Photograph:



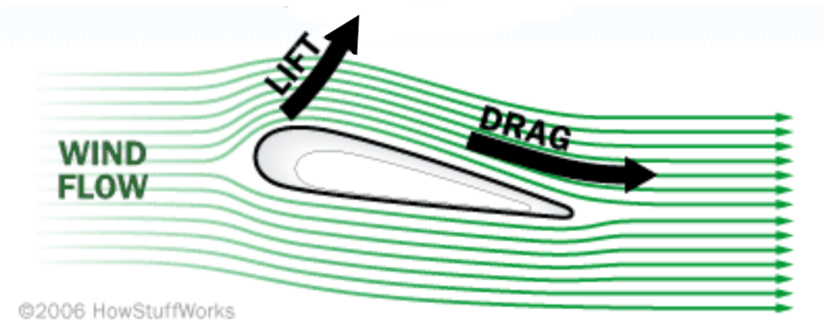


Fig 14-17. Image Sources (Pirrera) (“Wind Turbine Blade Design, Flat, Bent or Curved”) (Pixabay.com)

Applications and Tools Used

Fusion 360 - Student Licence - 3D Modeling Software
Ultimaker Cura 4.2 - 3D Printer Slicer
Ender 3 Pro - 3D Printer
PLA Filament 1.75mm
2 Part Epoxy Resin

Procedures:

This style of wind turbine rotor design most commonly features three blades radiating out from the centre of the rotor on a straight line; with an airfoil which initially, when moving outwards from the centre, widens and then progressively reduces in width until the blade nearly reaches a point. This blade operates on the principle of lift, as the airfoil creates a longer path for the air to flow along on one side of the blade, creating a region of low pressure and a lift force which drives the rotor. This style of rotor design is one of the easiest to produce at large scales.

To simplify and remove the possibility of different airfoil designs between the models interfering with the validity of my experimental results, I decided that all of my rotor designs would use the same airfoil design. After some research and finding a publication by NREL titled: “NREL Airfoil Families for HAWTs”, I considered using NREL’s S804 Airfoil for the root of the blade, S801 primary for the and S803 airfoil for the tip, after further research I came to understand that NREL no longer recommends these airfoil section designs.

So after some more looking I decided to use the S835 root airfoil, S833 primary airfoil and the S835 tip airfoil, as these are the designs recommended for use in 1-3m rotor diameter wind turbines on wind.nrel.gov. Then for the VAWT models, I would use the S833 airfoil throughout.

- Source (“NREL Airfoil Families for HAWTs”) (“Wind Turbine Airfoil List”)

1. Firstly to design the rotor I opened Fusion 360, created a new design and imported the images of the airfoils that I planned on using.

2. Next I created a sketch plane and traced the outline of each airfoil using the “Fit Point Spline” tool. Then I extruded each at 5mm thickness and created a new component for each.

3. Then after I made the airfoil sections I first rotated each of them 90° clockwise on the Z axis about their centres, making it so that when looking down at the model the airfoils were standing as if they had been sections taken out of a whole rotor that was just sitting there.

Then I created another sketch and drew a line 150mm long from the centre point of the tip airfoil perpendicular to its surface.

4. Then along this line I began marking with sketch points and moving the components to, where the root and primary airfoils of the wind turbine blade would be. After some investigation online I concluded that the middle or widest section of the airfoil should be no more than 15mm from the root. The root airfoil naturally will go to the end of the 150mm line, and at the opposite end would be the tip airfoil. For this design I decided not to introduce any rotation in the blade from root to tip as this from my understanding strayed into other variations like "Scimitar-Shaped" or "Swept Bladed" rotors and was adding another layer of complexity which I didn't think would have made my design still be a direct model of the standard "Straight Bladed" HAWT.

5. Next I created a centre line guided loft from the tip airfoil, to the middle, to root, guided by the 150mm centre line. Now at this point, I had the first blade.

6. Then I set out to make the centre hub which the blades would meet and directly drive the shaft of the motor. To do this I first created a 15mm diameter two-point circle from the 'root-end' of the 150mm sketch line that I used to make the blade, then I extruded it upwards another 15mm and finally I used the fillet command to round the top and create a nice cone at the centre of the rotor.

7. Before combining the blade component of the centre hub, I decided to investigate what was the best-suited angle of attack for blades of this size and scaling, from these quick searches I was able to find sources pointing towards an angle of attack of around 5° was best for small scale turbines. So I next selected the blade component and rotated it 5° clockwise along the axis of the original 150 mm guideline.

   Source (Voelker)

8. Next after applying the angle of attack to the blade, I first created a new sketch and drew a circle of diameter 150 mm, on the same plane as the blade was lying. Then I used the "circular pattern" command to create two copies of the blade and combined all three of them to the centre motor hub using the "combine" command.

9. To complete the design I finally extruded a cylinder at the base of the rotor 10 mm high with a hole of diameter 2.25 mm that the motor shaft could fit directly onto.This model served as the base design from which I modified to create the 3 final variations which I used for testing.

Fig 18.

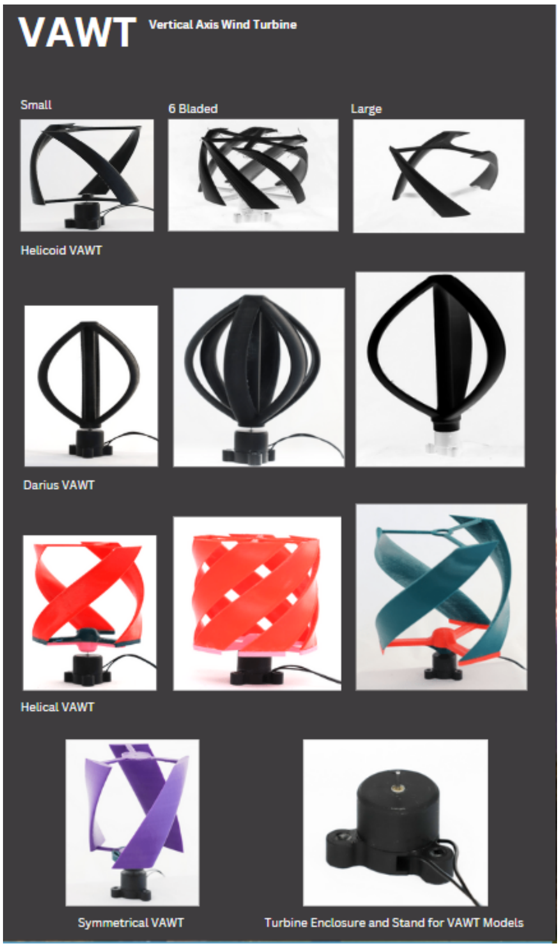
Designing all Rotor Model Categories

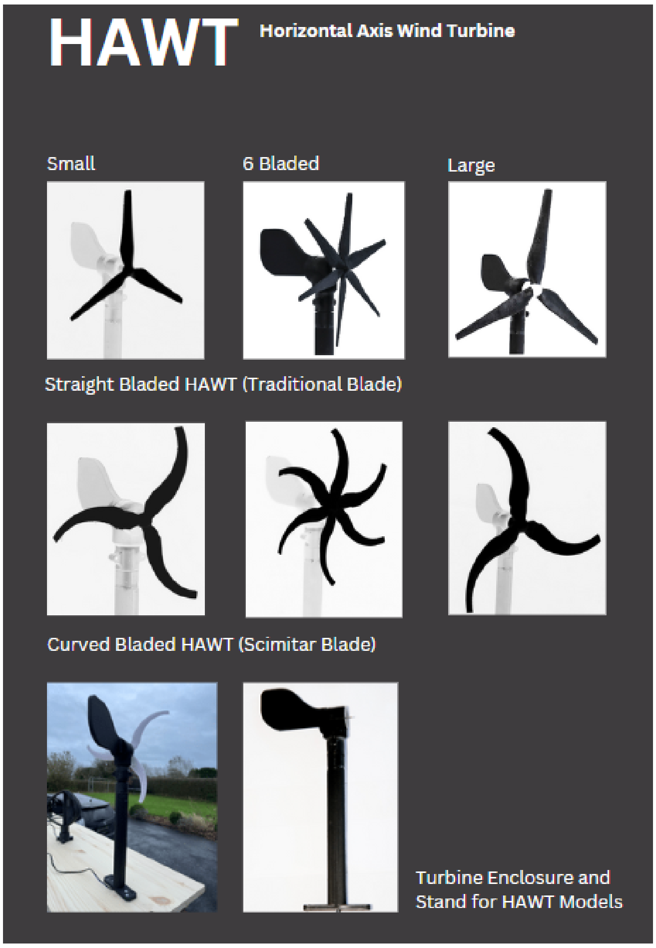
Throughout my project, I created a total of 16 final turbine rotors. Six of these were HAWTs and ten were VAWTs. In these design procedures, I documented in detail exactly why I selected each of these rotor variations for my testing. In total, this portion of the design procedures was made up of around 50 pages of my initial draft of the report book. In these design procedures, while I detail why I chose each turbine rotor variation, I also provide detailed steps describing how I designed each of the designs in Fusion 360, final photographs of each rotor 3D model, and finished assembly.

This design process was undertaken for all turbine rotor variations. Pages 15-17 are a direct example of this.

<u>All of the turbine rotor design procedures can be found in **Appendix C.**</u>

Feel free to browse through this process if you are interested in learning more about how I designed and made each of the rotor designs. I believe that it's important to add that a lot of this process became quite repetitive, and if you want to completely understand how I came about choosing each of the designs I would recommend just reading the brief introductions I will provide.
Fig 19,20.





Rotor Category 2 - Scimitar (Convex Curved) Shape Blade HAWT

Introduction:

In comparing different variations in HAWT designs, I wanted the investigation to compare completely alternative turbine rotor variations instead of minute changes of the same overall design. I decided that the primary objective of my project was not to develop the most perfected wind rotor design, but rather to compare distinctly different blade designs at micro-scale wind generation. The majority of said variations I found online were only separated by different airfoil designs, less or more blades, pitch angle and twisted blades; but after a while, I came across an interesting form of rotor design which I had not once seen in any commercial model, and struggled to find any studies investigating its effectiveness. A convex curved blade wind turbine, also known as a scimitar shape bladed HAWT, where instead of the blades radiating outwards from the centre of the rotor in a straight line, this variation had the airfoil follow the path of an arc after halfway up the blade. Supposedly increasing surface area and blade stability, while not changing the operational sweep area, but only making sense to use under very rare specific cases, and unusable at a commercial scale due to it causing dynamic instabilities in the blades. I concluded that this would have been an excellent opportunity to investigate how HAWT performance would differ from the ubiquitous straight-bladed variation at a micro-scale to one which is known to be more efficient at smaller scales, but not at a commercial level, and as such had little experimental data.

According to a Former Mechanical Engineer: "

Under rare specific cases blades are bent sideways (i.e., scimitar shape) but that technique comes in handy only for smaller turbines. Large MW range turbines have blade lengths from 50–100m. A scimitar shape bend in such blades would increase the participation factor of torsion vibration modes of the blade structure. Torsion modes are known to have a significant influence on dynamic instabilities like the flutter of blade structures.

Advantages include:

1. Increased surface area without increasing blade length. This results in a larger area exposed to wind flow thereby improving the capacity of the turbine.
2. Improves blade stability.
3. Increases distance between the blade tip and tower" - Source (Voelker)

When discussing this turbine blade category or any of its respective variations, as a form of shorthand I referred to it as the "Curved Bladed HAWT".

Example Photograph: Fig 20, 21. Image Sources ("White Curved Fan Wind Turbine | 3D model" (NREL)

Rotor Category 3 - Helicoid VAWT

Introduction:

Category 3 was the first “final" VAWT blade design I made in this project. As I have covered in my background research, initially when I was considering this project, and thinking about, and researching the whole topic of investigating the viability of micro-level wind generation. I came across a huge discussion split between whether VAWTs or HAWTs were the better choices for small-scale wind generation, and when I looked into studies investigating it some results were saying that VAWTs were better suited for smaller-scale generation in the likes urban applications due to their “preferred” wind flow being turbulent wind; but then, on the other hand, other studies flat out saying that HAWTs were the best at and that commercial level VAWTs naturally run at low RPMs but high torque, but as a product produce no noise and significantly reduced safety concerns. Where they would then have to be paired with a gearbox to generate the same levels of electricity as that of the HAWTs. From said studies, I also found that VAWTs were supposedly less affected by outdoor increases in wind speed and after cutting in would maintain a very consistent RPM, in comparison to HAWTs which when operating are very responsive to changes in wind speed and turbulence.

As explained in “A critical review of vertical axis wind turbines for urban applications” by Rakesh Kumar from Sciencedirect.com:

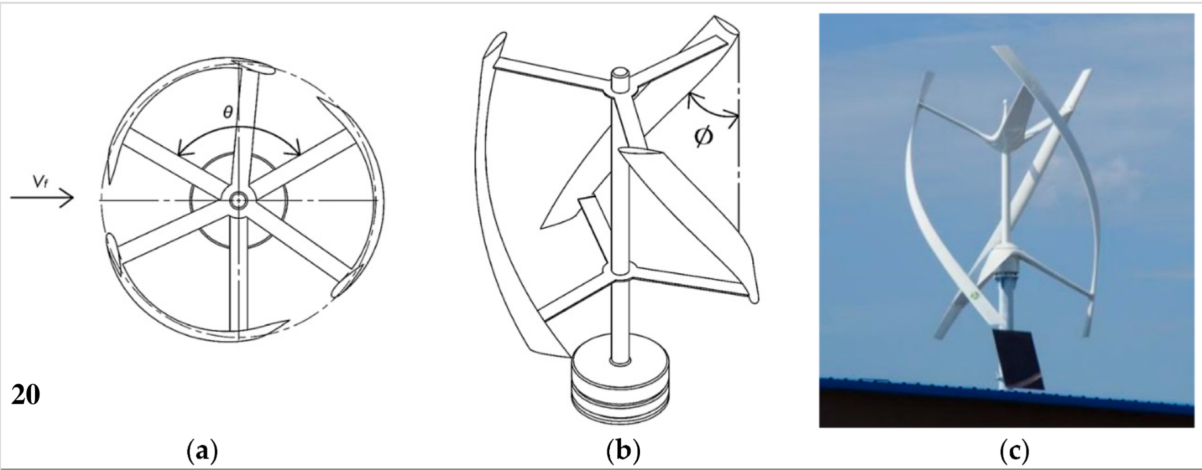
“HAWTs are used in many countries for medium-to-large scale power projects, and most commercial installations around the globe are solely based on these turbines. On the other hand, HAWTs are not recognized as a viable option to harness the energy of the wind in urban areas, where the wind is less intense, much more chaotic and turbulent.”

This first design is what is called a “Helicoid Darrieus VAWT ", most commonly used variations use three blades, each rotor blade is of constant airfoil thickness and follows a path lifted the height of the rotor while also rotated ninety degrees clockwise. Operating on the lift principle this rotor design is driven through the asymmetrical surfaces of the blades, and where all HAWTs

- Sources (“Strategies for Enhancing the Low Wind Speed Performance of H-Darrieus Wind Turbine—Part 1”) (Trepka) (Kumar 281-291)

Example Photograph:

Fig 22. Image Source (“Strategies for Enhancing the Low Wind Speed Performance of H-Darrieus Wind Turbine—Part 1”)



Rotor Category 4 - Darrieus VAWT

Introduction:

In researching VAWT variations and designs, I soon came to understand, like with the HAWTs, there was one category that made use of airfoils in every way that they could: Darrieus types, and then many others also very popular designs which didn't use any airfoils, such as Savonius and other drag based systems. I chose not to investigate the effectiveness of these drag-based VAWT rotors, as I felt that if I did I would be straying out of the realms of equal comparison, as with both all of my VAWT and HAWT designs, I aimed to keep as much about their design as common as I could, that being airfoil, sweep area blade length. In this initial research, I discovered that there was a selection of VAWT types that held the highest popularity among all others, these being the Darrieus VAWTs. One of the most notable types of this wind turbine known as the "egg-beater" was first designed by Georges Jean Marie Darrieus, a French aeronautical engineer; filing for a patent in 1926. Darrieus-type VAWTs are symmetrical,

It must be noted that while I use "Darrieus" to describe this turbine style specifically, there are various other models (for example Helical Darrieus, H-Type, and Helicoid Darrieus rotors) that all fall under the umbrella term of "Darrieus VAWT".

This variation of a wind turbine is known to be the most popular VAWT style and naturally replaces the trade-offs from HAWTs bringing its own to the table. Darrieus-based wind turbines do not have a high operational RPM but rather provide high torque and commercial models are designed to drive a gearbox. Naturally, this style of a wind turbine can be driven by wind flowing from any direction, but it cannot be mounted on a tower and harness the same level of wind that HAWTs have to use, but this also means that maintenance is significantly more straightforward. This type of turbine design has been proven to be more effective in turbulent wind flow than HAWTs, and various studies have been published investigating the viability of Darrieus wind turbines in urban settings. Despite this, Darrieus VAWTs have not been nearly as successful commercially as HAWTs. It must be noted that Darrieus turbines alone generate very low levels of torque at the beginning of their generation curve, meaning they aren't self-starting and are usually paired with a Savonius turbine rotor, or forced to use electricity to get themselves started, but it's commonly thought that at small scales the wind turbulence can provide enough energy to start them. There are also major difficulties in protecting the Darrieus turbines from extreme wind conditions, despite this, Darrieus model wind turbines are significantly safer than conventional HAWTs and still offer the potential for Micro-scale wind generation, due to their preference for turbulent wind flow and low to the ground design.

- Sources (Khudri et al.) ("EXPERIMENTAL STUDY OF DARRIEUS WIND TURBINE- A Detail Review") ("Darrieus Wind Turbines – Turbines Info") ("Darrieus wind turbine") (Voneschen)
  Fig 23. Image Source ("Dornier Darrieus 55 - 55,00 kW - Wind turbine")

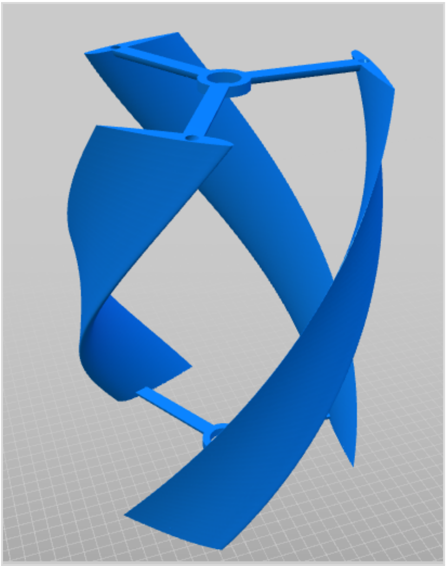
Rotor Category 5 - Helical VAWT

Introduction:

In light of the UL Testing and the abrupt unsuccessful results from all of my VAWT designs across the board. I discussed the issue with Professor McEvoy, who helped me with all of the wind tunnel tests, and said that they have had this issue in the past. After some more research, I concluded that VAWTs are designed to operate in turbulent wind flow and only in wind tunnels when their designs are highly optimised, so I decided to take another working design and use its blade design and apply it to my previous model in a new category of VAWT, and try to see if that could make any difference to performance. After further research, I concluded that HAWTs require less fine-tuning and optimisation to generate higher levels of electricity because when operating all blades are contributing to generating electricity. Yet with VAWTs because of their "Yaw-less" design only a fraction of the blades are helping to push the turbine at any given time, the rest are dragged around and in some cases can push the turbine backwards and create a state of equilibrium. It should be noted that regardless of how optimised VAWTs are, they still lag far behind the efficiencies of their HAWT counterparts.

Here is the source of the customisable blade design that I referenced:
Customizable Vertical Axis Wind Turbine by B3rn475 - Thingiverse

Example Photographs:



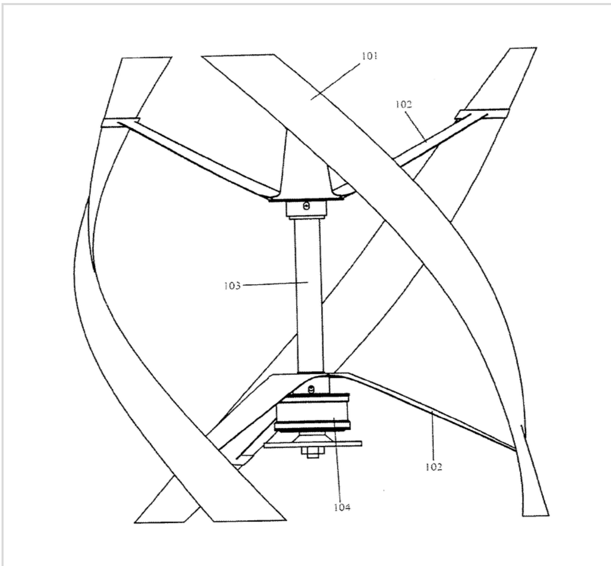


Fig 24, 25. Image Sources ("Vertical Axis Wind Turbines") ("Customizable Vertical Axis Wind Turbine by B3rn475")

Rotor Category 6 - Symmetrical Airfoil Helical VAWT

Model 6.1

Introduction:

An interesting discussion which I came across when researching what airfoil design was considered the best airfoil for VAWTs be that laminar flow airfoil, cambered, or symmetrical. As explained in the 2018 study "Performance assessment of Darrieus wind turbines with symmetric and cambered airfoils"

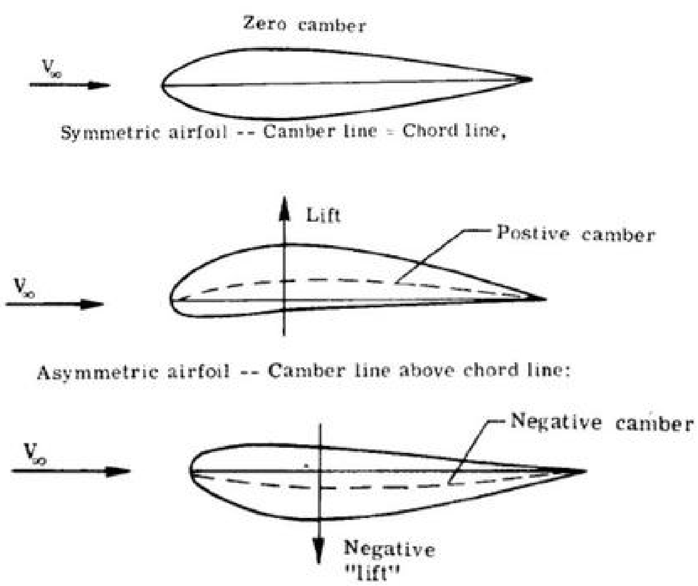
"Where NACA's symmetrical airfoils family are predominant in VAWT development for their good efficiency within a wide range of operating conditions, cambered (asymmetrical) airfoils can tend to produce higher maximum torque and power coefficients.

The laminar airfoil lift-to-drag ratio at a low angle of attack and appropriate Reynolds number gives better efficiency than a conventional symmetrical airfoil at highTSRs; the high static stall angle of the cambered airfoil allows higher power production than a symmetrical airfoil, but at high wind speeds."

- Source ("Performance assessment of Darrieus wind turbines with symmetric and cambered airfoils")

Based on this I decided as a very minor investigation, to briefly look into how airfoil design affects the energy generated by VAWTs, depending on what wind flow conditions they were tested in.

Example Photographs:



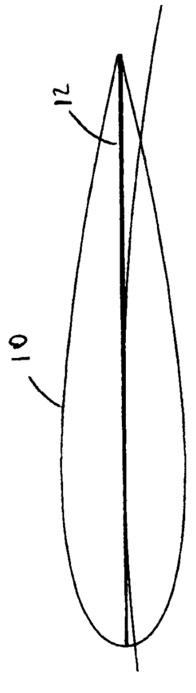


Fig 26, 27. Image Source ("What is a symmetrical airfoil?") ("US20080256795A1")

Motor Housing Assemblies

Introduction

In making the HAWT Motor Housing Assemblies my goal was to design and 3D Print two finished waterproof models complete with a tower and nacelle with an inbuilt wind vane which could rotate on a steel ball bearing and right itself into the wind, a way of securing the motor with no potential for shaking, and a way of threading the wires from the motor all of the way back down through the assembly and then to the Arduino unit.

I ended up creating many working prototypes, each needing plenty of troubleshooting with tolerances and parts breaking in between. Below is the process detailed.

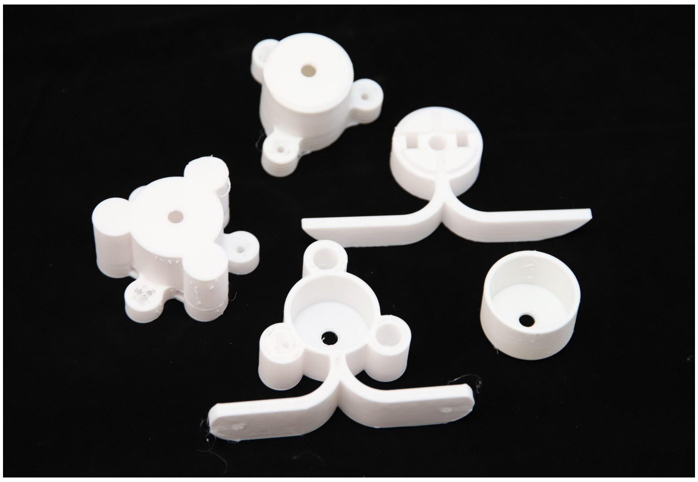
Prototypes

First Prototypes: I came up with just the motor housing on its own, a way of securing the motor using the cross of plastic on its back, two components which slide together, explain how the majority of time spent on this prototype was in getting the tolerances just right

Second Prototypes: In this design, I took the motor housing prototype with the correct tolerances and made two versions, one for the HAWTs and another for the VAWTs, in this prototype I added a way of mounting the motor assembly to a piece of wood using screws, and a hole at the back of the design for wires.

Third Prototypes: In this prototype, I improved the cover that would slide down and secure the motor to the VAWT motor housing assembly, alongside this I thickened the base and removed the wire holes, replacing them with two paths that exit not through the base but the side of the assembly, to help with waterproofing. As for the HAWT motor housing assembly, I began trying to design a complete unit fitted with a tower, and nacelle which could pivot on a steel ball bearing and face into the wind from wherever it was coming, I also needed to add a hole going through the entire design for the output wires. Still have many tolerances and issues with print quality to fix. Below are some examples of prototypes that I came up with during this process.

Fig 28.



Finished HAWT Motor Assembly Design

Introduction

The goal I had in mind when making the HAWT motor assembly was to make a waterproof, and a relatively robust unit which could hold the rotor clearly above the board of wood I planned on mounting it on. Although in the initial phases, I went through many prototypes and variations exploring different ways of mounting and holding the motor, below is the description of how I made the final turbine motor assembly and tower design. In the end, it consisted of eight components, not including the ball bearing. The finished product was a tower with a pivoting nacelle on top which could turn to face the wind from any direction, ad be mounted with four screws.

Design Description

The design shown in the photographs below is the fourth and final prototype of my HAWT motor assembly design. This design consists of eight components. The tower, the main body of the nacelle, the wind vane, the motor assembly cover, two identical hollow semi-cylinders that when assembled fit around the ball bearing, a connector cylinder which goes up through the two joined semi-cylinder wedges into the circle at the centre of the bearing, finally a small hollow cylinder which the tower and the connector cylinder assembled with the rest of the nacelle connect to and join together

Below Features 2 “3D” views of the completed motor assembly, one exploded view, and two in-person views of the completely assembled and finished design.

Fig 29, 30.

Finished VAWT Motor Assembly Design

Introduction

In comparison to the final HAWT motor assembly design, this VAWT motor assembly was in a significantly easier and less time-consuming world of its own. I had planned on making it entirely waterproof, able to withstand all of the irregular forces that the largest size VAWTs would exert when operational

Design Description

This model consists of just two components, the base which the motor fits into and could be secured to a piece of wood using three screws; and the top cover which would slide down over the motor when finished. The base features wire holes that thread down and then through the side of the model, meaning that it is completely waterproof.

Below Features 2 “3D” views of the completed motor assembly, one exploded view, and two in-person views of the completely assembled and finished design.

Fig 31.

Making the Data Collection Units

Prototyping

Introduction

My goal in making the data collection units was that I would have two Arduino Boards. One which could measure the energy generated by the four-rotor testing turbine units write that data to an SD card, note at what time that was, measure the wind speed and have an LED which flashed after each cycle of the code to know that it was successfully written to the card. The second Arduino board was to be used for measuring the energy generated by the 500w turbine, where the anemometer unit could be wired into it when I plan on testing. Now as you will see below, this idea was not feasible due to various reasons, but after all of this prototyping, I was left with this solution to the targets above.

In the end, I had two Arduino setups, one board which through using four voltage dividers to split the voltage generated by each of the four turbines exactly in half, I could measure the energy generated by each and calculate the real measured voltage. Alongside this, board one was also fitted with a micro-SD card reader which I would use in the outdoor tests to collect the data, a button that when clicked would create a gap in the data, to be used for synchronising test data later on, and a simple red LED which would flash signalling that the Arduino was successfully saving to the card. This board also could write all of its data out to the serial port and have it recorded and saved to a text file using a program called coolTerm (for the likes of the UL wind tunnel testing).

The second Arduino Board had an anemometer, a set of four stacked voltage dividers which could measure the voltage generated by the 500w Turbine, and a button for the synchronisation of test data. This board would print all of its data through the serial port and have it recorded and saved to a text file using coolTerm.

Procedures

I began researching ways of tracking the energy provided by each motor, as well as timestamps and wind speeds, and eventually writing it all to an excel sheet using Arduino serial outputs. I figured out how to utilise the Analog pins as quantifiable inputs, then measure the milliamp hours produced and convert it to volts. Currently, I want to have two Arduino setups, one for measuring the power generated by the four testing motors and another for measuring the electricity generated by the 500w turbine. I'll need to get another Arduino Uno and create the housing modules.

I've begun looking at anemometers and the possibilities of 3D printable solutions. If I create these, I'll most likely need to buy some cheap Arduino clones.

For the outside testing phase of my project, I seriously considered purchasing an Arduino-compatible anemometer from Amazon. That is not something I will do. The lowest price I could find was €60. I discovered that I could get one from Adafrui for $40 and have it mailed to the place where I'll be staying on my American exchange trip, so that's what I'll use in my project.

I brought the 500w Wind Turbine home from school, assembled it and made a voltage divider circuit which can measure the energy generated after the 3 Phase, 24V AC has been converted to 24V DC. It's four resistor-based voltage divider circuits stacked on top of each other, equally dividing the voltage to the point that the Arduino can measure it, as the Arduino Uno's analogue pins can only measure up to 5V. Then by using a variable power supply and recording the raw analogue inputs and graphing them into the likes of Geogebra, you can derive an equation to generate the real voltages measured. By using 1M Ohm resistors, I have massively reduced the potential heat generated. I did a bit of research into how resistors heat up and burn out and it appears that heat isn't actually to do with the level of resistance that the electricity has to flow through, but rather how fast it's moving through the resistor. So resistors with a large level of resistance generate significantly less heat while still being used, for example in what I did today: To measure the voltage that my turbine and rotor are producing in real-time. I applied the same reasoning to measuring the voltage generated by the smaller testing rotors, and as their maximum output is somewhere around 3 Volts, so I just could plug their outputs straight into the Arduino.

I think that I've found a way to measure the voltage generated by the small units and the 500w Turbine. Through using the voltage divider circuit, knowing what voltage is generated, and knowing the resistance of the resistors, I can use the voltage divider circuit to step down the potential 4.5V+ from the motors when in full capacity to 2.25, and then in the code just double the converted voltage.

So what I did was run a small experiment where I took each motor unit and ran them at the same speed using a battery drill measuring the voltage and amperage generated. Then in Geogebra, where x was voltage and y was amperage, I plotted the energy generated by all four motors, and then I created a best-fit line passing between (0,0) and the average of the points. Creating the relationship between voltage and current when the motor is running.

I worked on the voltage divider circuits for the four motors all morning while also attempting to fix the anemometer, which is still not working.

After spending the entire day trying to get the anemometer to work with my variable power supply, I realised that one of the connection pins was too short, which meant that the Arduino would have never received any data from it. Once I fixed that, I realised that the anemometer would need to be powered by the Arduino Uno because the outputs it was giving were beyond what the Arduino could measure. I also started trying to get the SD card reader working but to no avail.

Got the SD card reader for the outdoor tests working, I had some pins incorrectly connected. I ran into issues getting the Anemometer working, today I tried to get the anemometer wired and connected to the 4 turbine Arduino board but it was reading completely wrong inputs. I think that it was because I also had the SD card reader, and clock module powered by the 5v pins from that Arduino; and in a separate test on the other Arduino rig, when I just powered it through straight 12v, not from the Arduino it gave out completely messed up inputs, but when powered through the 5v pin it gave out exactly what you would expect. Initially, I thought that it could have been some ground loop issue, but

I now think it simply that it requires pretty much of the power that the Arduino - which is already trying to power another led, and SD card reader - can provide. Also to note: all 5v and ground pins on the Arduino Uno are common, so I believe that could also have been in play, as when the SD card reader is writing to the SD card the flashing led is visibly brighter. I also ended up killing the clock module while trying to redo the soldered connections and then got them working again. So now I've finally decided how I will be able to record all of my data. I will have two Arduino boards, one dedicated to measuring the energy generated by the four testing rigs and writing to the micro-SD card, and another which will measure the wind speed with the anemometer, and the energy generated by the 500w turbine. Both boards will have the same polling rates and will be synchronised by a button, which when pressed creates a division in the outputted data and marks a change in the experiment, and a separation marked with "— Power Cycle —" is created every time the Arduino turns on. Now I just need to get the anemometer working and match the inputs of the motors to the screw connector receivers of the voltage divider inputs and then I'll be done.

I decided to flat remake all of the circuitry for the 4 turbine Arduino setup for the last time and got it all working again. Made two forks in the 4 turbine Arduino setup, one which prints all inputs to the serial and another which ignores serial completely and just saves all measured inputs to the card.

I got a plank of wood cut thanks to Mr O'Connor, a Woodwork teacher, who mounted and screwed turbine housings onto it and got it recording data and working in the school. I also fixed some catastrophic errors in the 4 turbine code, got the button working and then just sealed the box. I also got the anemometer reading correctly and printing to serial on the other Arduino board. I also tried multiple times to get the button and led working for the new unit, but got the button working, not the led, now that I look back at it I think it was all stopped because at the top of the script it was trying to start a clock module when the actual clock module wasn't even there.

In short; the first Arduino setup is done, and the second one has died. I tried remaking the anemometer setup and killed the board and data logger shield by short-circuiting the +5V Pin. We have replacements in school, all will be fine. Today I also realised just how wrong I was in trying to measure the amperage generated from the small motors using the shunt resistor. I ran a quick little experiment and fixed that and the corresponding code, and then sealed the box.

Remade the second Arduino setup and got it to record wind speeds and a button for synchronising with the other testing unit. Also tried adding a clock module to it, and ran out of time, but now looking at it I don't believe that it's necessary. I set the polling rate to the same as the 4-turbine setup Arduino.

I glued all of the rotors and motor housings together and got this program called coolTerm to work with both Arduino setups, which automatically saves the serial outputs of the two Arduino boards to file. Now through the serial port, I can record, for example in the UL Testing, in real-time, what wind speed is being measured, the energy being generated by all four turbines, each in an instance of coolTerm, and also synchronise them using the "Change" button.

Today was the first day there had been proper wind since I came back from America. I got the 4 Turbines Arduino Setup and Anemometer Arduino Setup both mounted and recording data in my first experiment. Both units worked as planned.

During the UL Testing, I found that I needed to calibrate my anemometer, and after some attempts at tweaking the code for converting the analogue input to m/s, I decided I was wasting too much time and ran through a simulation of the experiment and saved all of the analogue inputs (which can range between 0 and 1023, 1023 = 5V,) to file and then moved on. A couple of days later, I used Geogebra.org to plot the wind speed in m/s vs analogue input and found that there was a linear relationship between the two. After considering whether I should calculate the milliamps and milliwatts generated by the testing motors I concluded that it wasn’t worth the extra data, as the voltage is proportional to amperage, and isn’t relevant to my testing. Originally I considered measuring the amperage generated by the 500w turbine. The motor control unit detected it as a short circuit and would consistently cut out and lock up as if the brake was activated. So I decided not to measure the amperage generated by the 500w

Now both Arduino boards are finished.

Final 4 Turbines Testing Unit

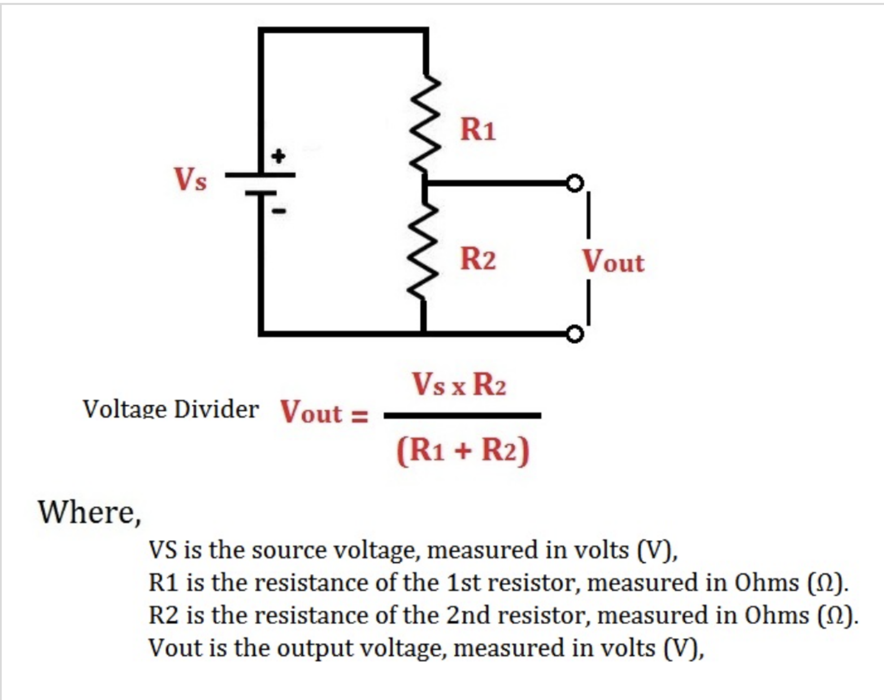
Introduction

This Arduino setup was the final design from which I was able to record the electricity generated by the four turbine units I created, in all of the experiments that I ran. It consists of four resistor-based voltage dividers which each take an input voltage from one of the four turbine assemblies and each divides their respective inputs by two, meaning that instead of only 5V the Arduino can measure up to 10V on each turbine input. A synchronisation button would create gaps in the data and allow me to synchronise data between tests when processing, for example, the start of the experiment and changes in conditions (ie. set wind speed in the wind tunnel). A Micro-SD card reader for writing the experiment data to file, and finally LED which I programmed to flash at every cycle of the code, signifying that data was successfully being written to the SD card and everything was working. I found a universal Arduino project box online and a 3D Printed one for this testing rig.

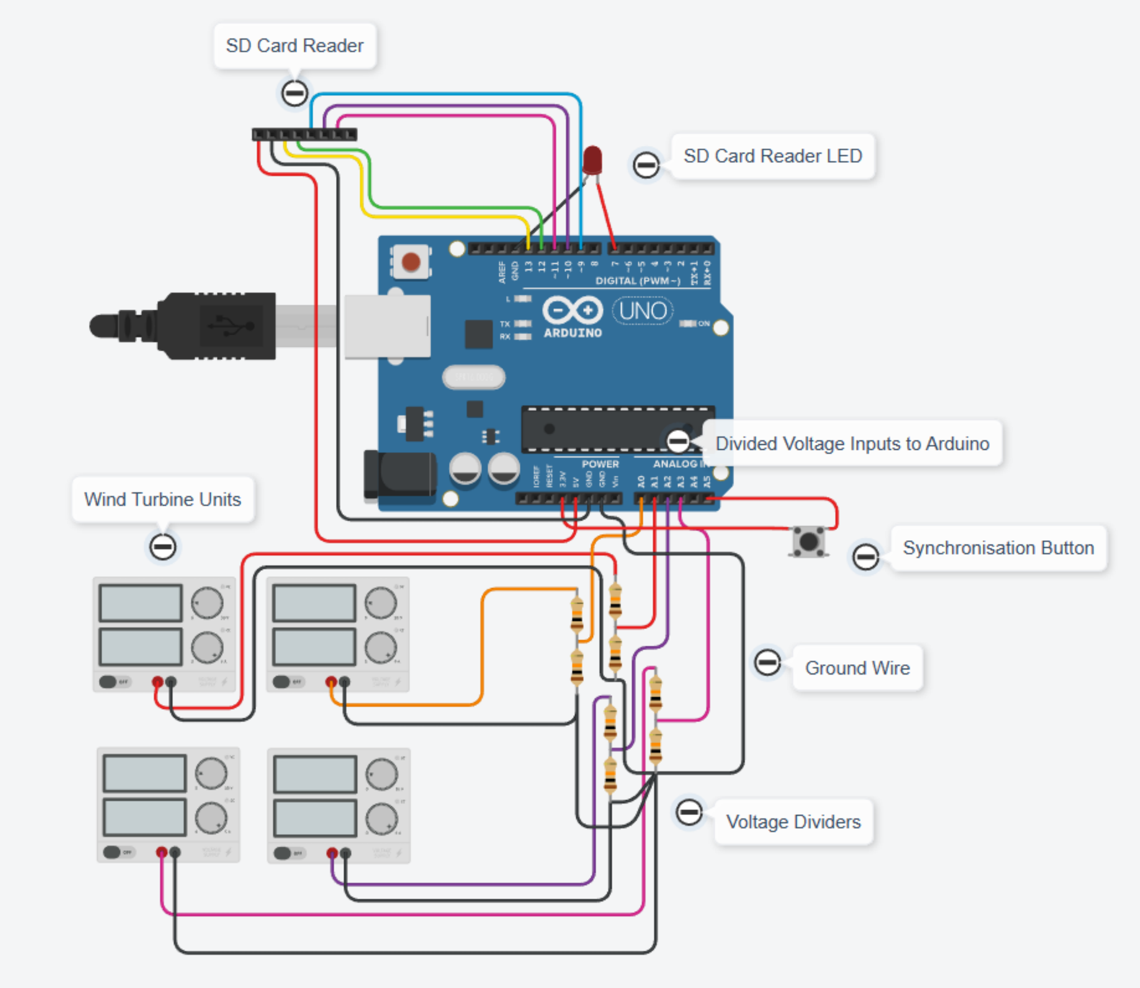
There was no need to calibrate voltage dividers on this Arduino Unit because it has only one voltage divider, I didn't need to calculate the relationship between analogue input and voltage, instead just after it was converted from the analogue input to read voltage in the code, multiply it by 2 and you would get real voltage.

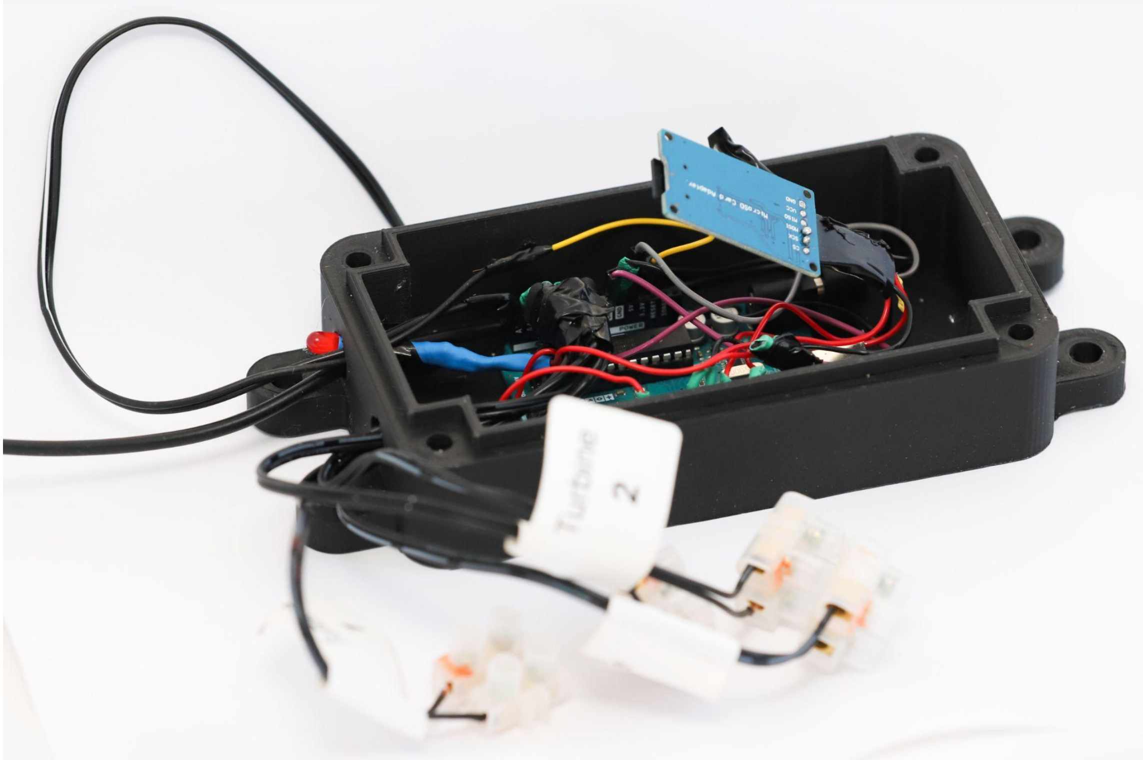
Below is a basic diagram explaining how resistor-based voltage dividers work.

Fig 32-35. Image Source ("LEETS ACADEMY | Voltage Divider Circuit")



Wiring Schematic:





Final Code:

4 Turbines Unit Final Code

```
// Code here
#include <SD.h> //Load SD library
#include <Wire.h>

int offset = 0; // set the correction offset value
int chipSelect = 10; //chip select pin for the MicroSD Card Adapter


void setup() {

  File file; // file object that is used to read and write data
  Serial.begin(9600);

  digitalWrite(7, OUTPUT); // Set LED output pin
  digitalWrite(A5, INPUT); // Set Button input pin
  Wire.begin();
  pinMode(chipSelect, OUTPUT); // chip select pin must be set to OUTPUT mode

  if (!SD.begin(chipSelect)) { // Initialize SD card
  }

  Serial.println(); // Create empty line
  Serial.println("              Power Cycle"); // Mark power cycle in serial
  Serial.println(); // Create empty line

  file = SD.open("TEST.csv", FILE_WRITE); // open "file.txt" to write data
  if (file) {
    file.println(); // Create empty line
    file.println("              Power Cycle"); // write power cycle to file
    file.println(); // Create empty line
    file.close(); // close file
  } else {
    Serial.println("Failed to open Test.csv");
  }
}


void loop() {
  digitalWrite(7, HIGH); // turn on LED

  int buttonState = 0; // Set button to off

  float volt = analogRead(A0);// read the input from Turbine
  float volt2 = analogRead(A1);
  float volt3 = analogRead(A2);
  float volt4 = analogRead(A4);
  double voltage = map(volt, 0, 1023, 0, 500) + offset; // map 0-1023 to 0-500 and add correction offset
  double voltage2 = map(volt2, 0, 1023, 0, 500) + offset;
  double voltage3 = map(volt3, 0, 1023, 0, 500) + offset;
  double voltage4 = map(volt4, 0, 1023, 0, 500) + offset;
  voltage /= 100; // divide by 100 to get the decimal values
  voltage2 /= 100;
  voltage3 /= 100;
  voltage4 /= 100;
  voltage *= 2; // Calculate real voltage measured
  voltage2 *= 2;
  voltage3 *= 2;
  voltage4 *= 2;
  voltage4 = abs(voltage4 - 0.15); // Remove background noise

  voltage *= 1000; // Convert V to mV
  voltage2 *= 1000;
  voltage3 *= 1000;
  voltage4 *= 1000;

  int ifbutton = 0;
  buttonState = analogRead(A5); // Check if button pressed
  if (buttonState < 800) {
    ifbutton = 1;

    Serial.println(); // Create empty line
    Serial.println("              Change"); // Print change to serial
    Serial.println(); // Create empty line

```

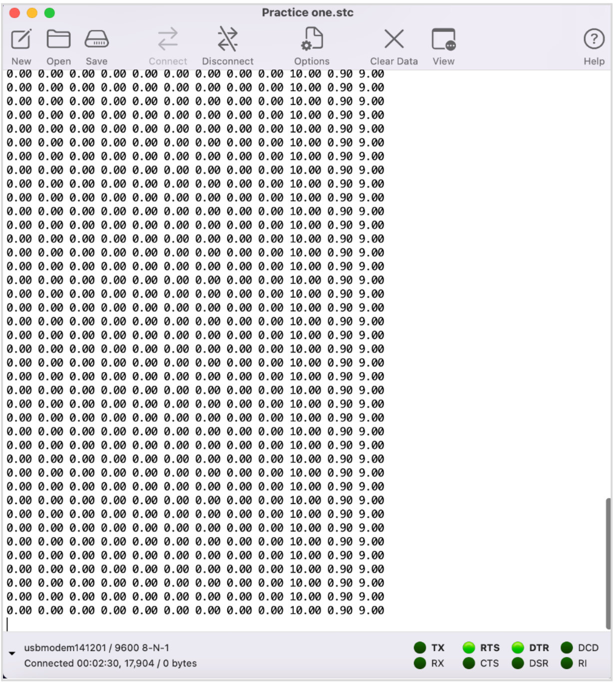
```
    file = SD.open("TEST.csv", FILE_WRITE); // open "Text.csv" to write data
    if (file) {
      file.println(); // Create empty line
      file.println("              Change"); // write change to file
      file.println(); // write number to file
      file.close(); // Create empty line
    } else {
    }
  } else {
    ifbutton = 0;
  }


  file = SD.open("TEST.csv", FILE_WRITE); // open "Test.csv" to write data after calculating voltages

  if (file) {
    file.println((String)voltage + " " + (String)voltage2 + " " + (String)voltage3 + " " + (String)voltage4); // serial print data
    Serial.println((String)voltage + " " + (String)voltage2 + " " + (String)voltage3 + " " + (String)voltage4); // write data to file
    file.close(); // close file
  } else {
    Serial.println("Failed to open Test.csv");
  }

  digitalWrite(7, LOW); // Turn off LED

  delay(500); // Wait for 500ms
}
```

Code Explanation:

This code is designed to take the analogue inputs from each of the individual wind turbines, measure and calculate the voltage generated by each and save it to an SD Card or print it out to Serial using coolTerm to record the inputs and automatically save them to a text file.
Here is the format of the output data: mV1 (Space) mV2 (Space) mV3 (Space) mV4), each line of data was automatically printed onto a new line. Then using Microsoft Excel I could convert space-delimited text to columns, and from there I could use all of the data from each turbine in side by side and individual comparisons of electricity generated during the same test in the same conditions.

Alongside a way of measuring the energy generated by each turbine and saving the data, this code also allows the Arduino to be fitted with a “Sync” button which I used during the testing to synchronise the data between this board and the Anemometer (and 500w wind turbine) Unit in the outdoor tests, or changes in the experimental conditions during the wind tunnel test. The code is also designed so that an LED would flash after each cycle if the Arduino had successfully connected to and written to the card.

Fig 36.



Testing reliability of Generating Motors

Introduction

To test and verify that all of the 3V 100mA DC motors I planned on using produced the same voltage when run at approximately the same RPM, I decided that I should run a quick test. I planned to run each of the motors using a battery drill and measure the output voltage and amperage using a multimeter, and also mark their polarity when being driven in a clockwise direction as that's how the turbines I designed rotated.

Required Materials

4X 3V 100mA DC motors
Battery drill with adjustable chuck
Bench vice
Multimeter
Access to Geogebra.org

Procedures

1. To begin with, I first took each of the four motors out of their 3D Printed assemblies, disconnected all of the wires threaded through and mounted one in a bench vice.

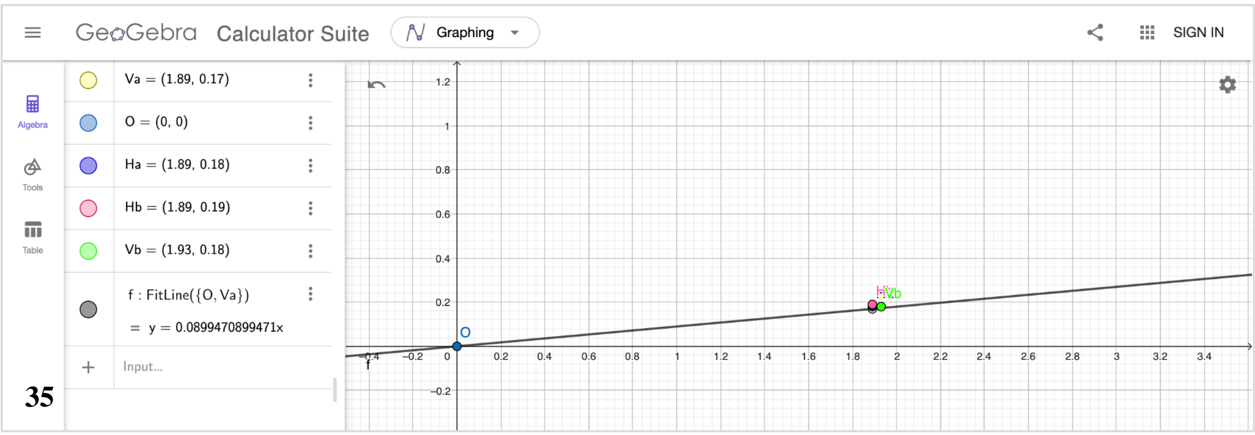
2. Then using the adjustable chuck on the battery drill I fitted the shaft of the motor and then ran the battery drill at full speed for ten seconds twice, the first time recording peak voltage and the second time recording peak current. I repeated this for all four of the motors.

3. Then finally using Geogebra.org I plotted all of the data points in the form: A = (voltage, amperage), and then I created a best-fit line passing between (0,0) and the average of the points. Creating the relationship between voltage and current when the motor is running.

Results

From this graph I can conclude that the motors are very consistent and similar in their capacity to generate electricity and that the relationship between voltage and current is approximately 0.09.

Fig 37.



Verifying and testing the accuracy of 4 Turbines Testing Unit

Introduction

After assembling, prototyping and coding the 4 Turbine Arduino Testing Unit I naturally had to perform a quick test to show that it was working properly. To do this I planned on using my variable power supply to provide 3V 1.5A between each of the four turbines and have the Arduino Uno printing the information in real-time through the Serial to coolTerm

Required Materials

4X 3V 100mA DC motors
Battery drill with adjustable chuck
Bench vice
Printer Cable
Arduino IDE
Multimeter
Variable Power Supply
Access to CoolTerm

Procedures

1. Firstly I connected the Arduino to my laptop using an extended printer cable and uploaded the final iteration of the code to the board.
2. Next I opened a coolTerm window and connected it to the Arduino and began saving captured data to a text file.
3. After this I plugged in and turned on my power supply and set it to output 3V, and then for each turbine connection I connected the probes for 10 seconds, checked if the printed reading matched the read reading on the multimeter, and if it did the experiment was a success, and if not something in the circuitry was likely to blame and would have meant me remaking the entire voltage divider at fault.

Results

This method of verifying the accuracy of the 4 Turbine Testing unit came in very handy during the prototyping phase as it showed immediately where the problems lay and often gave you a pretty good idea about what was wrong based on the output. This method saved me a lot of time.

Fig 38.

Final Anemometer and 500w Turbine Testing Unit

Introduction

This Arduino board was the final prototype for measuring the wind speed during the outdoor experiments and also measuring the electricity generated by the 500w turbine in the overnight test

As this Arduino in theory (and as seen in the experiment) could be measuring 30V + I had to stack four resistor based voltage dividers on top of each other to step the voltage down enough to be measured by the Arduino. Then after doing this and completing the relevant calibration steps, finding what analogue value is measured for 3V, 4.5V, 6V, 7.5V, 9V and 12V, I could calculate the correlation, graphing the points on Geogebra and seeing that the relationship between voltage and measured input is indeed linear. Meaning that this circuit works exactly as intended. In theory, this circuit could allow the resistor to measure up to 40V safely, dividing the input voltage by eight, but just to be sure I tested it and calibrated the code to match.

By using 1M Ohm resistors, I massively reduced the heat generated during operation. I did a bit of research into how resistors heat up and burn out and it appears that heat isn't actually to do with the level of resistance that the electricity has to flow through, but rather how fast it's moving through the resistor. So resistors with a large level of resistance generate significantly less heat while still being used, for example in this design. As long as all of the resistors in the voltage divider are of the same value resistance, the voltage divider will still work as intended.

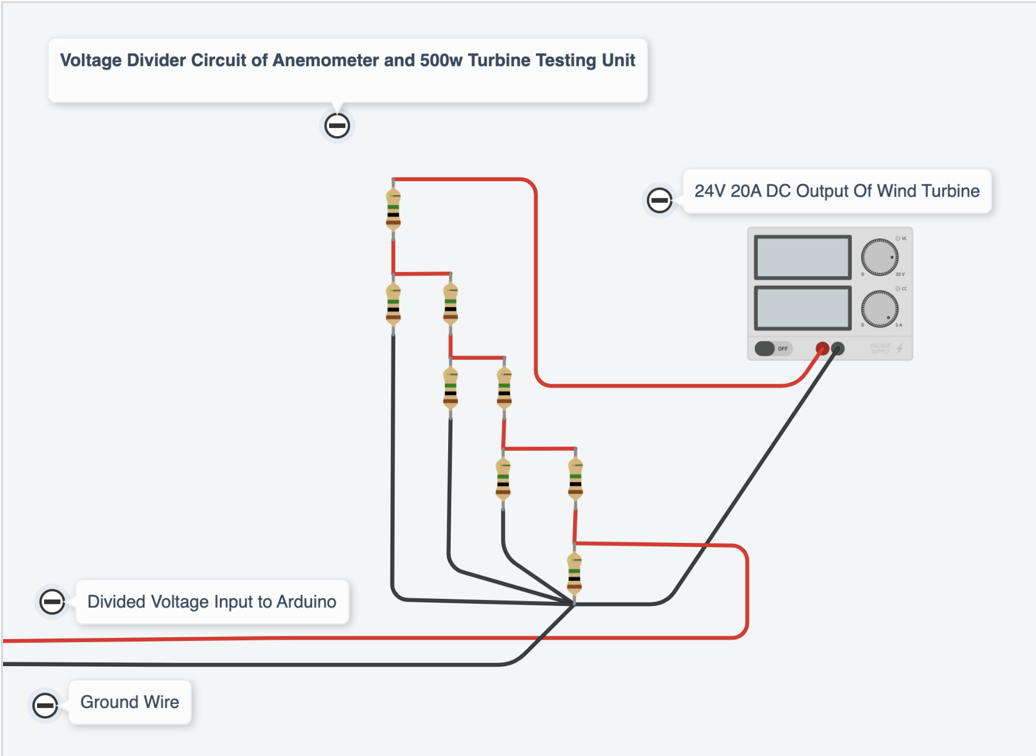
This Arduino Unit also simultaneously takes input from an anemometer and a "Sync" button for the synchronisation of data.

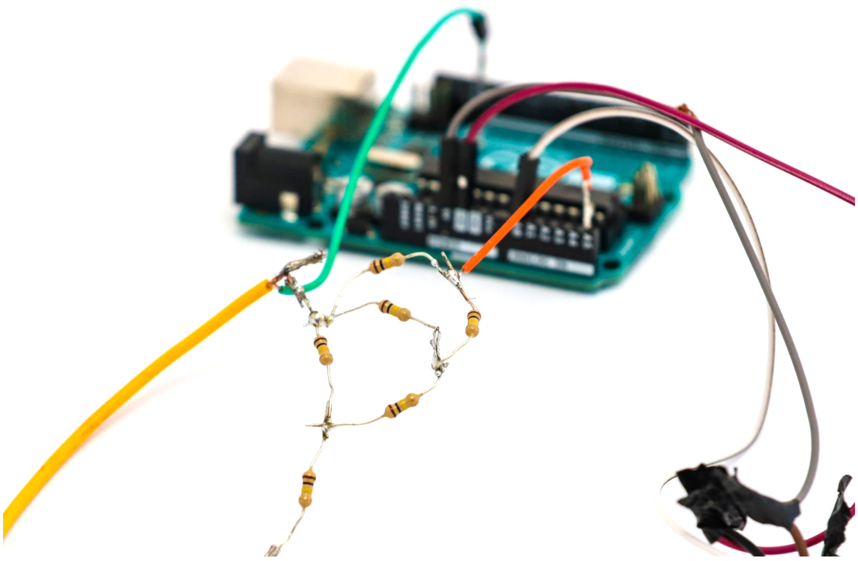
On the next page is a basic wiring diagram of the four stacked resistor-based voltage dividers used in this Arduino Testing Unit.

Fig 39. Image Source ("Anemometer Wind Speed Sensor w/Analog Voltage Output")

Wiring Schematic:

Fig 40, 41, 42.





(Arduino Board was kept in a waterproof 3D Printed case for outdoor tests)

Final Code:

500w Turbine and Anenometer Unit Final Code

```
void setup() {
  Serial.begin(9600);
}

void loop() {

int volt=analogRead(A5); // Meaure voltage after voltage dividers
int anenoutput = analogRead(A0); // Measure anenometer input

float finalvolt=(volt/16.66666666)+(6/16.6666666);
  // Convert input to actual volts
float finalwind=(anenoutput/6.833333)-10.844;
  // Convert input to real windspeed

Serial.println(String(finalwind)+" "+String(finalvolt));
  // Print final data to serial

int ifbutton = 0;
float buttonState = 0;
buttonState = analogRead(A5); // Check if button is pressed
if (buttonState < 800){
    ifbutton = 1;

 Serial.println(); // write empty line
 Serial.println("               Change"); // print indent to serial
 Serial.println(); // write empty line

}else{
   ifbutton = 0;
 }

delay(5000);  // Wait 5 seconds
}
```

Code Explanation:

This code measures the input voltage from the 500w Turbine’s voltage divider circuit, and the anemometer, converts them to their respective final values and then prints them through Serial to the laptop for recording in coolTerm. There is also a button feature which is used to synchronise the testing data between the two boards and mark the start and end of the outdoor experiments.

Calibration of New Voltage Divider Circuit

Introduction

To be sure that I could measure the energy generated by the 500w Turbine, I decided, rather than just assume that the final output voltage was a defined fraction of the original voltage and guess from there, to test the circuit by inputting increasing voltage values and graphing how they related to their final analogue input value.

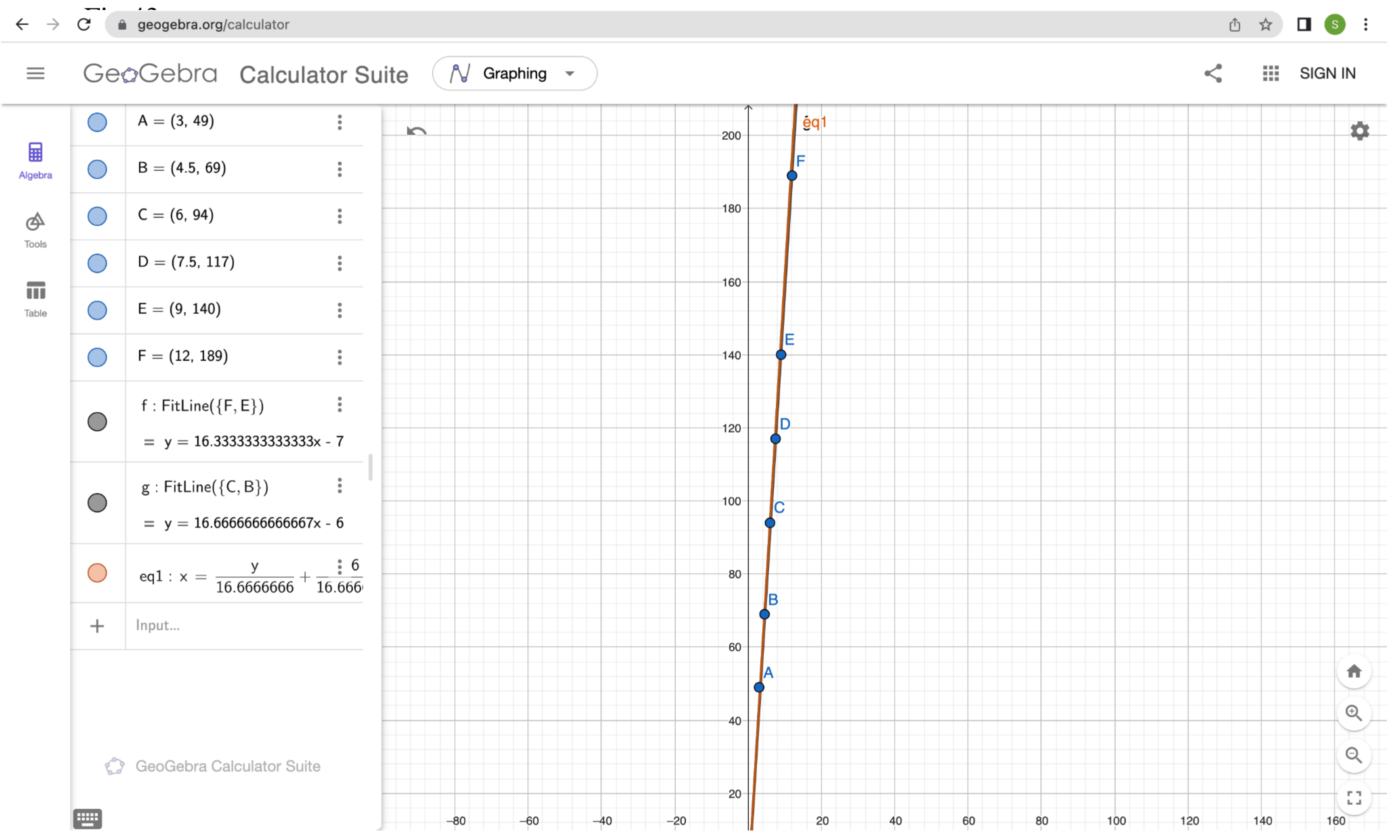
Procedure

1. To begin this experiment I connected the Anemometer and 500w Turbine board to the computer, opened a terminal of coolTerm, and then measured the recorded analogue input value at voltages from 3V to 12V incremented by 1.5V

Results

As can be seen from the graph below, the relationship between voltage and the analogue input value is:

Voltage = (Analog Input/16.6666666) + 6/16.6666666)



Calibration of Anemometer using Wind Tunnel and Micromanometer

Introduction and Procedure

This quick test was done so that I could calibrate the Anemometer to print the correct wind speed values. To do this I used the wind tunnel at the University of Limerick and the inbuilt micromanometer, increasing the wind speed by 1 m/s until it reached 7 m/s, doing a full run-through of the test I planned on using with the rotor designs, recording each of the corresponding analogue input values. As this played into the finalising of this Arduino Unit design for use in the outdoor tests but was also carried out at the University of Limerick during the wind tunnel testing, this procedure will be included in this section and the Experimental Investigations section.

Outcome

Arduino Analog Input = Range between 0-1023 = y
Wind Speed = m/s = x

$$y = x * 6.8\overline{3} + 74.1$$

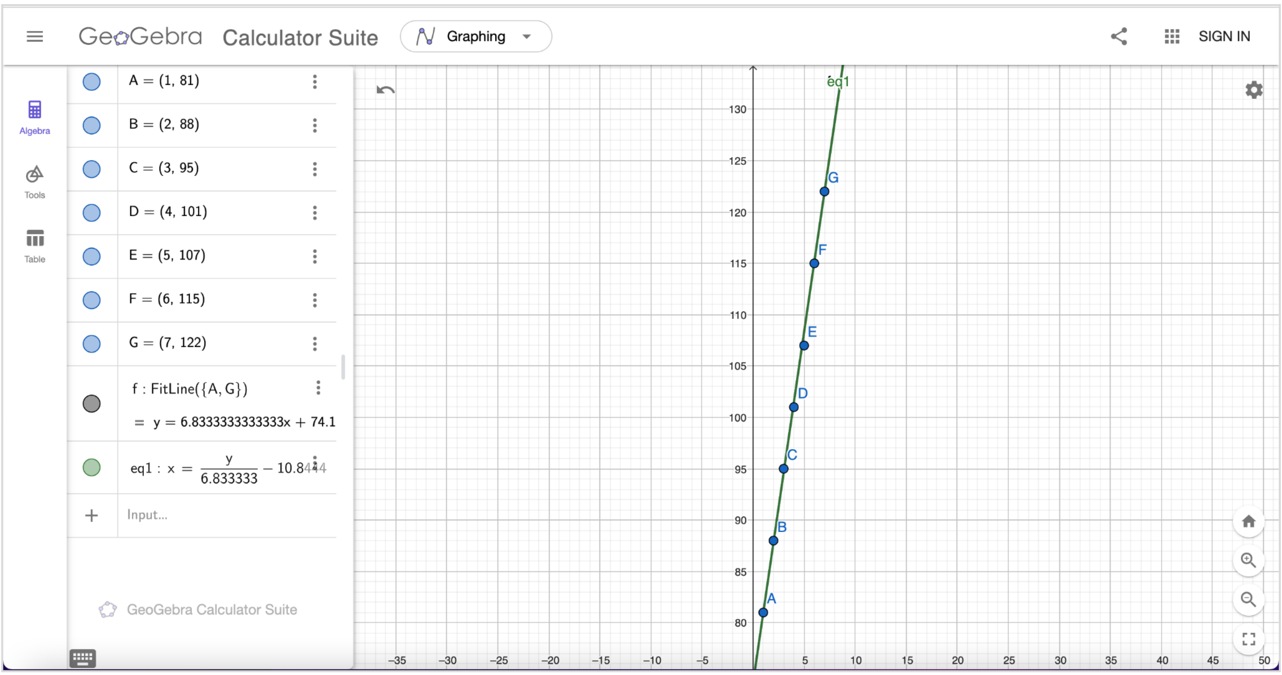
$$\therefore$$

$$x = (y / 6.8\overline{3}) - 10.844$$

The relationship between wind speed and analogue input is linear, so I can convert the two easily.

Resulting Graph

Fig 44.



Experimental Investigations

Experimental Investigation 1 - Outdoor Test #1

Type of Test: Outdoor test.
Duration of test: 10 mins approx.
Purpose: Initial testing of all equipment in advance of University of Limerick Wind Tunnel Testing.

Objectives:

Verify that the 4 Turbines Testing Unit works and accurately records data in the real world, irregular wind flow.
Test Anemometer electronics and communication with the laptop, and ensure that coolTerm can record the serial outputs.
Perform simultaneous testing and recording of 4 turbines.
Test all 3d printed models in blustery wind conditions.

Materials/Equipment Required

- Wooden mounting board for turbines
- Extension lead to power laptop and electronics
- 4 Turbine models, 2 x HAWT, 2 x VAWT
- Anemometer Arduino recording rig
- 4 turbines Arduino recording rig
- Laptop
- CoolTerm software
- Arduino IDE

Experimental Procedure:

1. 4 turbines were fixed to a mounting board.
    a. Model 2.1 - fixed to generator ID 1
    b. Model 4.2 - fixed to generator ID 2
    c. Model 3.1 - fixed to generator ID 3
    d. Model 1.1 - fixed to generator ID 4
2. All turbines were wired to the 4-turbine Arduino recording rig.
3. The Anemometer was connected to the Anemometer Arduino recording rig.
4. Both Arduino boxes were connected to a recording laptop.
5. Two serial connections were established to capture data from the Arduino boards.

6. Two CoolTerm instances were connected to record the serial data to individual files.
7. A stopwatch was used to time the test.
8. The Test ran for 10 minutes.
9. The synchronisation button on each Arduino unit was used to identify the data capture beginning and end as well as synchronise the recording for both Turbine and wind speed data.
10. The test data files were named and saved to the laptop.
11. Recorded data was viewed to verify the recording.

Test Outcome

1. Electronics, communications and raw data capture for Anemometer verified and working.
2. Electronics, communications and raw data capture for 4 turbines verified and working.
3. All 3D Prints for blades and mounts worked perfectly and withstood very blustery wind conditions. (~5 m/s)
4. Three out of the four models worked and recorded wind speed. The 3 bladed Darius model did not work effectively.

Fig 45.

Experimental Investigation 2

University of Limerick Wind Tunnel Test #1

Type of Test: Wind Tunnel Test (University *of* Limerick)
Wind Type: Controlled laminar flowing wind ranging from 1 m/s - 7 m/s
Duration of test: Each test lasted 4 minutes. A total of 13 tests were conducted.
Purpose: Calibration of Anemometer and testing of all turbines under wind tunnel conditions.

Objectives:

Test and calibrate Anemometer using the wind tunnel.
Test all turbine rotor design variations in laminar flow, wind speeds of 1 m/s - 7 m/s.

Materials/Equipment Required

- All turbine rotor models and motor housing assemblies
- Anemometer Arduino recording rig
- 4 turbine Arduino recording rig
- Laptop
- CoolTerm software
- Arduino IDE
- Wind Tunnel
- Screwdriver, screws, Kapton tape.

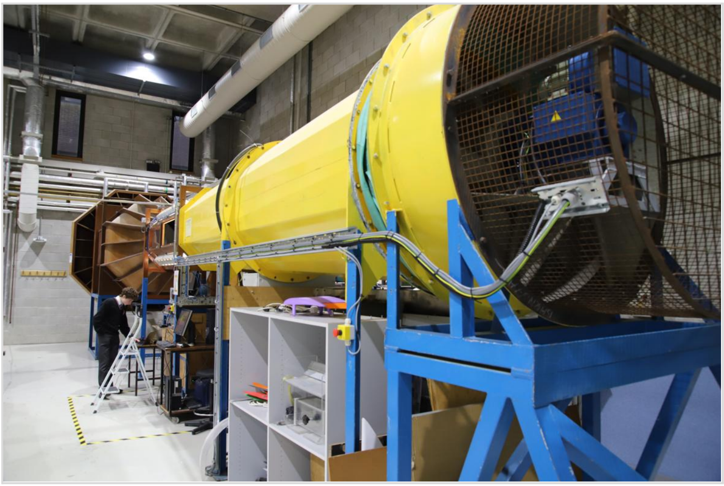
Wind Tunnel Specification

As provided by Adrian McEvoy:

The test Section is a Hexagonal Cross section, 920 mm across flats.
The test section is 2.32 M in length.
With Wind speeds of 0 to 24 M/s.
Equipped with a three-component balance.

Photographs of Wind Tunnel Testing Environment

Fig 46-48.



Experimental Procedure: Calibration of the Wind Tunnel Wind Speeds

Introduction

Before all testing the wind tunnel wind speeds needed to be calibrated. As the computer terminal inputs for driving the motor didn't align with measured wind speeds and are known to vary based on the air temperature.

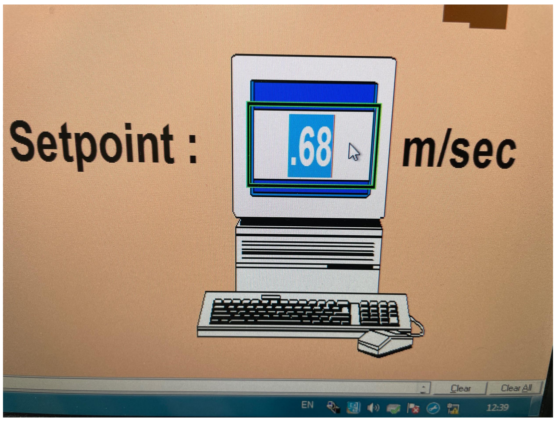
This was accomplished by gradually adjusting the motor computer until the required wind speeds of 1 m/s - 7 m/s were achieved. Then documenting the corresponding inputs and outputs for use later.

Procedure

1. Setpoint speeds were set using the motor control unit. These were changed incrementally until the desired wind speeds were recorded using a pressure-based micromanometer that was built into the wind tunnel. A Table was created to record all setpoint speeds for wind speeds ranging from 1 - 7 m/s (Table Below). This table was required to generate accurate wind speeds for the testing.

Photographs of Wind Tunnel Control Terminal, and Micromanometer

Fig 49, 50.



Setpoint Control of the Wind Tunnel Fan Motor

Micromanometer Reading

Final Table for Wind Speed Inputs

Fan Control Setpoint	Measured Wind Speed m/s
0.66	1 m/s
1	2 m/s
1.75	3 m/s
2.5	4 m/s
3.2	5 m/s
4	6 m/s
4.75	7 m/s

Conclusion

Now that I had figured out what Fan Control Setpoint represented 1 m/s - 7 m/s winds I could begin testing all of my designs, plus the anemometer in the same wind speeds throughout the same standardised test.

Experimental Procedure: Anemometer Calibration Using Wind Tunnel

Introduction

The purpose of this small test was to establish the format for testing all of the turbine rotor variations and also to calibrate the anemometer, capturing the recorded analogue values at increasing wind speeds.

Procedure

1. The Anemometer was installed in the wind tunnel using screws
2. Cable access openings were sealed using Kapton tape to prevent unnecessary turbulence.
3. The Anemometer was connected to the Anemometer Arduino recording rig.
4. The Anemometer Arduino recording rig was connected to a recording laptop.
5. A serial connection was established to capture data from the Arduino board.
6. A CoolTerm instance was established to record the serial data to file.
7. A stopwatch was used to time the test as follows.

    a. 0s The Synchronisation button was pressed to identify the beginning of the test.
    b. 0 - 30s - Wind Speed set to 1 m/s and allowed to settle
    c. 30 - 60s - Data captured with wind speed of 1m/s
    d. 60 - 90s - Data captured with wind speed of 2m/s
    e. 90 - 120s - Data captured with wind speed of 3m/s
    f. 120 - 150s - Data captured with wind speed of 4m/s
    g. 150 - 180s - Data captured with wind speed of 5m/s
    h. 180 - 210s - Data captured with wind speed of 6m/s
    i. 210 - 240s - Data captured with wind speed of 7m/s

8. The synchronisation button on the Anemometer Arduino unit was used to identify the start of the data capture, and each change in wind speed and to identify the end of the test period.
9. The analogue values from the Anemometer were recorded for each wind speed.

Conclusion

These recorded values would later be mapped using Geogebra to define the calculation required to apply to the measured analogue input to calculate accurate wind speeds using the anemometer.

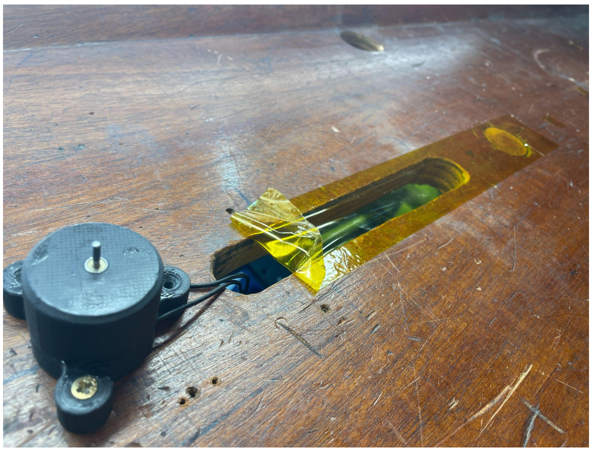
Fig 51.

Experimental Investigation: Voltage Generation Data Capture for all Rotors

The following procedure was undertaken for all turbine models.

Horizontal models were tested using the HAWT Tower Assembly.
Vertical models were tested using the VAWT Base Assembly.

Fig 52, 53.



Procedure

1. The HAWT mounting was installed and all HWAT designs were tested as per the procedure below. Once all HAWT models were tested, the VAWT mounting was installed and all models were tested as per the procedure below.
2. Cable access openings were sealed using Kapton tape to prevent unnecessary turbulence.
3. The turbine was connected to the wind Speed Arduino recording rig.
4. The Wind Speed recording rig was connected to a recording laptop.
5. A serial connection was established to capture data from the Arduino board.
6. A CoolTerm instance was established to record the serial data to file.
7. The appropriate turbine blade design was installed
8. A stopwatch was used to time the test as follows.

    a. 0s The Synchronisation button was pressed to identify the beginning of the test.
    b. 0 - 30s - Wind Speed set to 1 m/s and allowed to settle
    c. 30 - 60s - Data captured with wind speed of 1m/s
    d. 60 - 90s - Data captured with wind speed of 2m/s
    e. 90 - 120s - Data captured with wind speed of 3m/s
    f. 120 - 150s - Data captured with wind speed of 4m/s
    g. 150 - 180s - Data captured with wind speed of 5m/s
    h. 180 - 210s - Data captured with wind speed of 6m/s
    i. 210 - 240s - Data captured with wind speed of 7m/s

9. The synchronisation button on the Wind Speed Arduino unit was used to identify the start of the data capture, and each change in wind speed and to identify the end of the test period.
10. The voltage generation data was recorded for each wind speed.
11. All data files were named and saved to the laptop.
12. Recorded data was viewed to verify the recording.

To record the data of this experiment I modified the code on the 4 Turbine Module so that at any given time it would only print the measurements of the terminal block "Turbine 1", and print it into the serial and save automatically into a text file

Results and Conclusions

During this testing all of the HAWT models worked with no issues, as intended. Both motor housing assemblies withstood the forces and weren't damaged in any way. The VAWTs on the other hand were very surprising. Only a handful of the models worked, whereas others at the final speed of 7 m/s appeared to only be getting started and others were caught in this form of perfect equilibrium. After some discussion with Adrian McEvoy, the professor who helped me with this testing, he said that in the past students have done projects investigating the electricity-generated VAWTs and that unless the design had been optimised to be the best possible variation, it will not work in the wind tunnel. Now after further research, my suspicions were confirmed and I learned about how in reality VAWTs are designed to operate at their best in turbulent conditions and not the sanitary conditions of a wind tunnel. Hence why I decided to continue and retest in the wind tunnel, and then dedicate an outdoor test to investigating whether they would perform any better outdoors in turbulent wind conditions. The HAWTs worked exceptionally well in these laminar flow conditions.

Fig 54, 55.

Test Reference: 3 - University of Limerick Wind Tunnel #2

Type of Test: Wind Tunnel Test (University *of* Limerick)
Wind Type: Controlled wind speed from 1 m/s - 7m/s
Duration of test: Each new **VAWT rotor design** tested in wind speeds varying from 1m/s to 7m/s under wind tunnel conditions. Timings are detailed below.
Purpose: Further testing of Vertical Turbines in the wind tunnel conditions, to evaluate performance in laminar flowing winds.

Objectives:

1. Further Testing of Vertical Axis Wind Turbine Rotor designs.
2. Voltage to be applied to the turbine at wind speed changes to see if this would mimic turbulent wind flow and investigate whether this could initiate rotor movement.

Materials/Equipment Required

- All Vertical Turbine models
- 4 Turbine Arduino recording rig
- Laptop
- CoolTerm software
- Arduino IDE
- Wind Tunnel
- Screwdriver, screws, Kapton tape.

Experimental Investigation - Testing of New VAWT models

Procedure

1. The VAWT mounting was installed and all VAWT designs were tested as per the procedure below.
2. Cable access openings were sealed using Kapton tape to prevent unnecessary turbulence.
3. The turbine was connected to the wind Speed Arduino recording rig.
4. The Wind Speed recording rig was connected to a recording laptop.
5. A serial connection was established to capture data from the Arduino board.
6. A CoolTerm instance was established to record the serial data to file.
7. The appropriate turbine blade design was installed
8. A stopwatch was used to time the test as follows.

    a. 0s The Synchronisation button was pressed to identify the beginning of the test.
    b. 0 - 30s - Wind Speed set to 1 m/s and allowed to settle
    c. 30 - 60s - Data captured with wind speed of 1m/s
    d. 60 - 90s - Data captured with wind speed of 2m/s

e. 90 - 120s - Data captured with a wind speed of 3m/s
f. 120 - 150s - Data captured with wind speed of 4m/s
g. 150 - 180s - Data captured with wind speed of 5m/s
h. 180 - 210s - Data captured with wind speed of 6m/s
i. 210 - 240s - Data captured with wind speed of 7m/s

9. A voltage of 3V was applied to the turbine motor for one second after the wind speed change to see if this would mimic wind turbulence and provide enough energy for the turbine to start.
10. The synchronisation button on the Wind Speed Arduino unit was used to identify the start of the data capture, and each change of wind speed and to identify the end of the test period.
11. The voltage generation data was recorded for each wind speed.
12. All data files were named and saved to the laptop.
13. Recorded data was viewed, when printing to Serial to verify the recording.

Results and Conclusions

From the results of this experiment I was able to confirm and conclude that when the VAWTs were provided with a slight jerk of electricity at each increment to the next wind speed, they were able to cut in and begin producing electricity in the same laminar flow conditions that the other variations couldn't work in. This confirmed my suspicions about whether testing in the wind tunnel was actually representative of how the VAWTs would perform outdoors and I believe that this test also falsifies the testing of VAWTs in the controlled laminar flowing wind, as they simply aren't designed for it. As you will see in later outdoor experiments, even some of the variations that didn't generate electricity in the wind tunnel until the very end of the experiment begin generating at a mere fraction of the wind speeds.

Fig 56.

Experimental Investigation 4 - Outdoor Test #2

Fig 57.

Type of Test: Outdoor Test
Wind Type: Variable wind speed, (Average Wind Speeds 5-6m/s)
Duration of test: Each **Vertical turbine design** was tested in real-world wind conditions. Timings are detailed below.
Purpose: Further testing of Vertical Turbines in normal wind conditions

Objectives:

1. Further Testing of Vertical Turbine Models to evaluate effectiveness in real-world conditions.

Materials/Equipment Required

- Wooden mounting board for turbines
- 12v battery to power laptop and electronics

- All VAWT models only
- Anemometer Arduino recording rig
- 4 turbines Arduino recording rig
- Laptop
- CoolTerm software
- Arduino IDE
- Laptop
- CoolTerm software
- Arduino IDE

Experimental Investigation - Re-Testing of VAWT models

Procedure

1. The 4-turbine setup was used.
2. The 2 Vertical turbines were wired for this test (turbine 2 and turbine 3) and connected to the 4 turbine Arduino recording rig.
3. The Anemometer was connected to the Wind Speed Recording rig.
4. The 4-turbine Arduino was powered by a 12v battery.
5. The anemometer Arduino board was powered by the laptop via the connection cable.
6. The Anemometer recording rig was connected to the recording laptop.
7. The 4-turbine Arduino rig was connected to the recording laptop.
8. Two serial connections were established to capture data from both Arduino boards.
9. A CoolTerm instance was established to record the serial data to two files.
10. The appropriate Vertical Turbine designs were installed and tested in pairs
11. A stopwatch was used to time a 2-minute test for each pair of turbines
12. The synchronisation button on the Wind Speed Arduino unit and 4 turbine recording units was used to identify the start of the data capture and to identify the end of the test period.
13. The voltage generation data was recorded for each wind speed.
14. All data files were named and saved to the laptop.
15. Recorded data was viewed to verify the recording.

Results and Conclusions

From this experiment my hypothesis was proven correct, with nearly all VAWTs generating electricity at wind speeds a fraction of what they were running at in the wind tunnel. Two rotor models broke and failed to record data, they will be retested.

Fig 58.

For this testing, a van was used to keep the laptop dry as it was raining. (When testing the van was parked 10m away)

Test Reference: 5 - Outdoor Test

Fig 59.

Type of Test: Outdoor Test
Wind Type: Variable wind speed
Duration of test: 20 Minutes
Purpose: Test the top 4 turbine rotor designs (2 HAWT and 2 VAWT) in the same conditions.

Objectives:

1. Real-world Testing of all Turbine Models to evaluate effectiveness in real-world conditions.

Results and Conclusion

This test had to be abandoned after setup as wind speed exceeded 24m/s
(speeds of over double previous wind testing conditions)

Despite this I did manage to record the wind speeds just as the gusts began.

Test Reference: 6 - Outdoor Test

Fig 60.

Type of Test: Outdoor Test
Wind Type: Variable wind speed, (Average Wind Speeds 5-6m/s)
Duration of test: Timings detailed below. All **Turbine designs** were tested in real-world wind conditions. Timings are detailed below.
Purpose: Final testing of Turbines in normal wind conditions

Objectives:

1. Final testing of all Turbine Models to evaluate effectiveness in real-world conditions.
2. Conduct a 5-minute test for all models
3. Conduct a 30-minute parallel test for the top 4 performing models
4. Conduct a 10-minute comparison test between "Small" variations and the other 2 variations of the Convex Curved Blade HAWT

Materials/Equipment Required

- Wooden mounting board for turbines
- 12v battery to power laptop and electronics

- All Turbine models
- Anemometer Arduino recording rig
- 4 turbine Arduino recording rig
- Laptop
- CoolTerm software
- Arduino IDE

Experimental Procedure - Final Outdoor Testing of all models

Procedure

1. The 4-turbine setup was used.
2. All turbines were wired for this test and connected to the 4-turbine Arduino recording rig. This allowed the testing of designs in pairs.
3. The Anemometer was connected to the Wind Speed Recording rig.
4. The 4-turbine Arduino was powered by a 12v battery.
5. The anemometer Arduino board was powered by the laptop via the connection cable.
6. The Anemometer recording rig was connected to the recording laptop.
7. The 4-turbine Arduino rig was connected to the recording laptop.
8. Two serial connections were established to capture data from both Arduino boards.
9. A CoolTerm instance was established to record the serial data to two files.
10. The appropriate Vertical and Horizontal Turbine designs were installed and tested in pairs
11. A stopwatch was used to time a 5-minute test for each pair of turbines
12. The synchronisation button on both the Anemometer Arduino unit and 4 turbine recording units was used to identify the start of the data capture and to identify the end of the test period.
13. The voltage generation data was recorded for each wind speed.
14. All wind speeds were recorded.
15. All data files were named and saved to the laptop.
16. Recorded data was viewed to verify the recording.

(For this experiment a car was used in between the testing to keep the laptop dry as it was raining.)

z

The procedure above was undertaken to conduct a 5min test for all models
The procedure above was also undertaken to conduct a 30min test for the top 4 models identified from all testing to date
The procedure above was undertaken to conduct a 10 min side by side test of the 2 other variations of the convex curved HAWT blade against the best performing “Small” variation.

Conclusion

From this experiment I was able to test all of my turbine rotor design variations against each other in the same wind conditions. Very fortunately nothing went wrong and all data was collected.

Test Reference: 7 - 500w 24v Turbine Outdoor Test

Fig 61.

<u>Type of Test:</u> Outdoor Test
<u>Wind Type</u>: Variable wind speed, (Average Wind Speeds 2-7m/s)
<u>Duration of test:</u> 11 hours

Objectives:

1. Test the 500w Wind Turbine and anemometer in wind speeds between 2 m/s - 7 m/s over the course of 11 hours.

Materials/Equipment Required

- Wooden mounting boards for anemometer
- 12v battery to power laptop and electronics
- 500w wind turbine
- Anemometer and 500w Turbine Arduino recording rig
- Laptop

- CoolTerm software
- Arduino IDE
- Trailer
- 13 ft steel pole.
- Nuts and bolts provided with the turbine

Experimental Procedure - Final Outdoor Testing of all models

Procedure

1. With help from my Grandad, Uncle and Father I got the flange for the 500w Wind Turbine welded to the top of the 13 ft pole. Next, the 500w Wind Turbine was assembled and mounted to the flange at the top of the 13 ft pole using the nuts, bolts and spring washers that came with it.
2. Next we secured the pole assembly to the corner bar of a trailer using truck straps and positioned it in the front garden of their elevated house, at a total height of about 4 metres.
3. The 3 Phase output of the 500w turbine was converted to 24V 20A DC using the control box which came with the turbine and connected to the 500w and anemometer Arduino Board.
4. The Anemometer was connected to the Wind Speed Recording rig.
5. A CoolTerm instance was established to record the serial data to file.
6. The appropriate Vertical and Horizontal Turbine designs were installed and tested in pairs
7. The time at the beginning and end of the test experiment was noted.
8. The voltage generation data for the 500w Turbine was recorded.
9. All wind speeds were recorded.
10. The 85KB file was named and automatically saved to the laptop.
11. Recorded data was viewed in real-time to verify the recording.

Conclusion

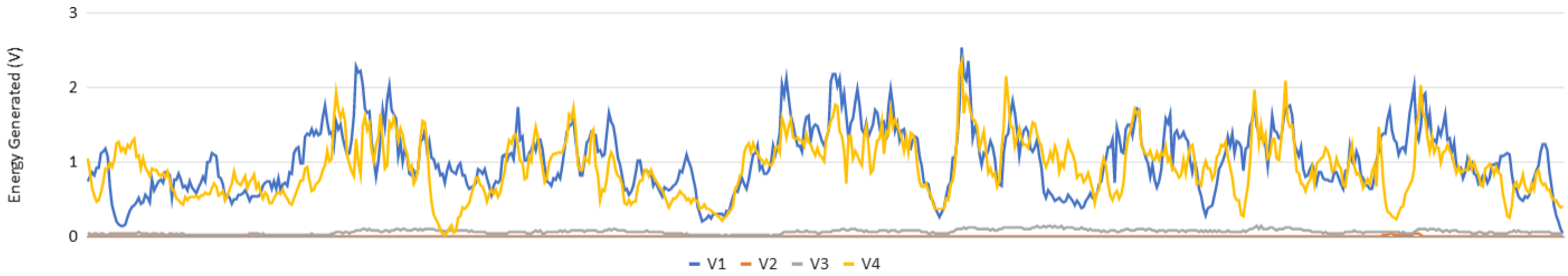
From this experiment I was able to capture and measure the electricity generated by the 500w Wind Turbine and the anemometer simultaneously over the course of 11 hours. From this test, I found that the wind turbine (with a wingspan of 1.35m and overall weight of 13Kgs) has a cut-in speed of between 3 m/s and 4m/s.

Experimental Data & Relevant Graphs

Test Reference: Test 1 - Outdoor Test

- The “Large” variations of the 4 turbine categories tested in parallel. The very first test I ran with the Arduino boards. Fig 62-64.

Model Number: 2.1	Model Number: 4.1	Model Number: 3.1	Model Number: 1.1
Small Curved __ HAWT	Darrieus Turbine - Small	Helicoid Turbine - Small	Small Straight HAWT

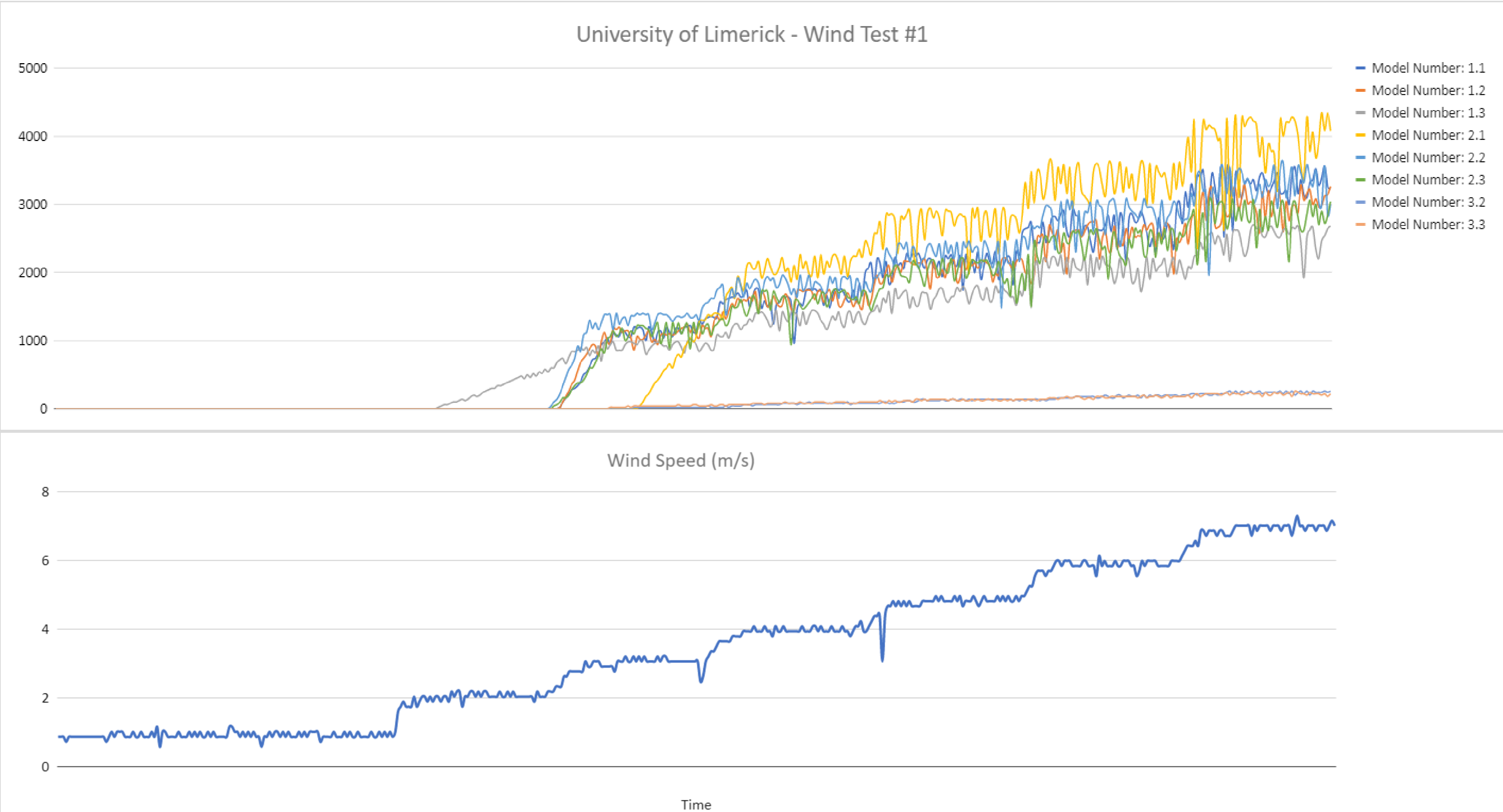


Model Number: 2.1		Model Number: 4.1		Model Number: 3.1		Model Number: 1.1	
2540.0	Max (mV)	40.0	Max (mV)	140.0	Max (mV)	2350.0	Max (mV)
40.0	Min (mV)	0.0	Min (mV)	0.0	Min (mV)	10.0	Min (mV)
1027.2	Avg (mV)	0.7	Avg (mV)	62.7	Avg (mV)	927.3	Avg (mV)

Test Reference: Test 2 - University of Limerick Wind Tunnel #1

- All models tested in wind tunnel conditions. The graph below displays an overall comparison between all of the turbines tested at UL #1. Fig 65.

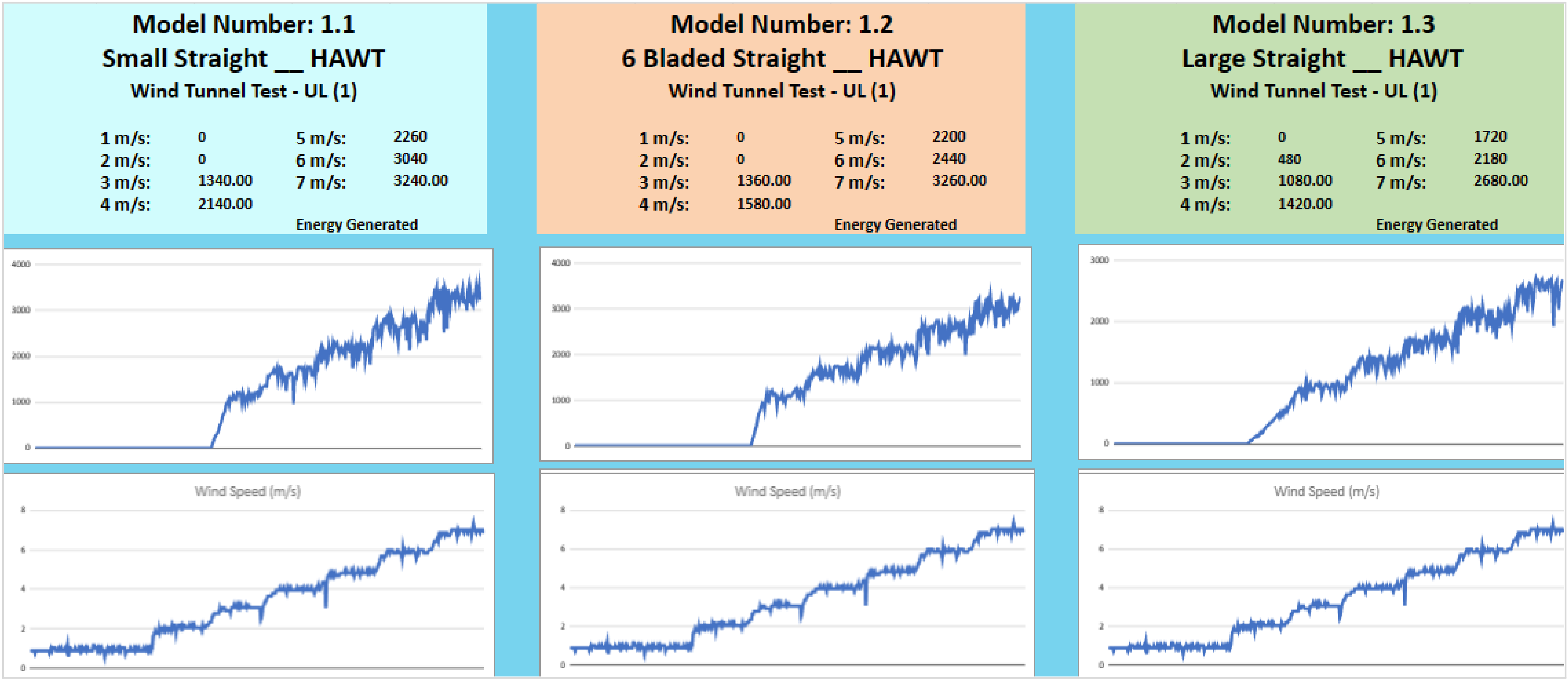
Overall Comparison



Individual Rotor Test Data - Straight Bladed HAWT

Below are the results from the Straight Bladed HAWT Category. The figures in the coloured boxes at the top represent mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test.

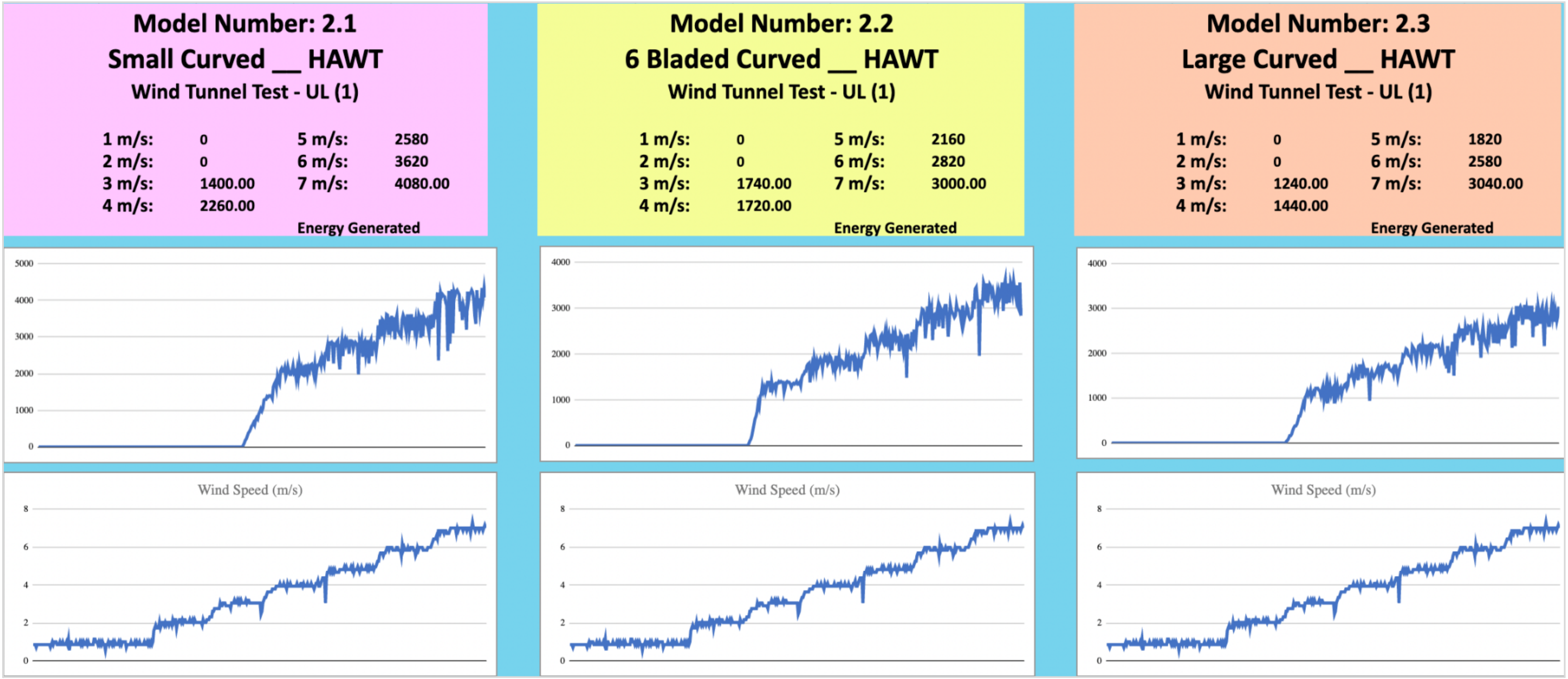
Fig 66.



Individual Rotor Test Data - Curved Bladed HAWT

Below are the results from the Convex Curved Bladed HAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test.

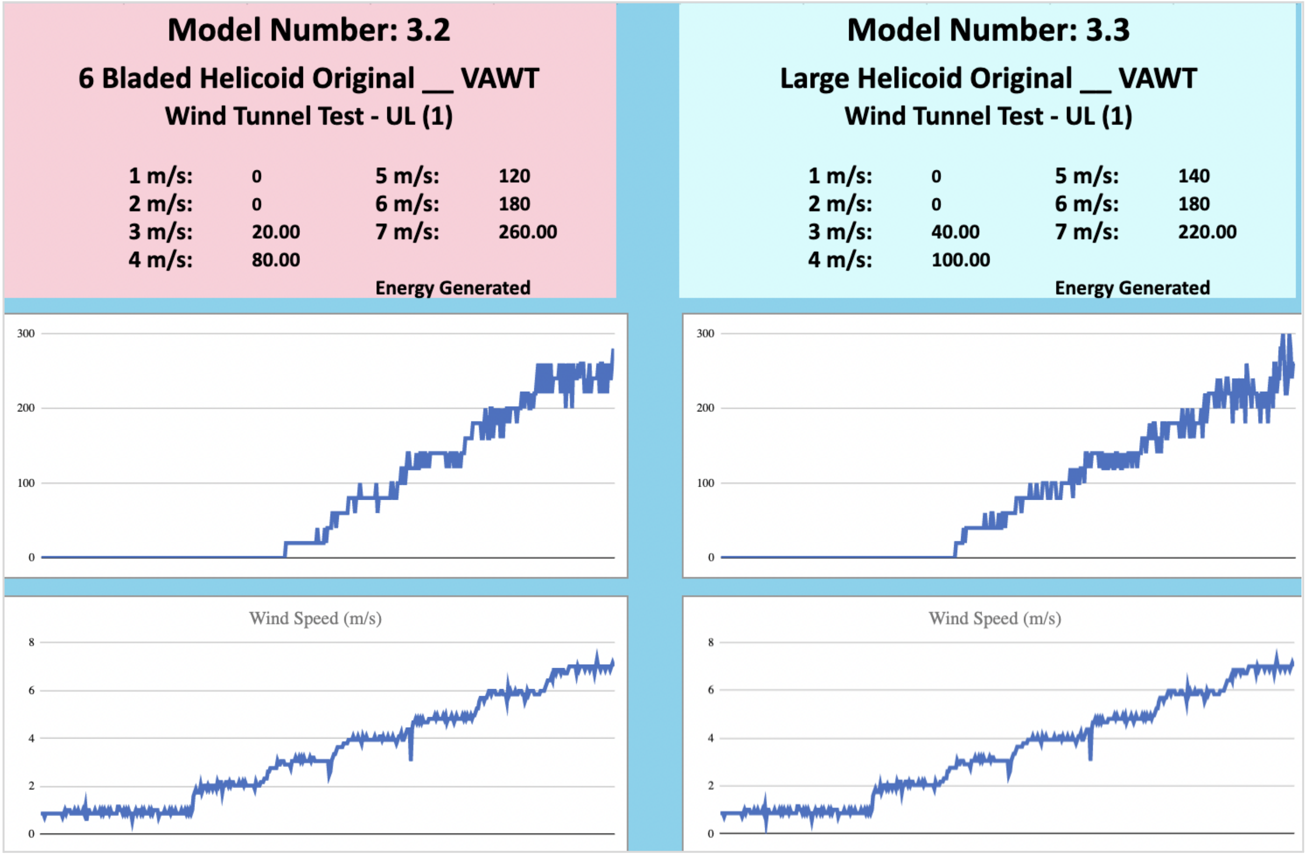
Fig 67.



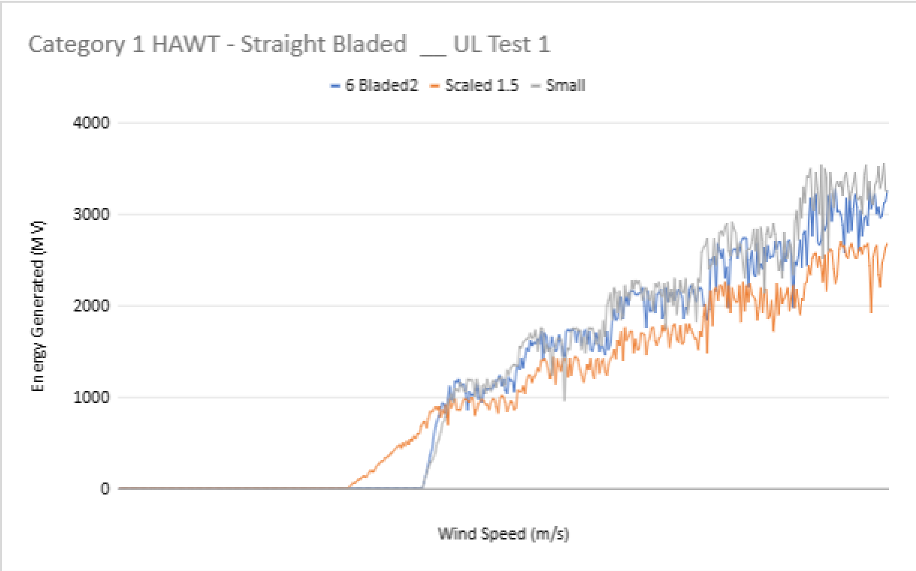
Individual Rotor Test Data - Helicoid VAWT

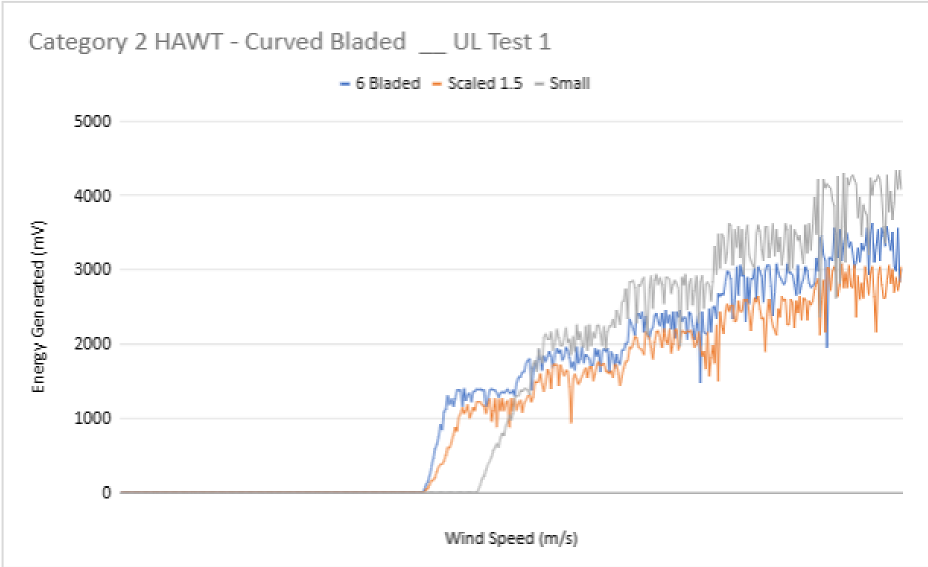
Below are the results from the Helicoid VAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test. In this test, the “Small” variation of this rotor did not generate any energy.

Fig 68.



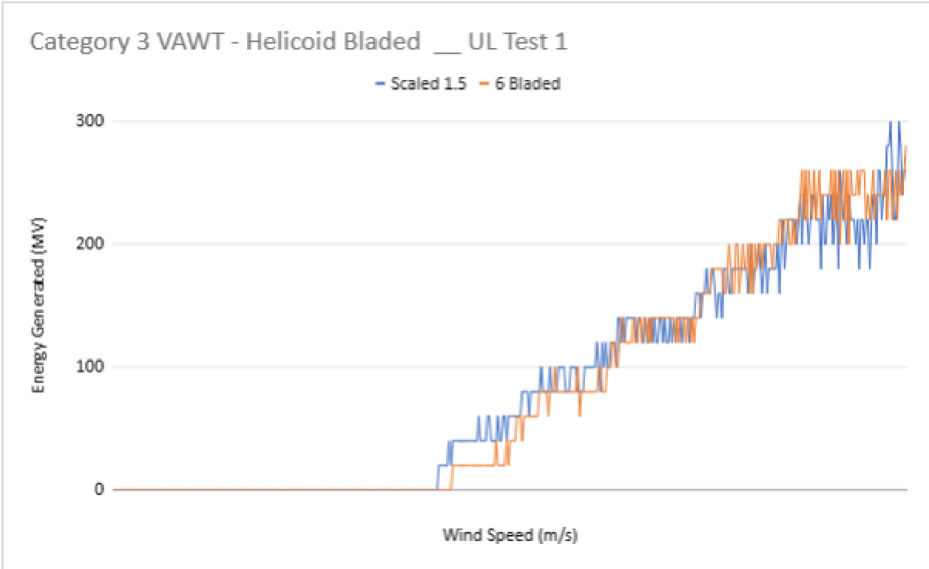
Individual Rotor Test Data - Design Categories



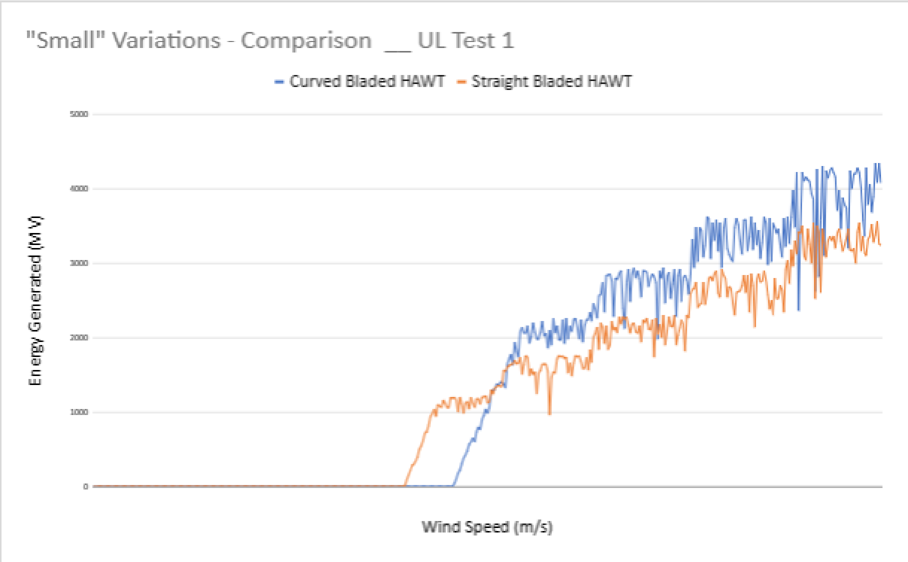


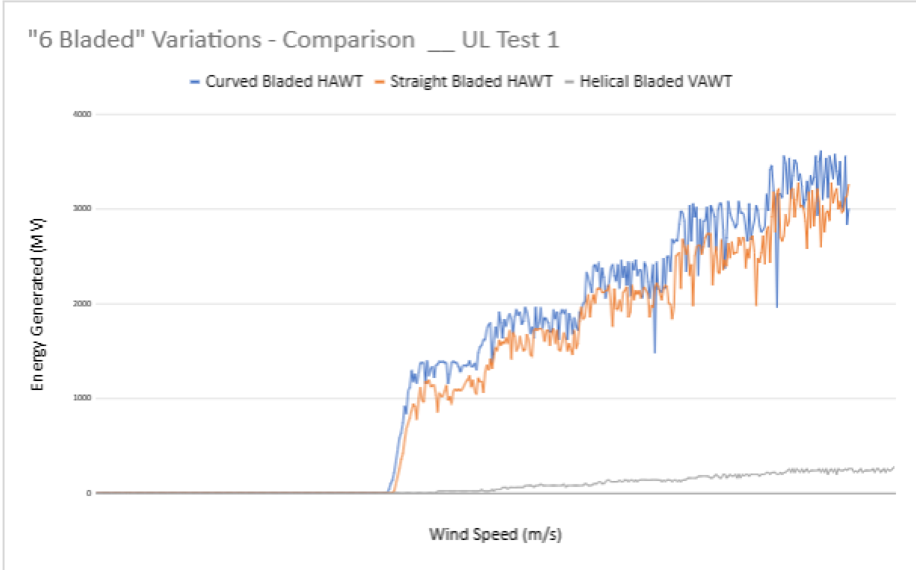
Here are the results gathered from each wind turbine category. Each graph represents the electricity generated over the course of the test. In this experiment, the Darrieus VAWT category didn't generate any energy, and the "Small" variation of the Helicoid VAWT did not generate any electricity either.

As it can be seen, the HAWTs had no issue getting started generating electricity. With the "Small" variations of each consistently outperforming all other variations, yet consistently cutting in later. For the Straight Bladed HAWT, the "6 Bladed" variation cuts in at much lower wind speeds yet maintains similar levels of electricity generation. Interestingly the "6 Bladed" and "Large" variations of the Curved Bladed HAWT cut in at around the same time yet performed considerably less than its "Small" variation counterpart. Both variations of the Helicoid VAWT performed similarly. Fig 69-71.



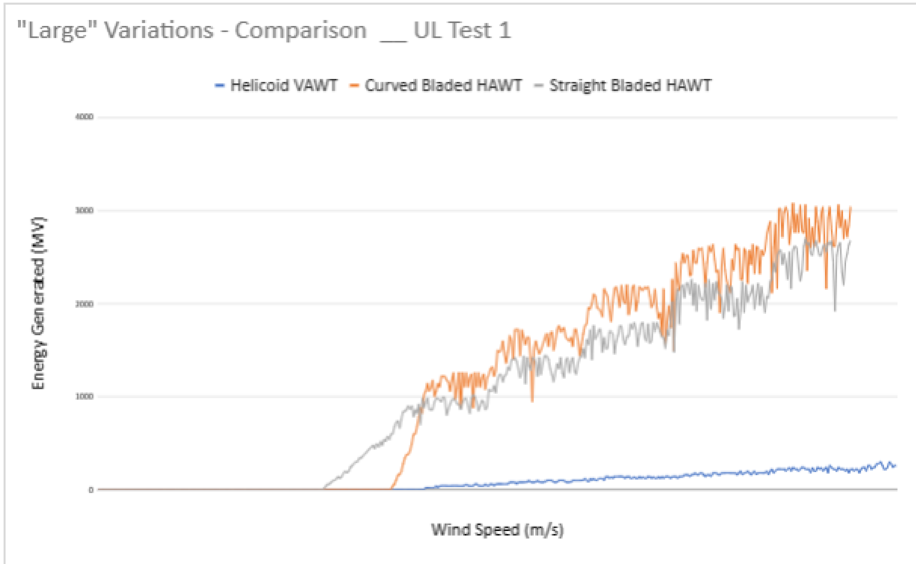
Individual Rotor Test Data - Category Variation





Here are the results gathered from each wind turbine category variation. Each graph represents the electricity generated over the course of the test. In this experiment, the Darrieus VAWT category didn't generate any energy, and the "Small" variation of the Helicoid VAWT did not generate any electricity either. (Fig 72-74)

The "Small" variation of the Curved Bladed HAWT, while it cut in considerably later than its Straight Bladed counterpart, generated significantly more electricity for the rest of the test. The "6 Bladed" HAWT variations were incomparable to Helical VAWT, with interestingly the "6 Bladed" Curved Bladed HAWT cutting in at a slightly lower wind speed than the Straight Bladed HAWT, and outperforming it for the rest of the test. The "Large" Curved Bladed HAWT cut in considerably later than the Straight Bladed, yet got up to speed in about half the time it took the other rotor.



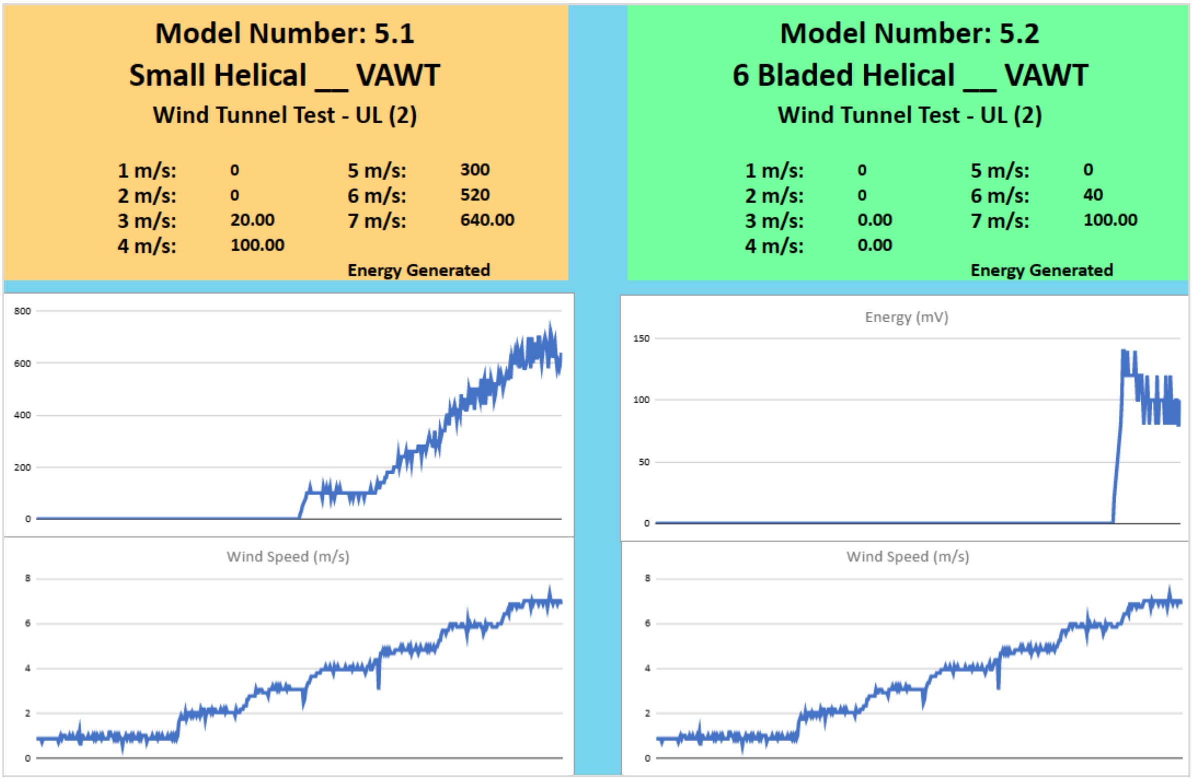
Test Reference: Test 3 - University of Limerick Wind Tunnel #2

- The VAWT retests at the wind tunnel.

Individual Rotor Test Data - Helix VAWT

Below are the results from the Helical VAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test.

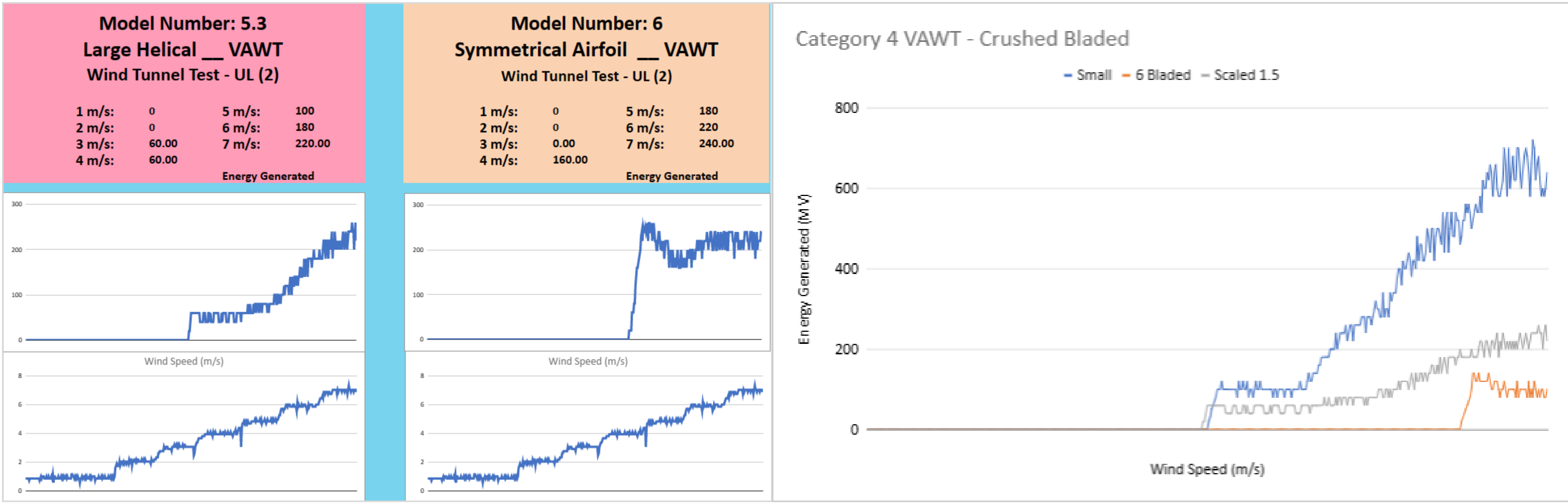
Fig 75.



Individual Rotor Test Data - Helix VAWT & Category Comparison

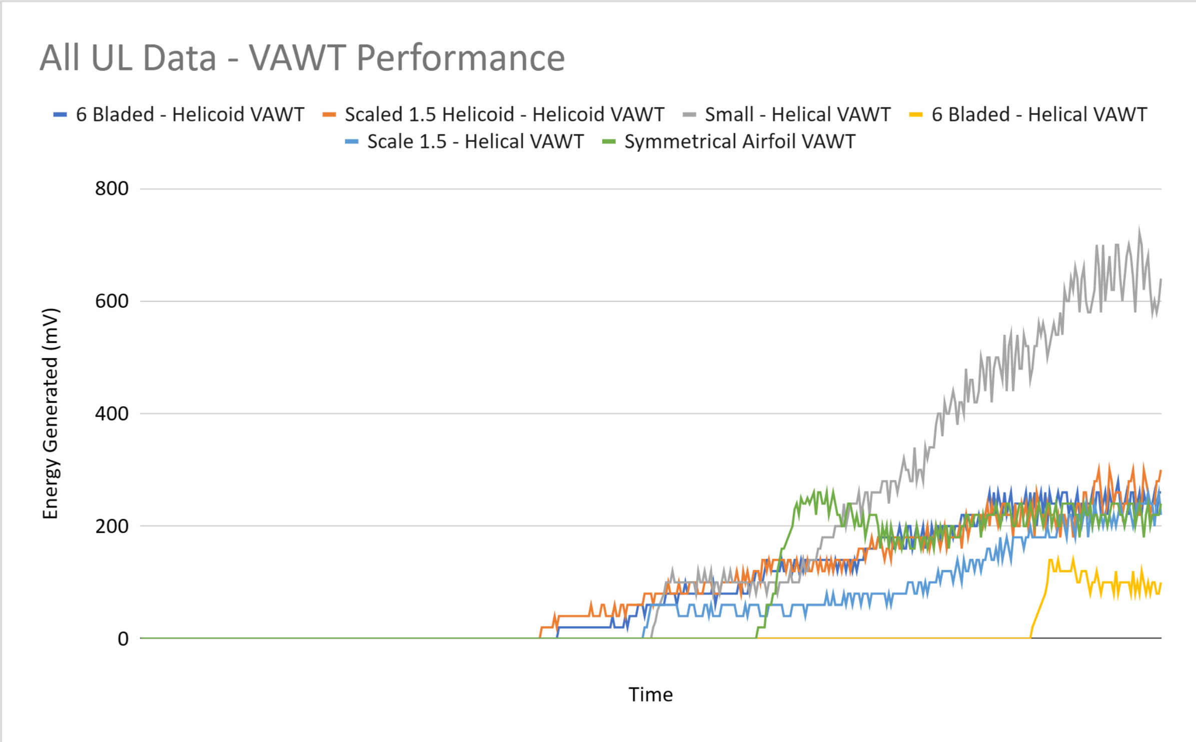
Below are the results from the Helical and Symmetrical Airfoil VAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test. The graph to the right represents all of the VAWT models from this category compared against each other.

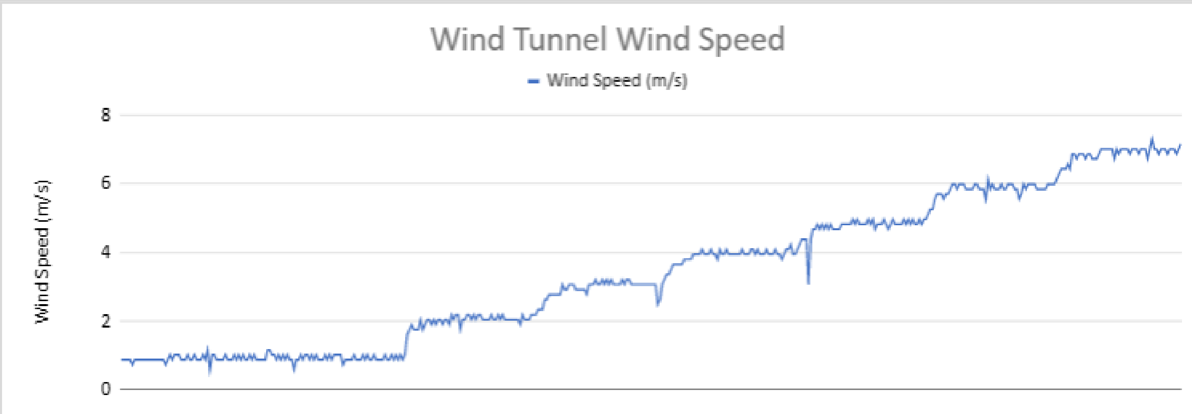
Fig 76.



All Test Data - VAWT Performance

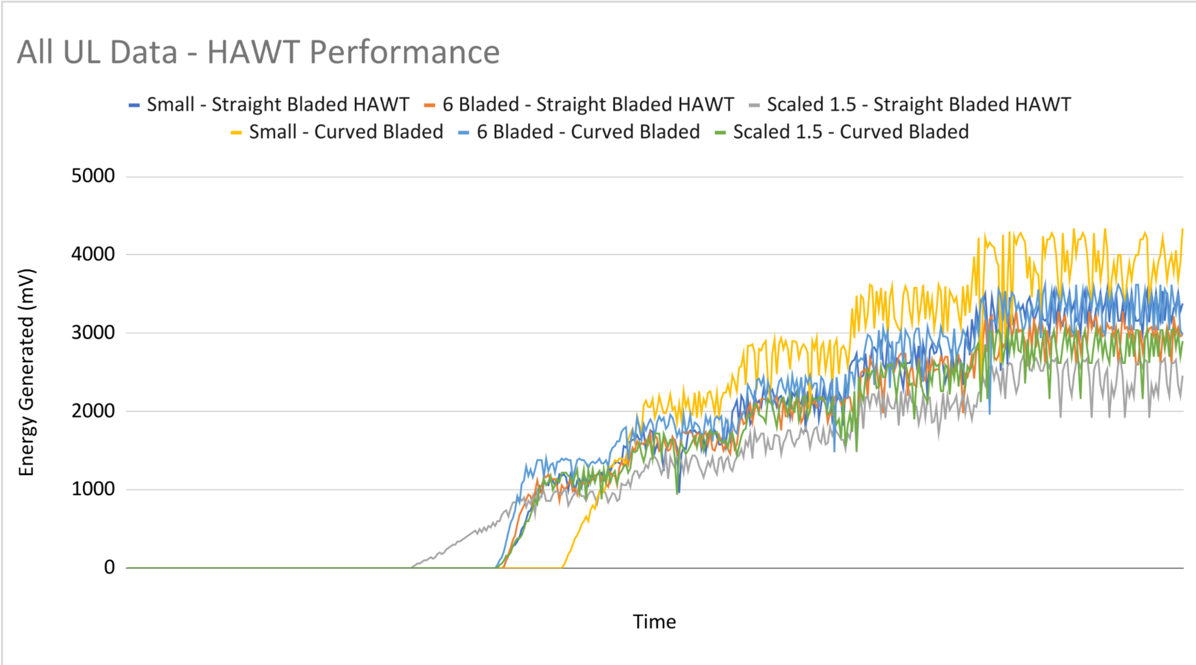
Below is a comparison of the performance of all VAWT models throughout all of the UL tests. Fig 77, 78.

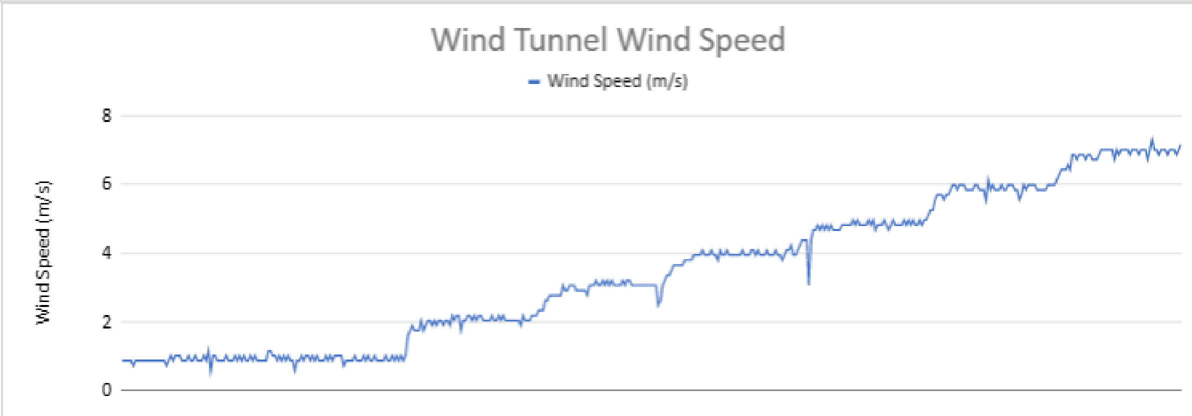




All Test Data - HAWT Performance

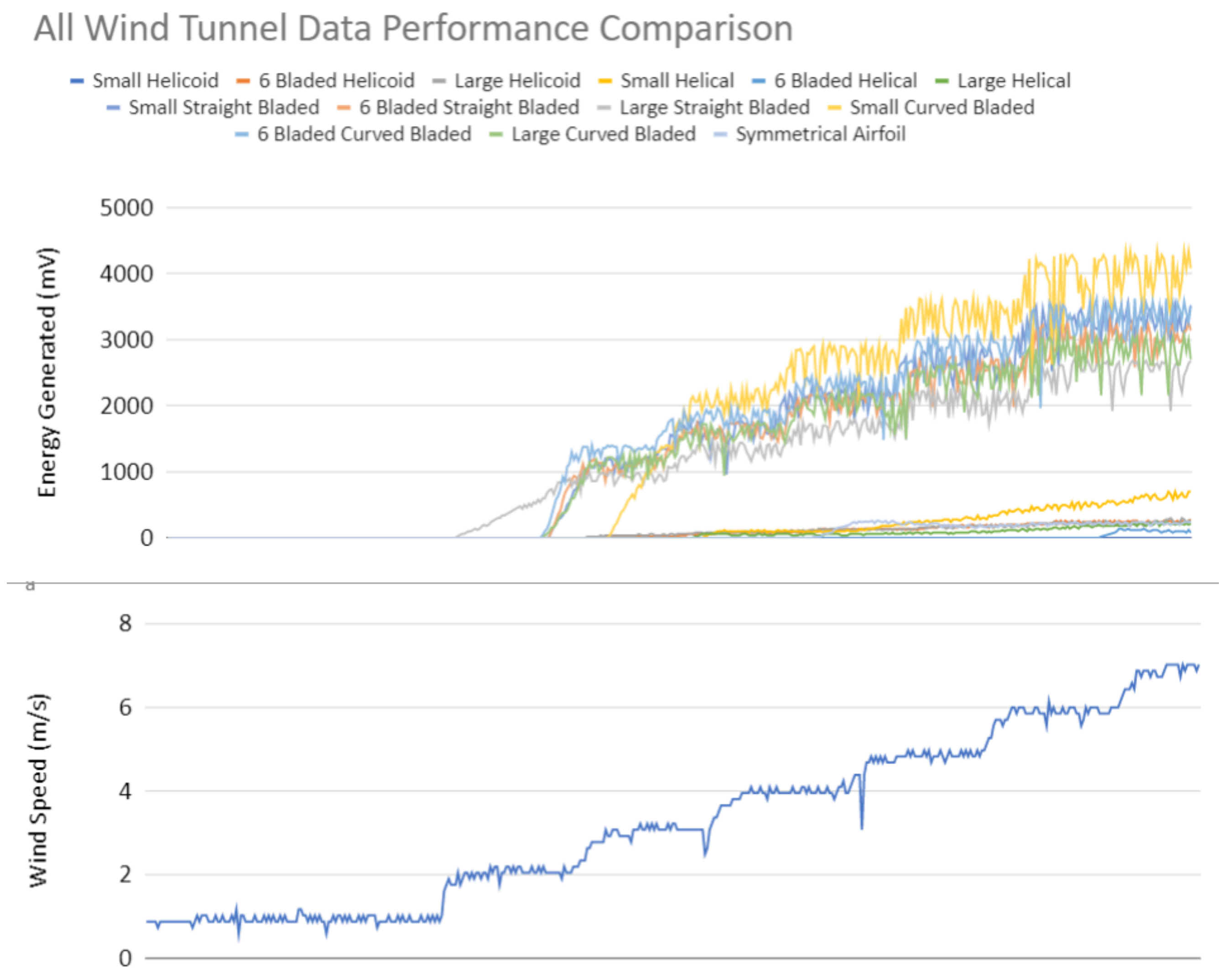
Below is a comparison of the performance of all HAWT models throughout all of the UL tests. Fig 79, 80.





All UL Test Data - VAWT & HAWT Performance

Below is a comparison of the performance of all turbine rotor models throughout all of the UL tests. Fig 81, 82.

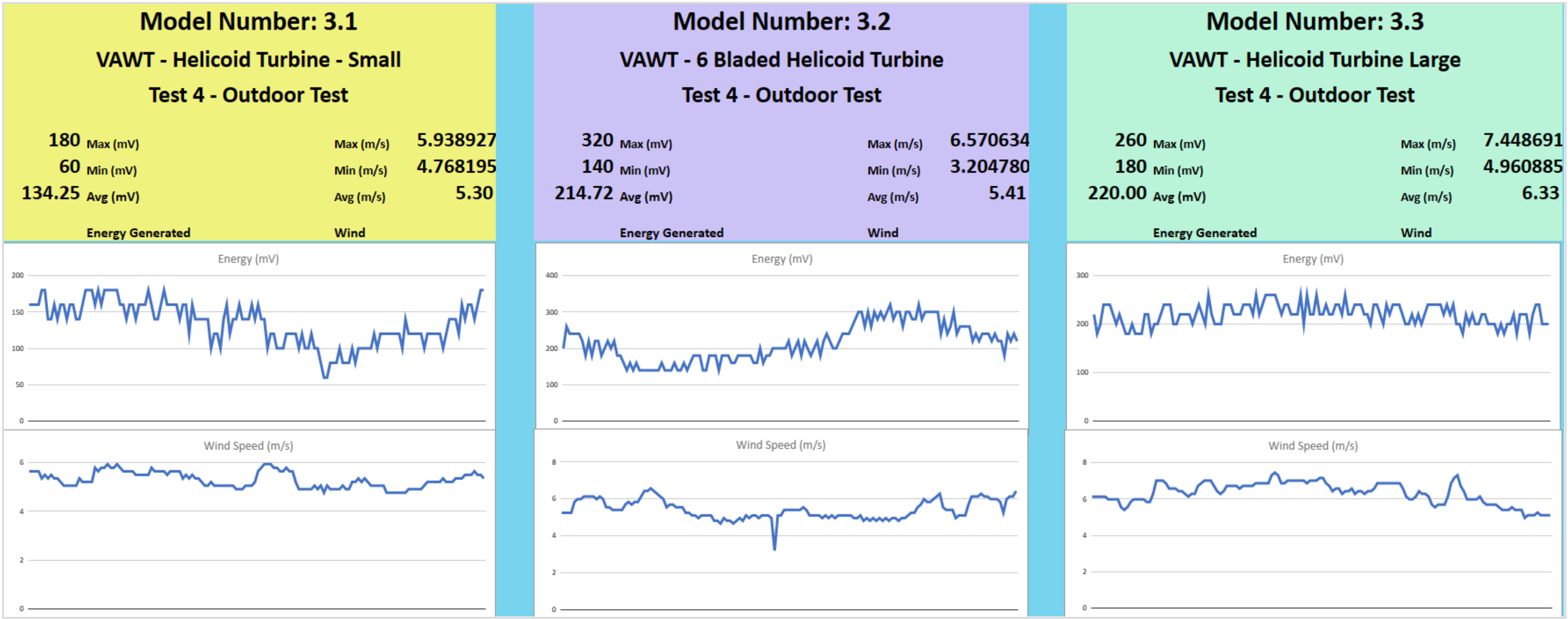


Test Reference: Test 4 - Outdoor Test for Verifying VAWT Models

- The outdoor test where I investigated whether the VAWTs performances improved in turbulent winds.

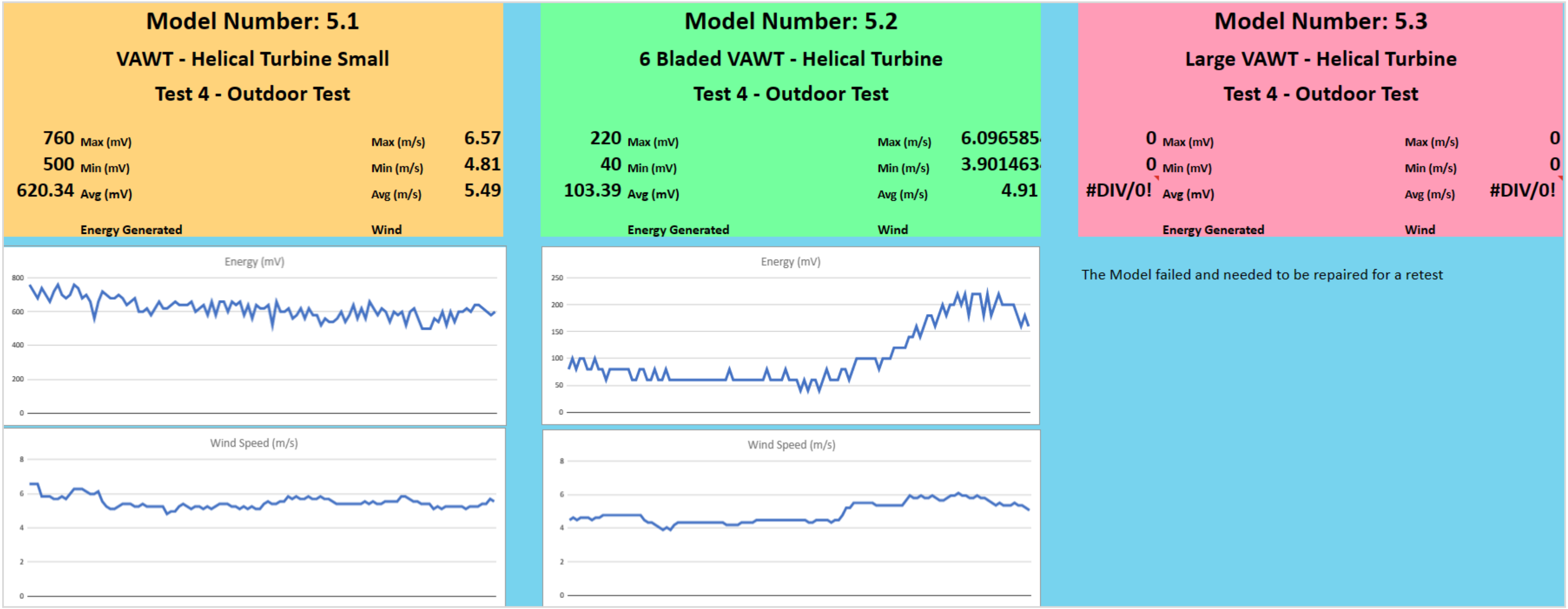
Rotor Category Test Data - Helicoid VAWT

Below are the results from the Helicoid VAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test. Fig 83.

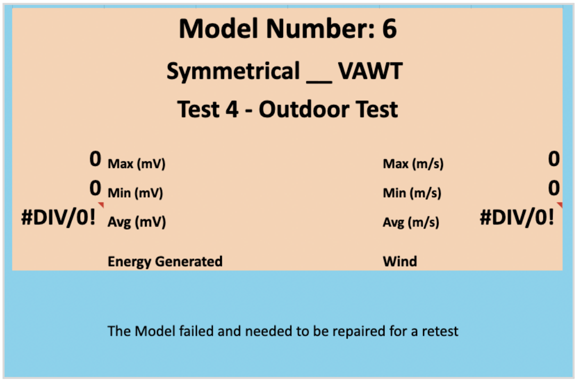


Rotor Category Test Data - Helical VAWT

Below are the results from the Helical VAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test. Fig 84, 85.



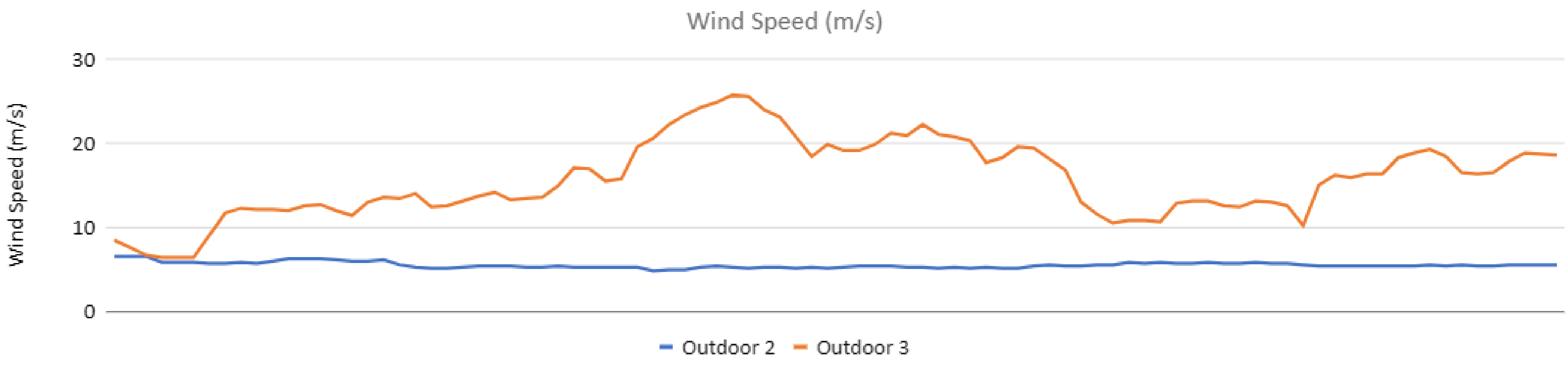
Rotor Category Test Data - Symmetrical VAWT



Test Reference: Test 5 - Abandoned Outdoor Test

Note: This Test had to be abandoned due to weather conditions. I did serve as a good test of the anemometer in extreme wind conditions.
The graph below illustrates the recorded wind speeds. The blue line illustrates the average wind speed for previous tests, and the red line shows the gusting winds of up to 25 m/s from this abandoned test.

Fig 86.

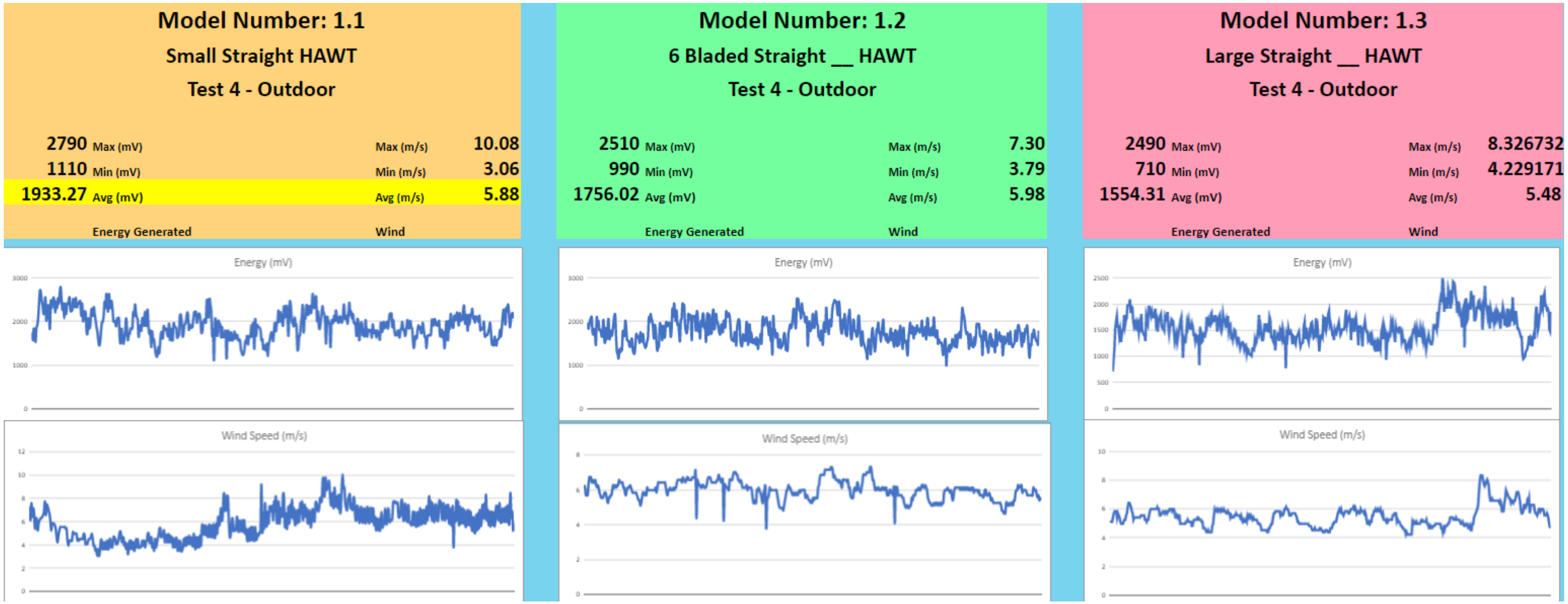


Test Reference: Test 6a - Final Outdoor Test
All models - 5 mins Test.

Rotor Category Test Data - Straight-Bladed HAWT

Below are the results from the Straight-Bladed HAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test.

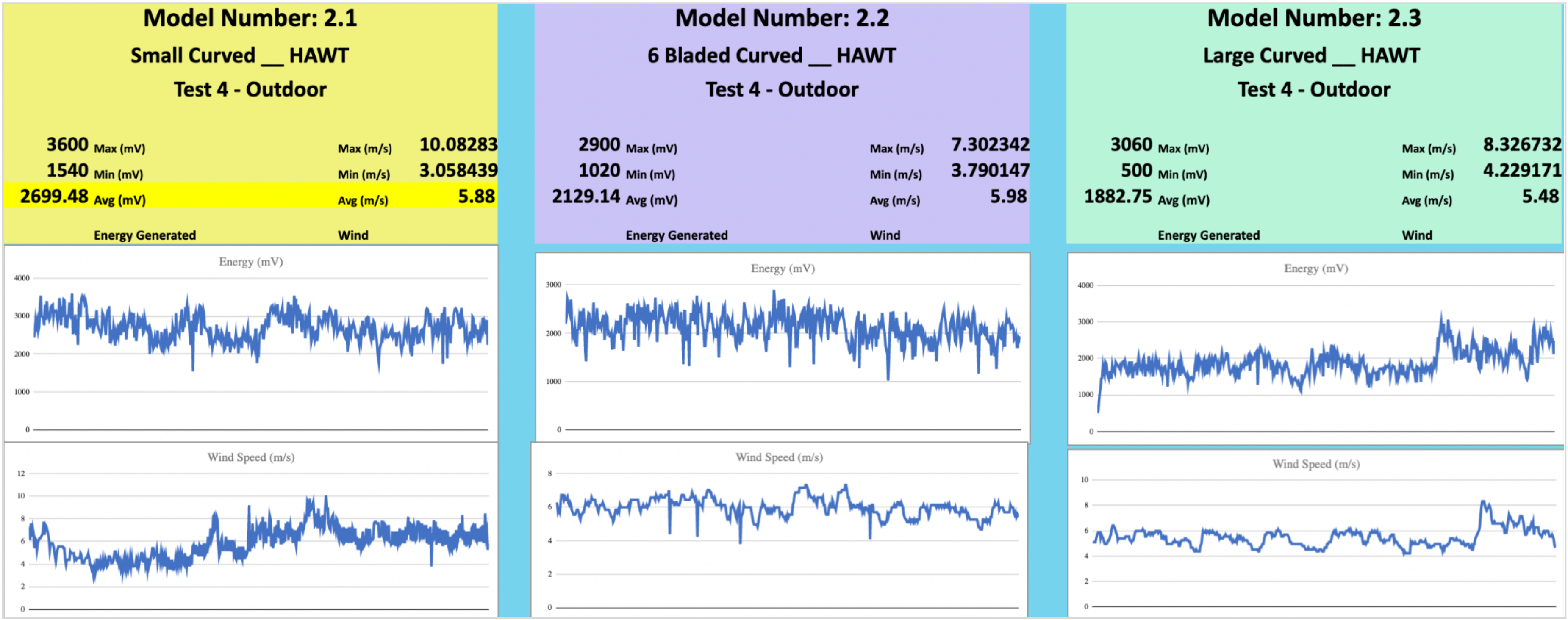
Fig 87.



Rotor Category Test Data - Straight Curved HAWT

Below are the results from the Curved Bladed HAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test.

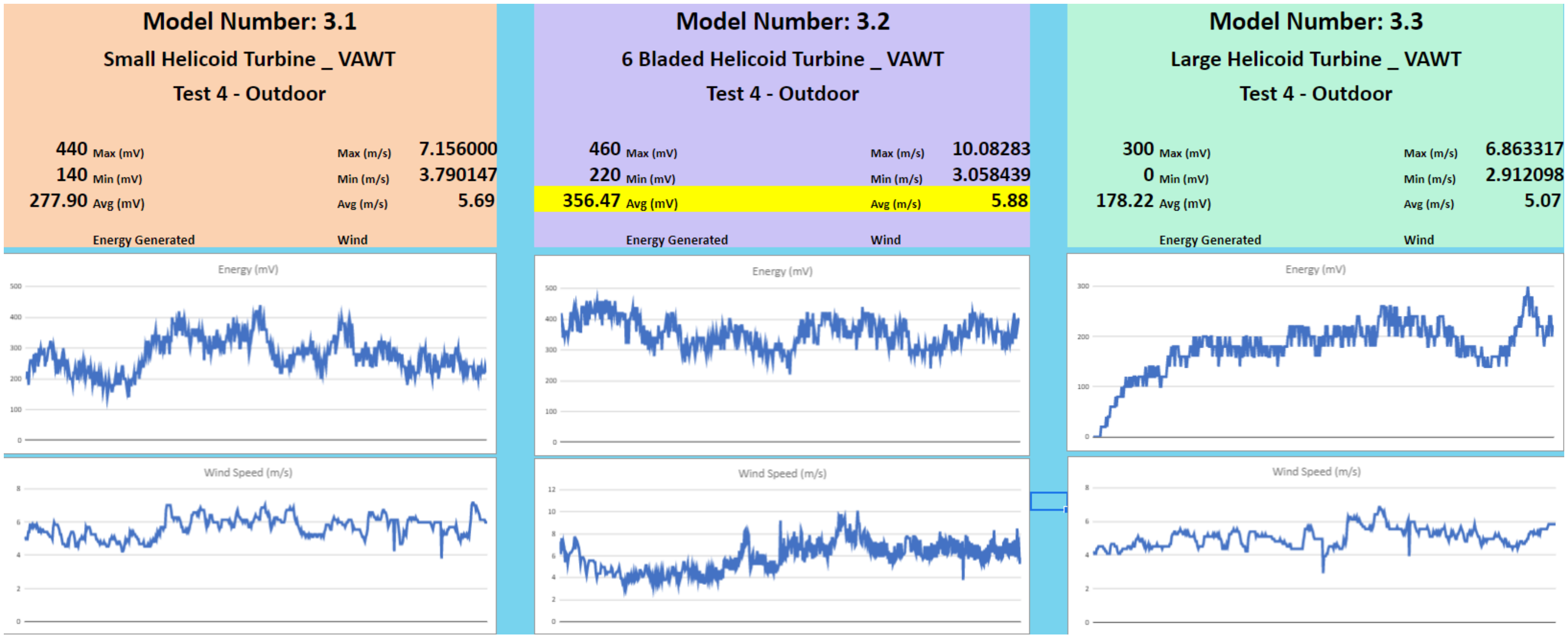
Fig 88.



Rotor Category Test Data - Helicoid Bladed VAWT

Below are the results from the Helicoid Bladed VAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test.

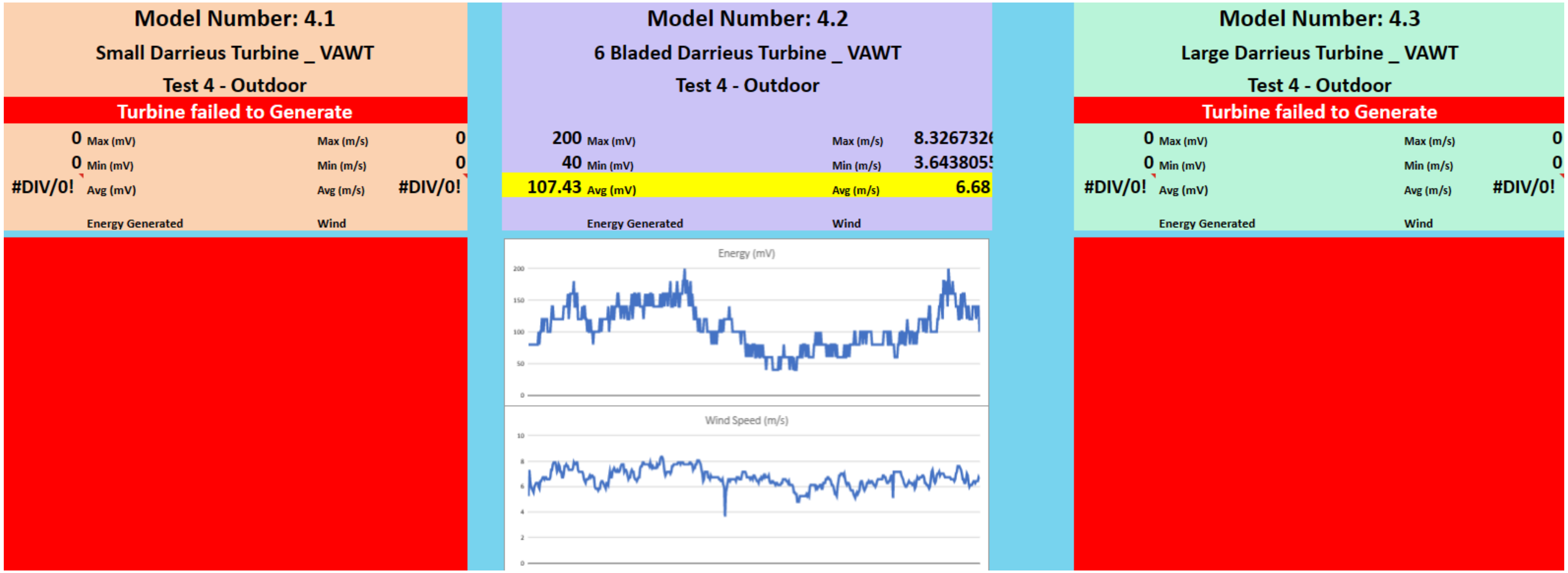
Fig 89.



Rotor Category Test Data - Darrieus VAWT

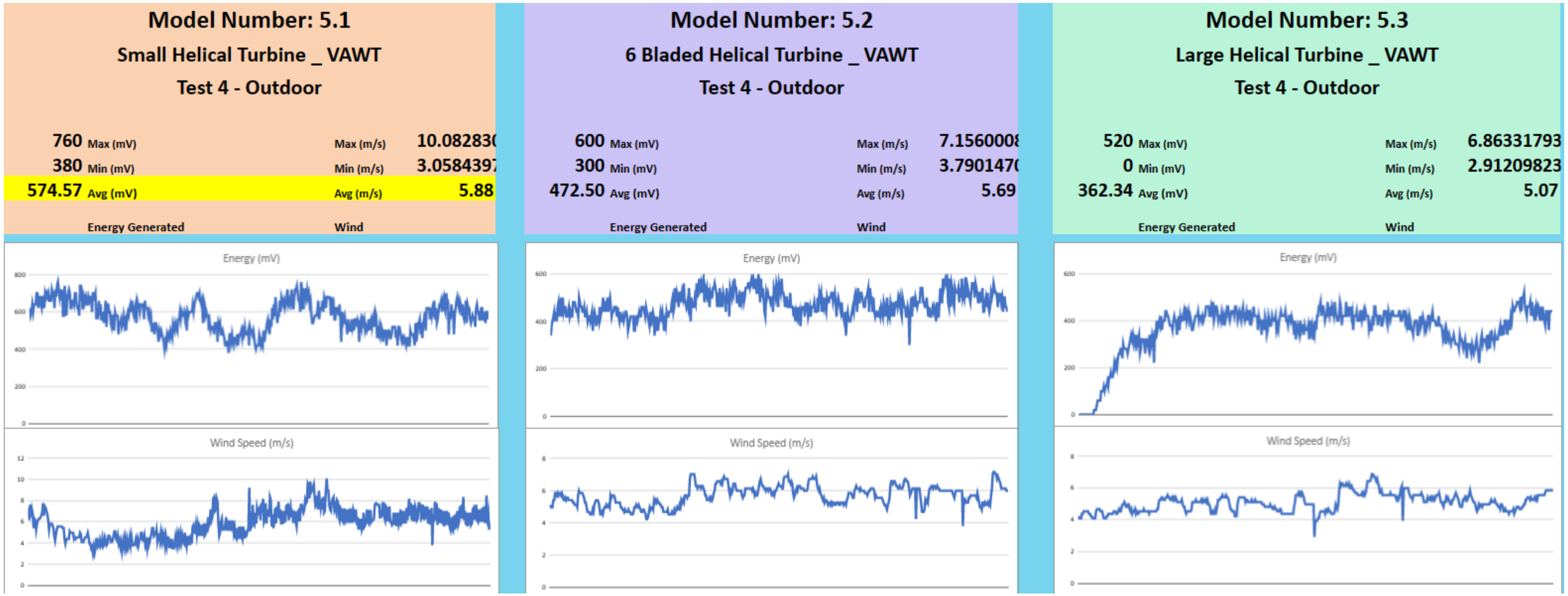
Below are the results from the Darrieus VAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test.

Fig 90.

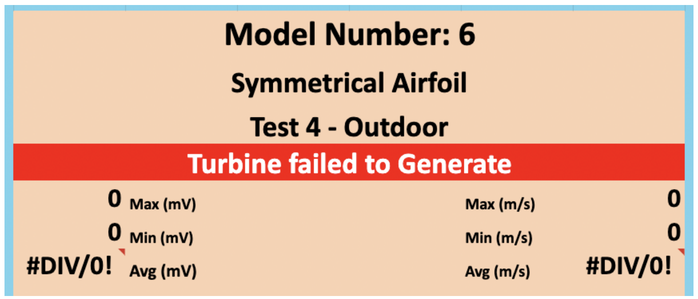


Rotor Category Test Data - Helical VAWT

Below are the results from the Helical VAWT Category. The figures in the coloured boxes at the top represent the mV generated at each wind speed. The graphs below each represent the energy generated by the turbine over the course of the test. Fig 91, 92

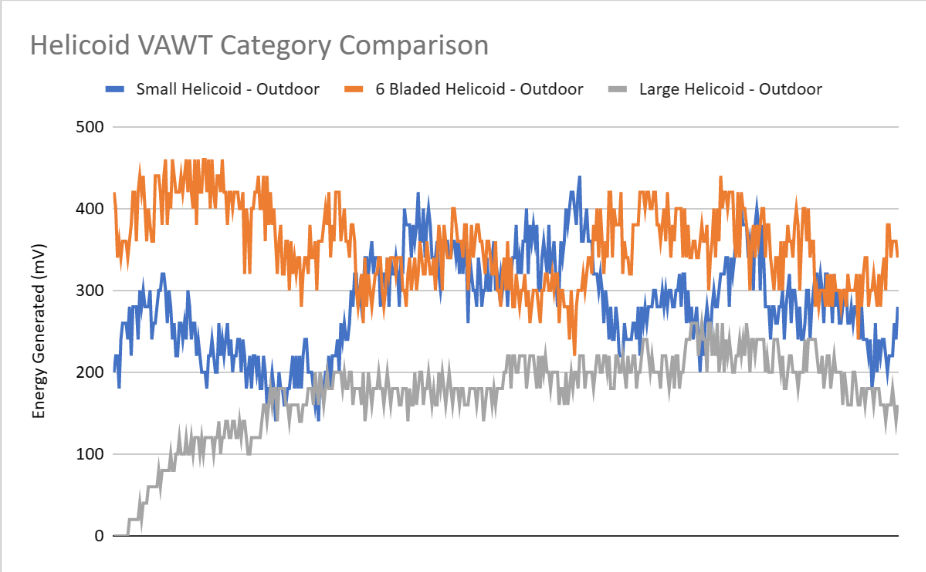


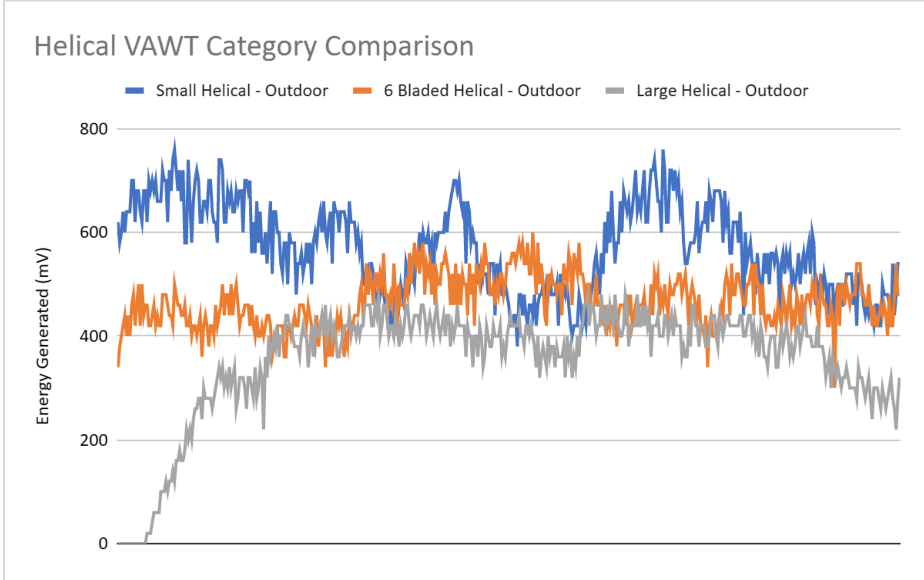
Rotor Category Test Data -Symmetrical Airfoil VAWT

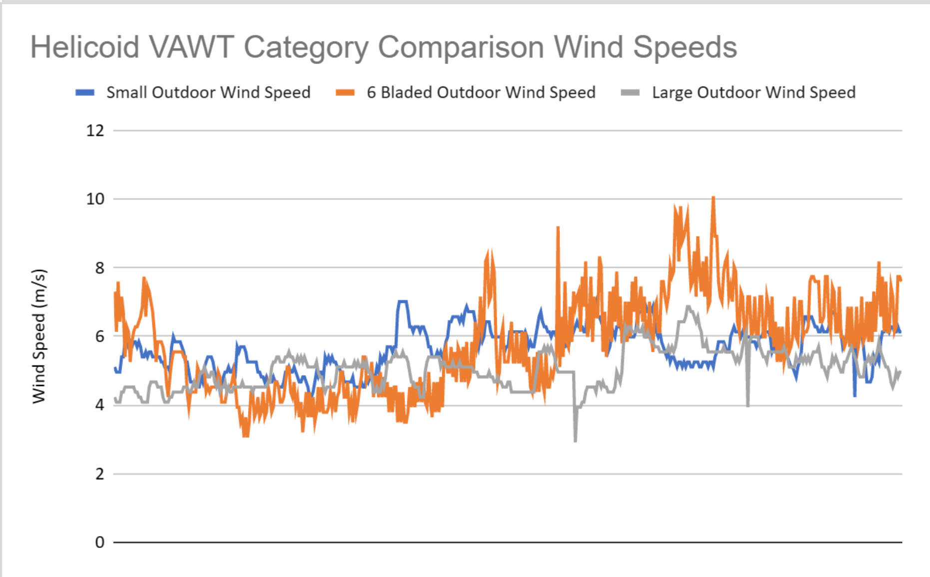


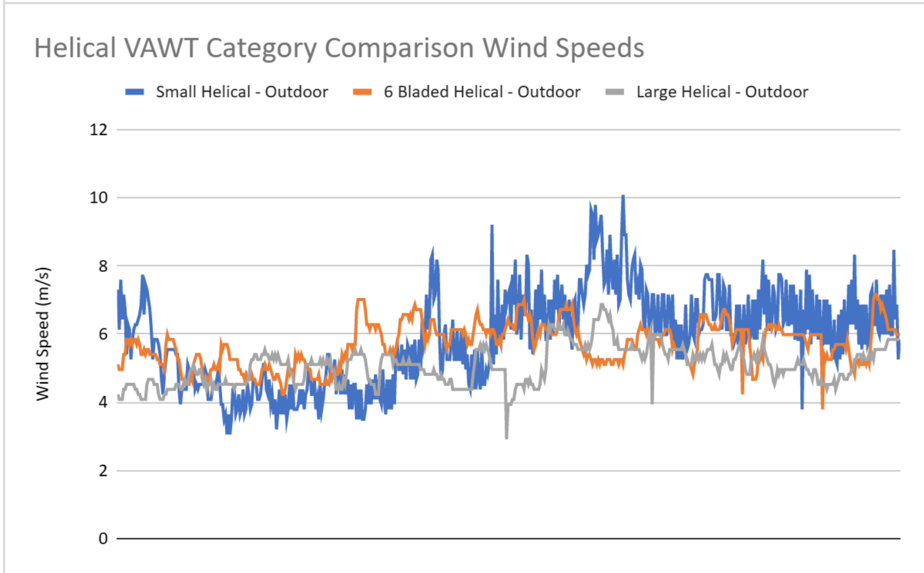
Individual Rotor Test Data - VAWT Design Categories

Below are the results from the VAWT Categories. The graphs below each represent the energy generated by each turbine from each category over the course of the test, and their respective testing wind speeds. Fig 93-96.



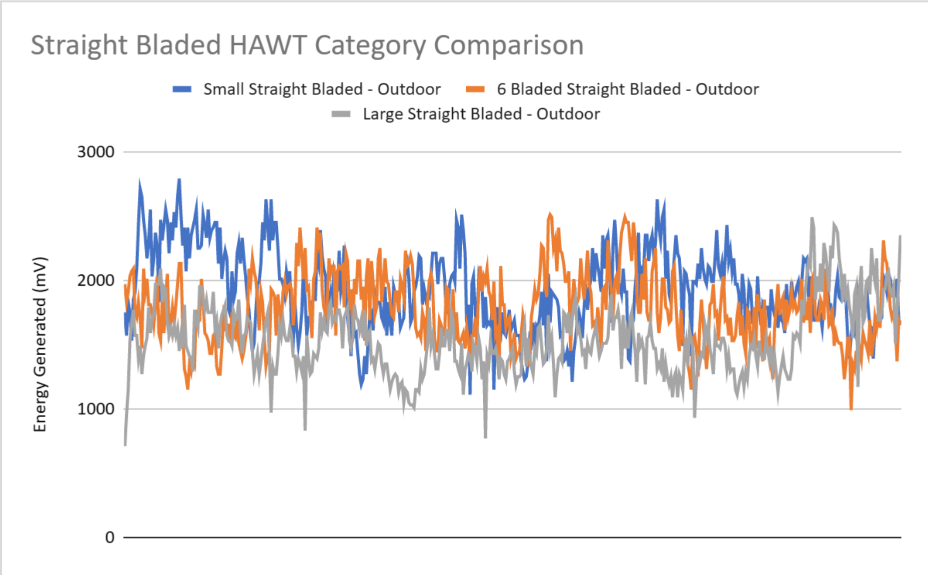


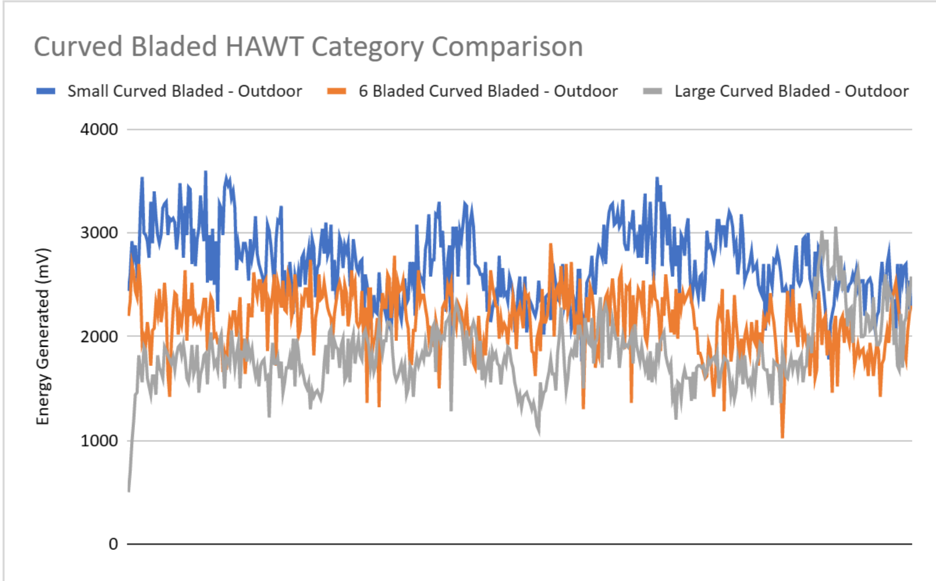


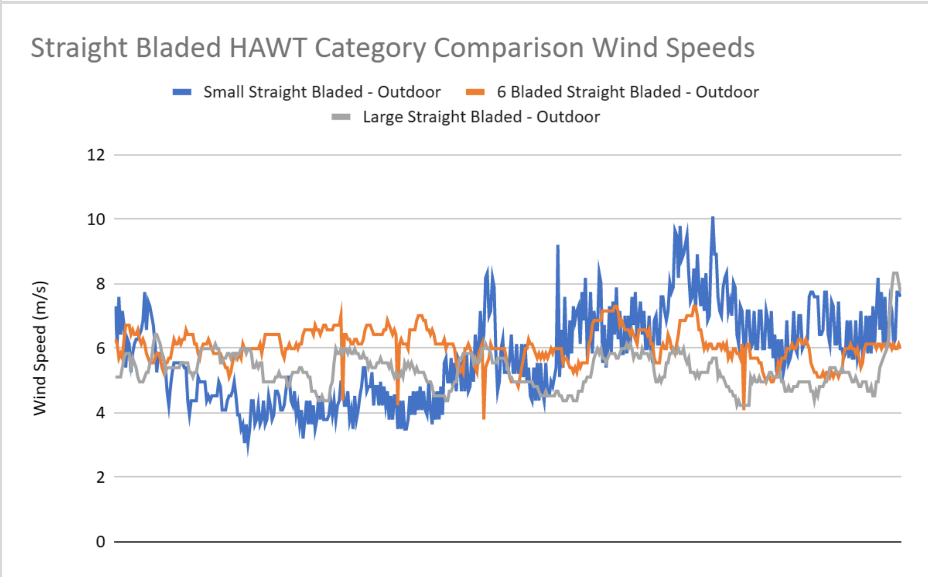


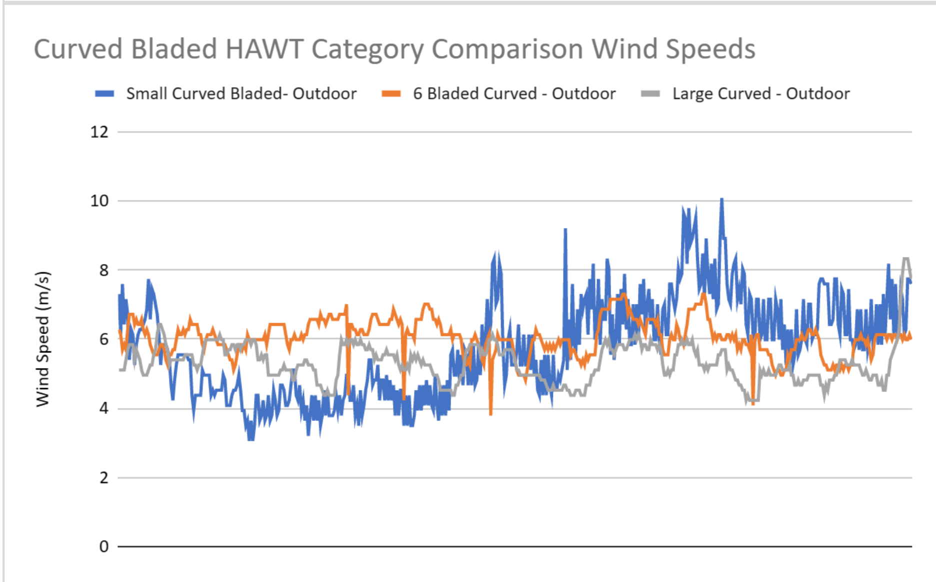
Individual Rotor Test Data - HAWT Design Categories

Below are the results from the HAWT Categories. The graphs below each represent the energy generated by each turbine from each category over the course of the test, and their respective testing wind speeds. Fig 97-100.



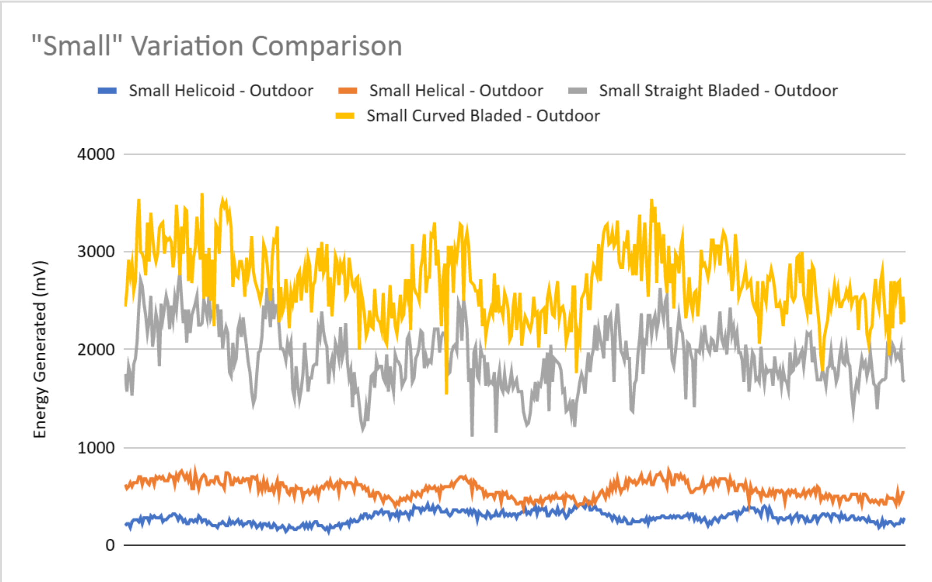


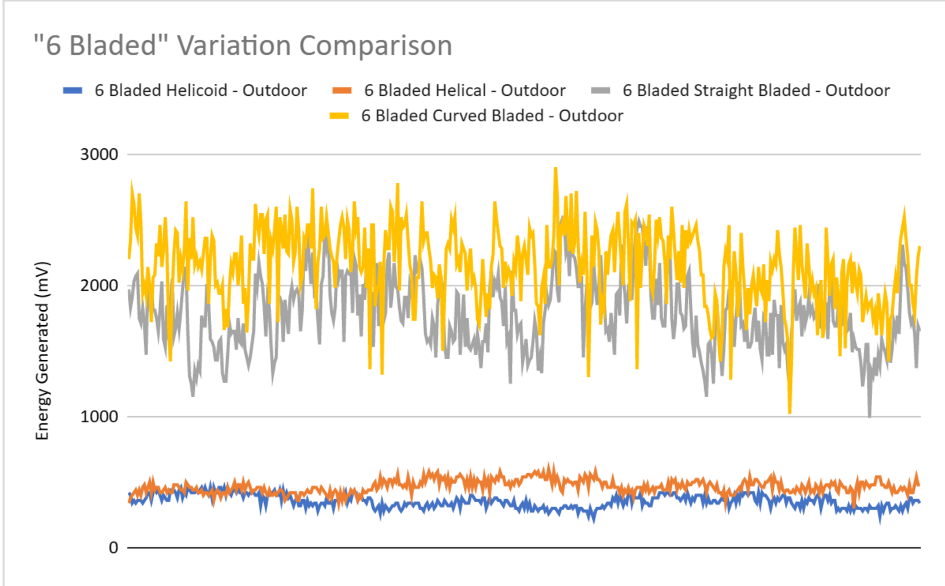


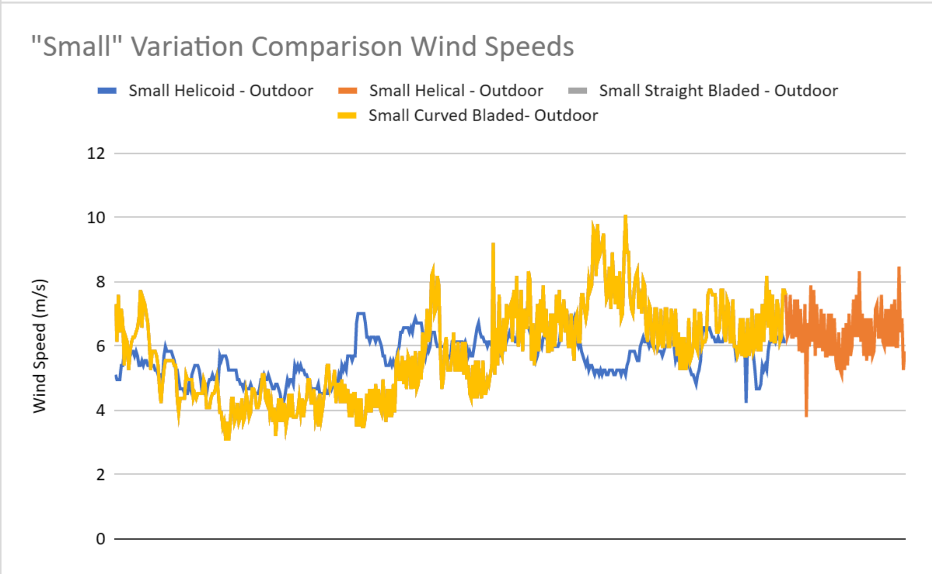


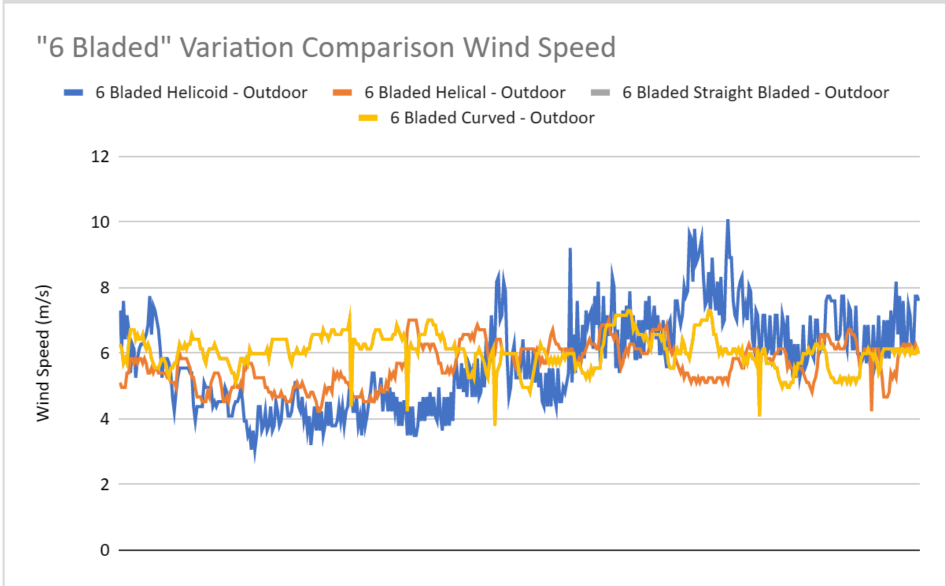
Individual Rotor Test Data - Category Variations

Below are the results from the design variation Categories. The graphs below each represent the energy generated by each turbine from each category over the course of the test, and their respective testing wind speeds. Fig 101-104.





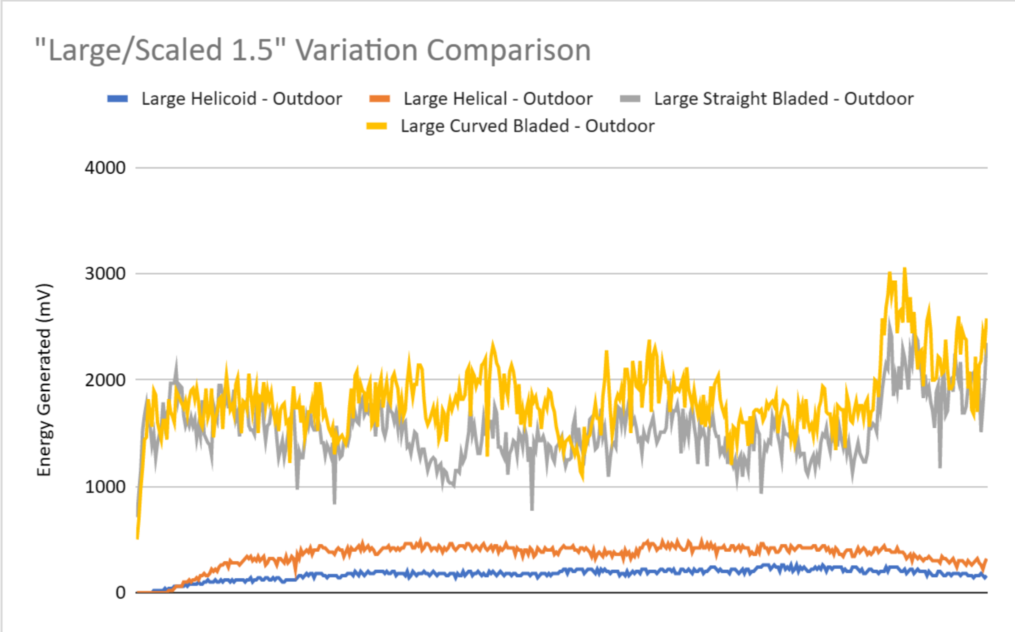


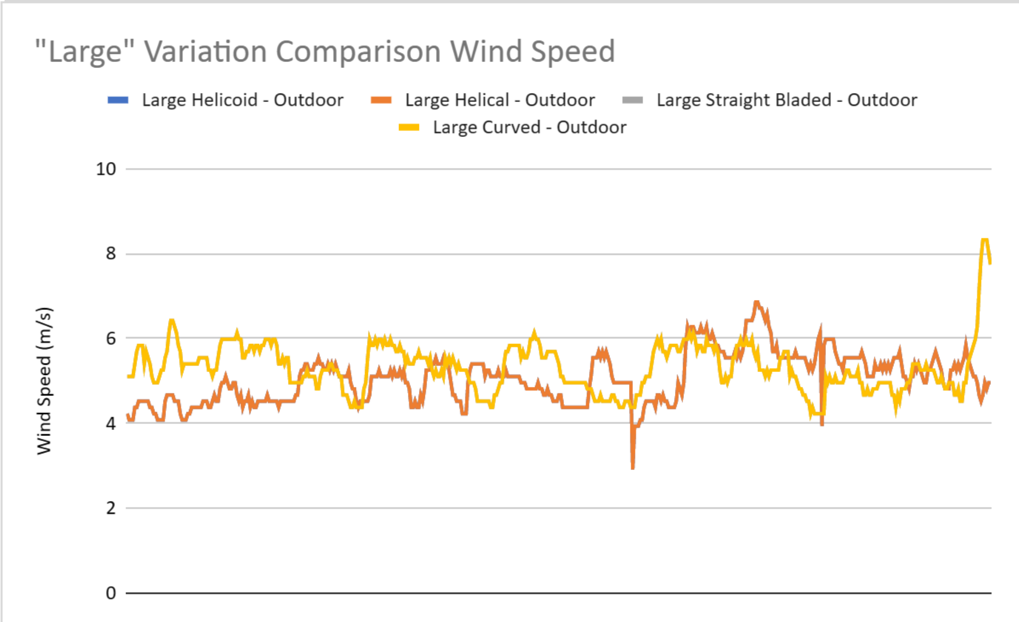


Individual Rotor Test Data - Category Variations

Below are the results from the “Large” design variation Category.
 The graphs below each represent the energy generated by each turbine from each category over the course of the test, and their respective testing wind speeds.

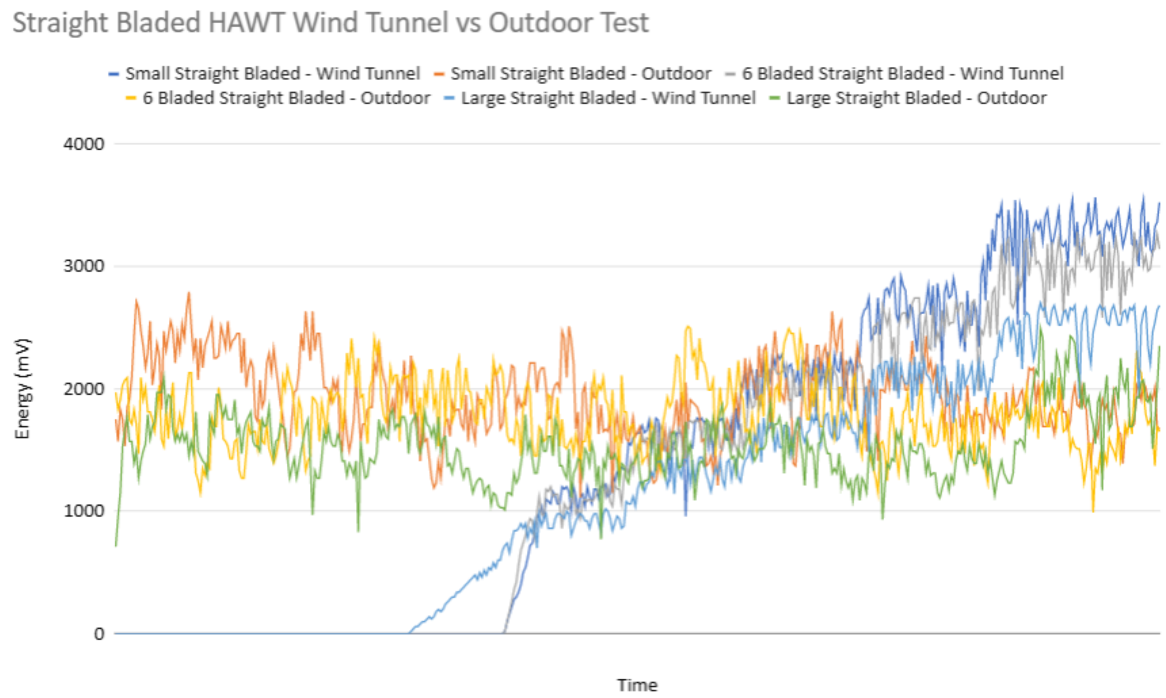
Fig 105, 106.

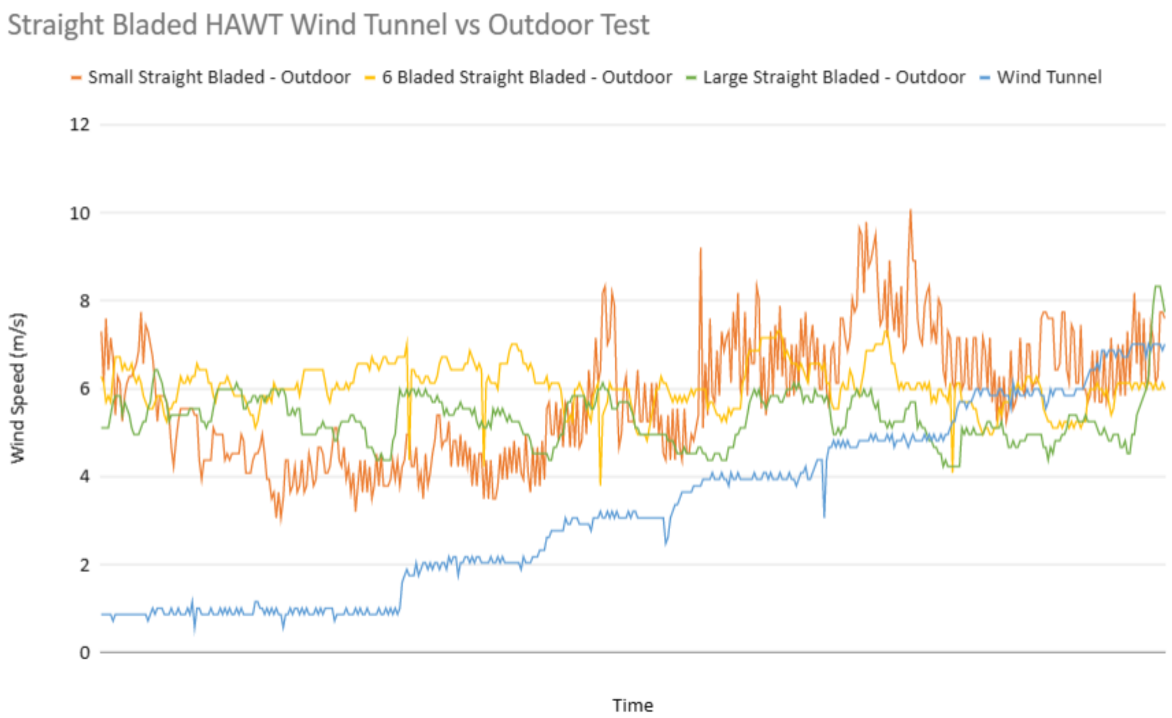




Wind Tunnel vs Outdoor Test - Straight Bladed HAWT

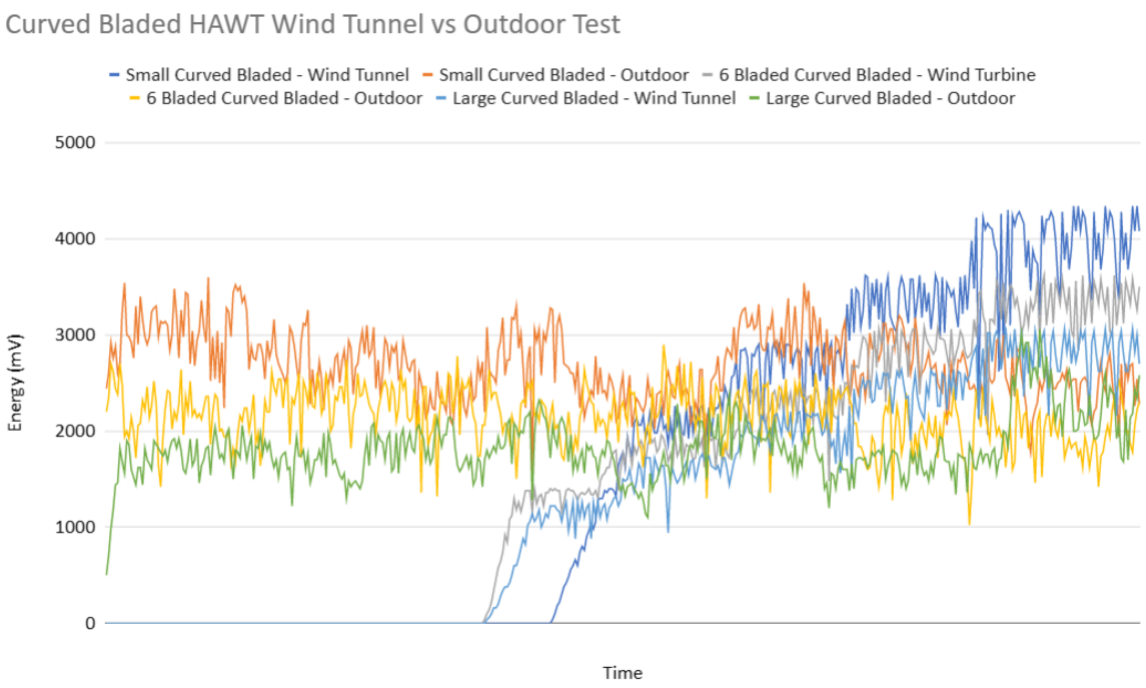
Below are the results from the Straight Bladed HAWT, in the Wind Tunnel vs Outdoor Test. The graphs below each represent the energy generated by each turbine from each category over the course of the test and their respective testing wind speeds. Fig 107,108.

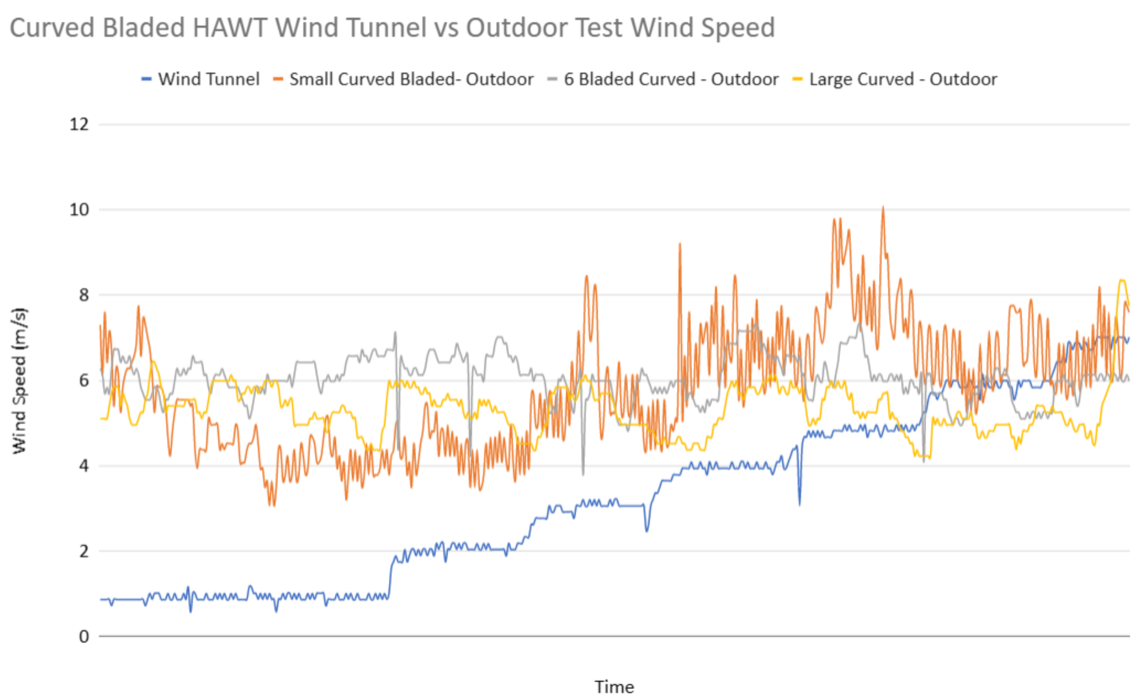




Wind Tunnel vs Outdoor Test - Curved Bladed HAWT

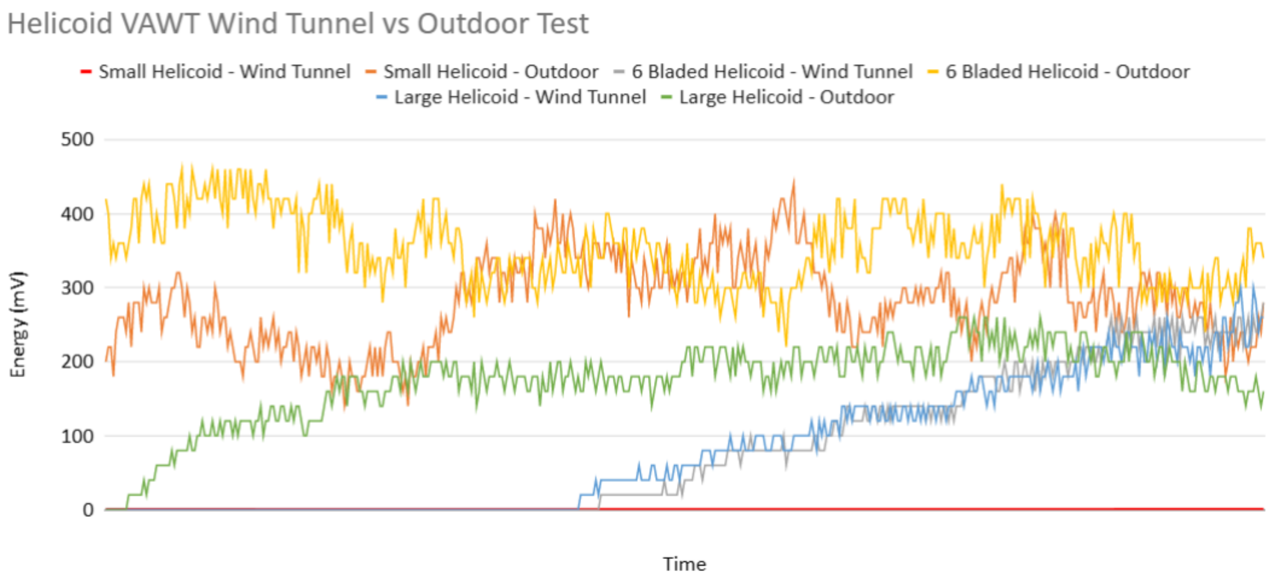
Below are the results from the Curved Bladed HAWT, in the Wind Tunnel vs Outdoor Test. The graphs below each represent the energy generated by each turbine from each category over the course of the test, and their respective testing wind speeds. Fig 109, 110.

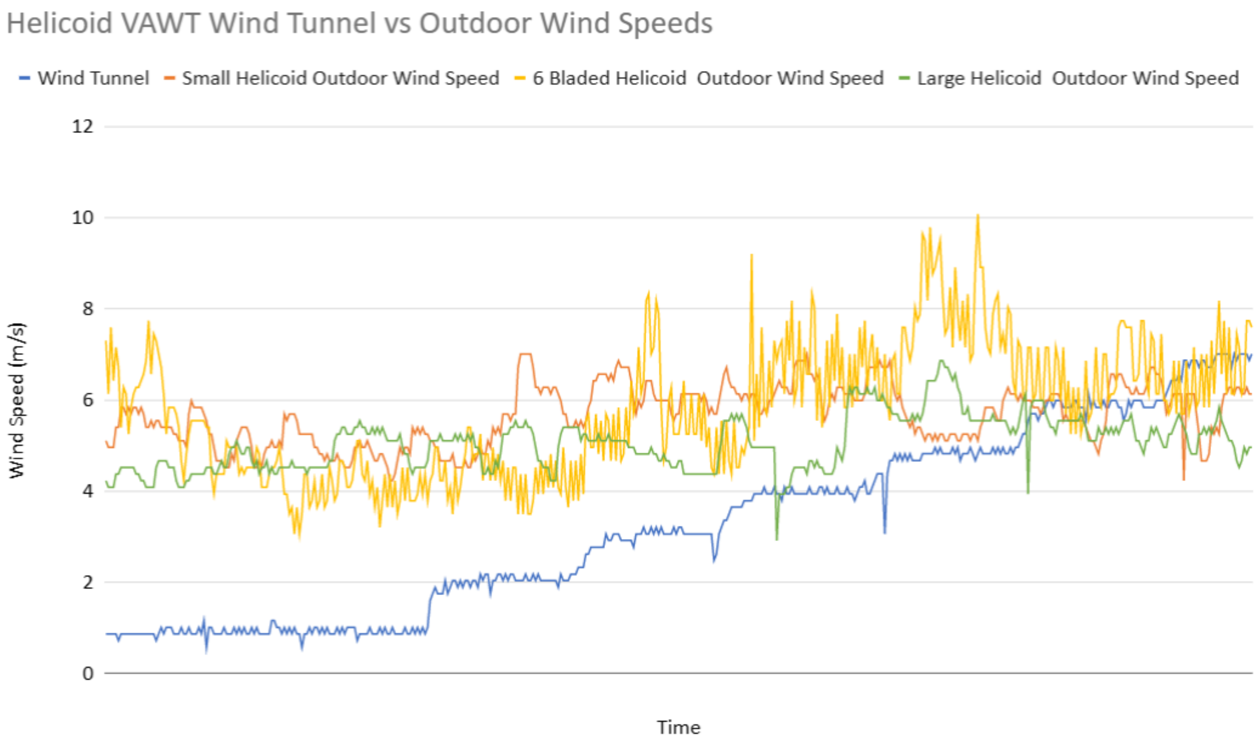




Wind Tunnel vs Outdoor Test - Helicoid Bladed VAWT

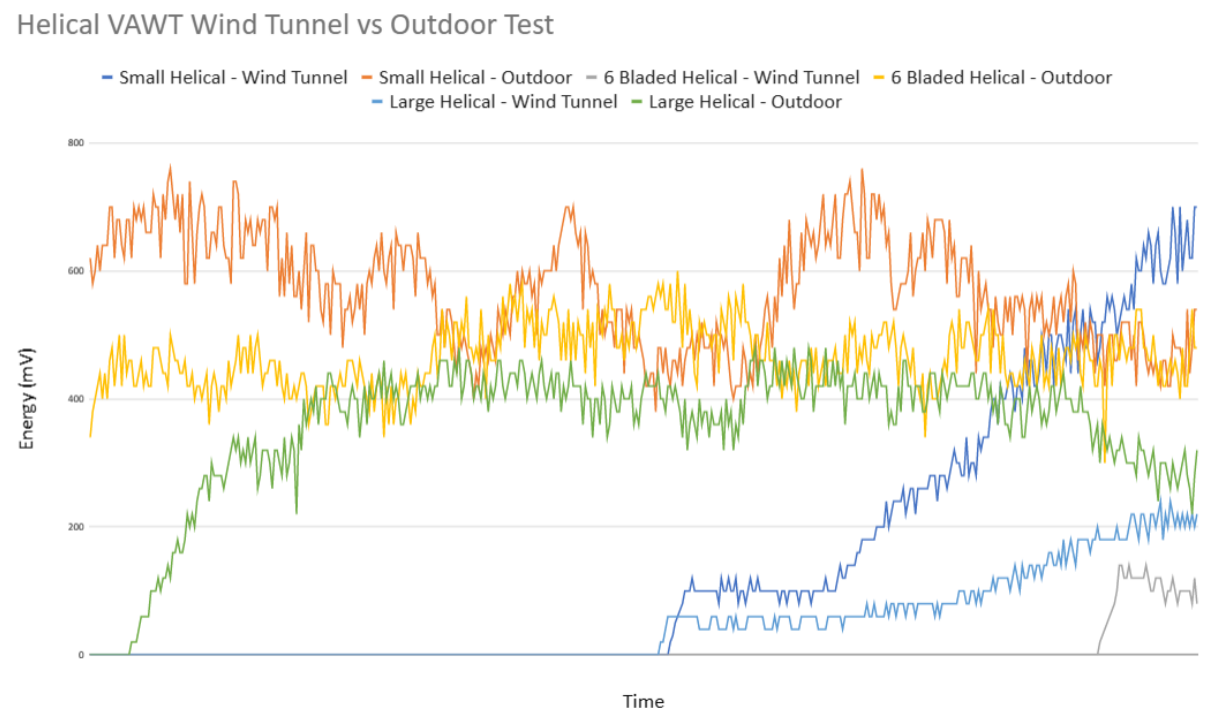
Below are the results from the Helicoid VAWT, in the Wind Tunnel vs Outdoor Test. The graphs below each represent the energy generated by each turbine from each category over the course of the test, and their respective testing wind speeds. Fig 111, 112.

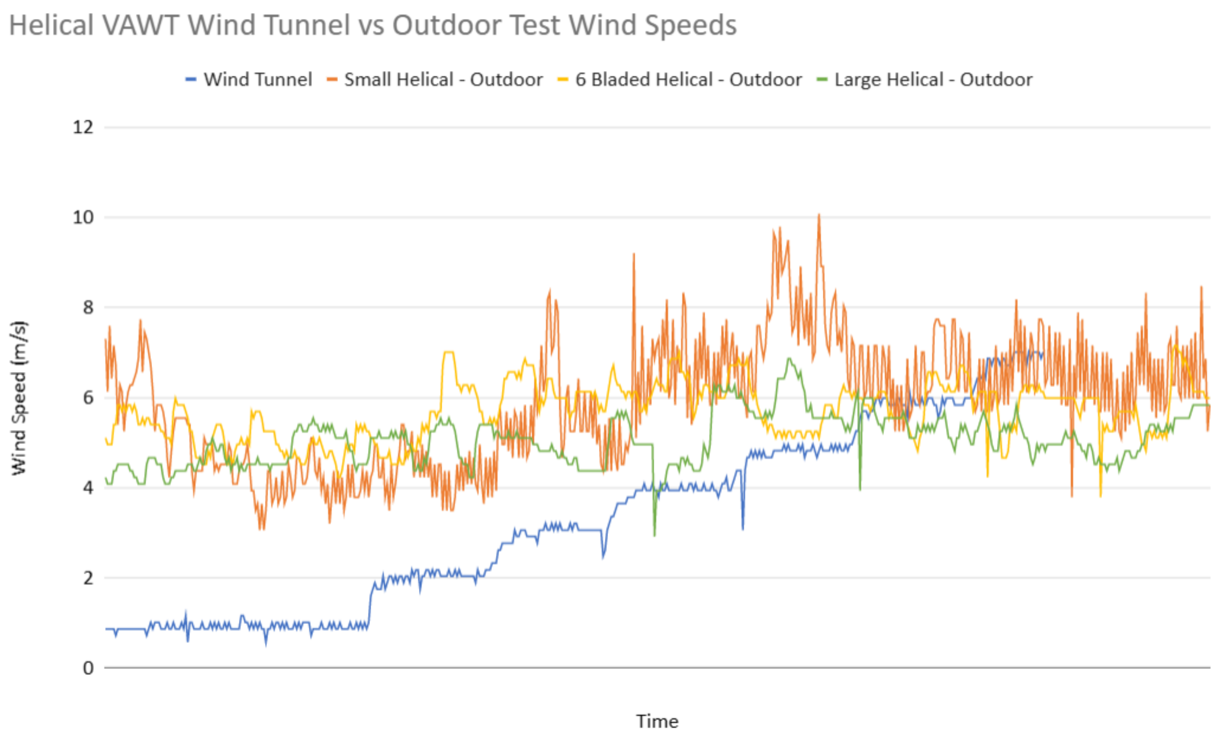




Wind Tunnel vs Outdoor Test - Helical VAWT

Below are the results from the Helical Bladed HAWT, in the Wind Tunnel vs Outdoor Test. The graphs below each represent the energy generated by each turbine from each category over the course of the test and their respective testing wind speeds. Fig 113, 114.

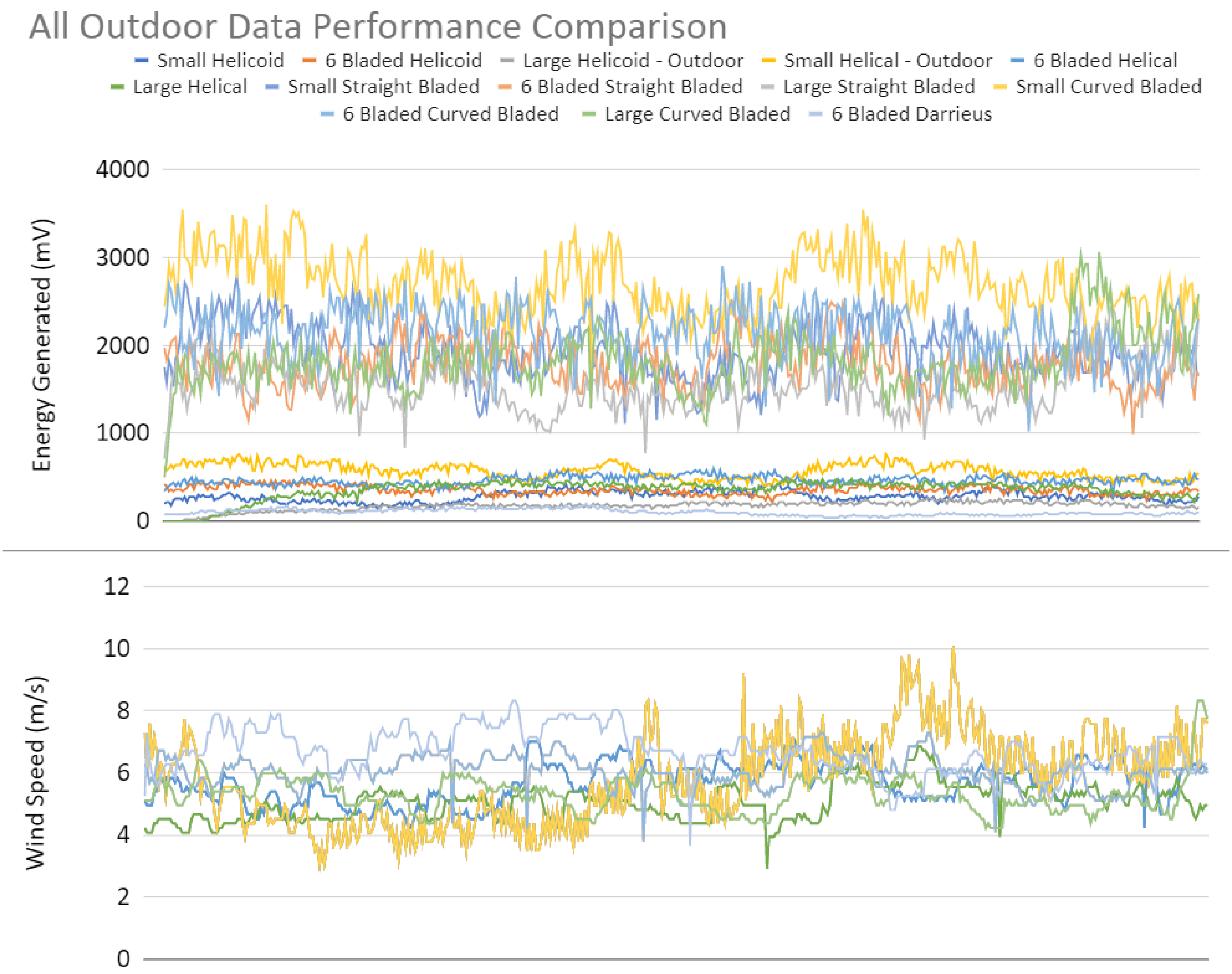




All Outdoor Test Data - VAWT & HAWT Performance

Here is an overall performance comparison between all of the models.

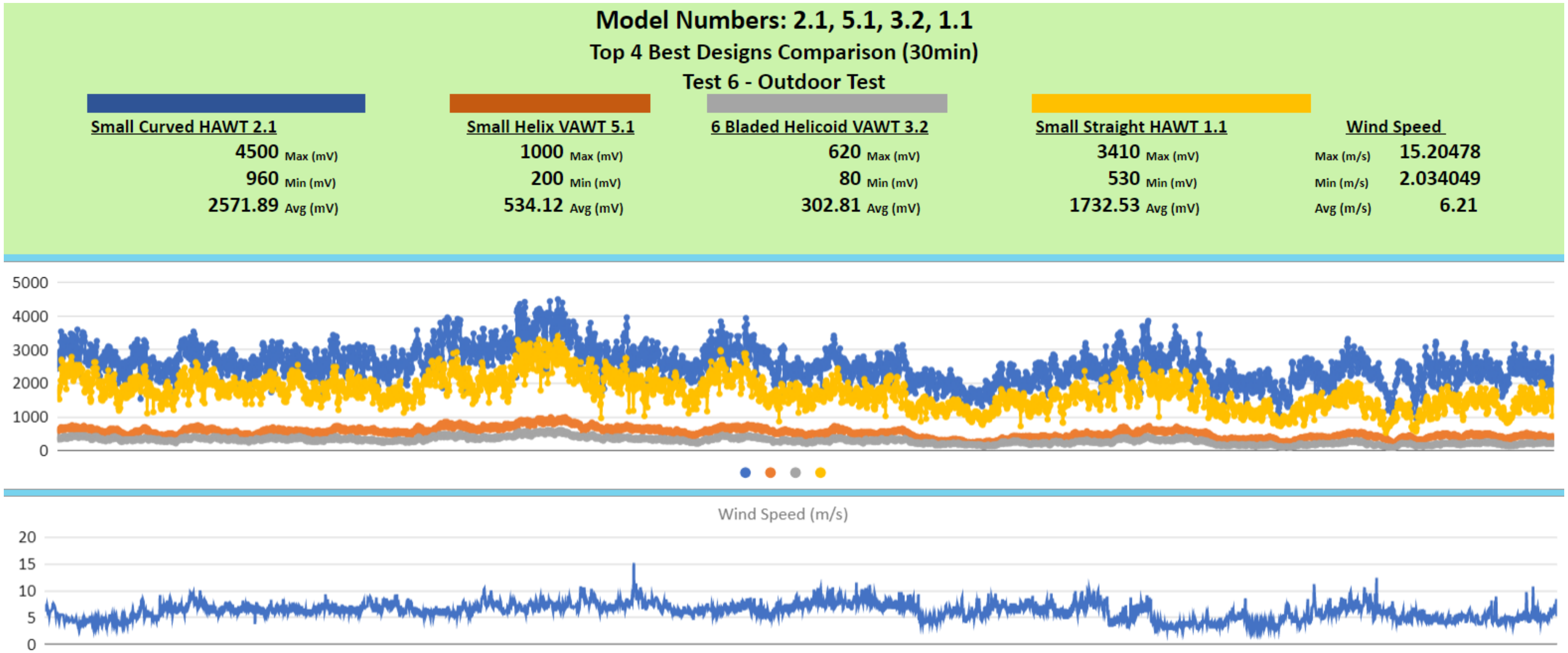
Fig 115, 116.



Test Reference: Test 6b - Outdoor Test
Top 4 models - 30 mins Test.

Outdoor Test - Top 4 Models

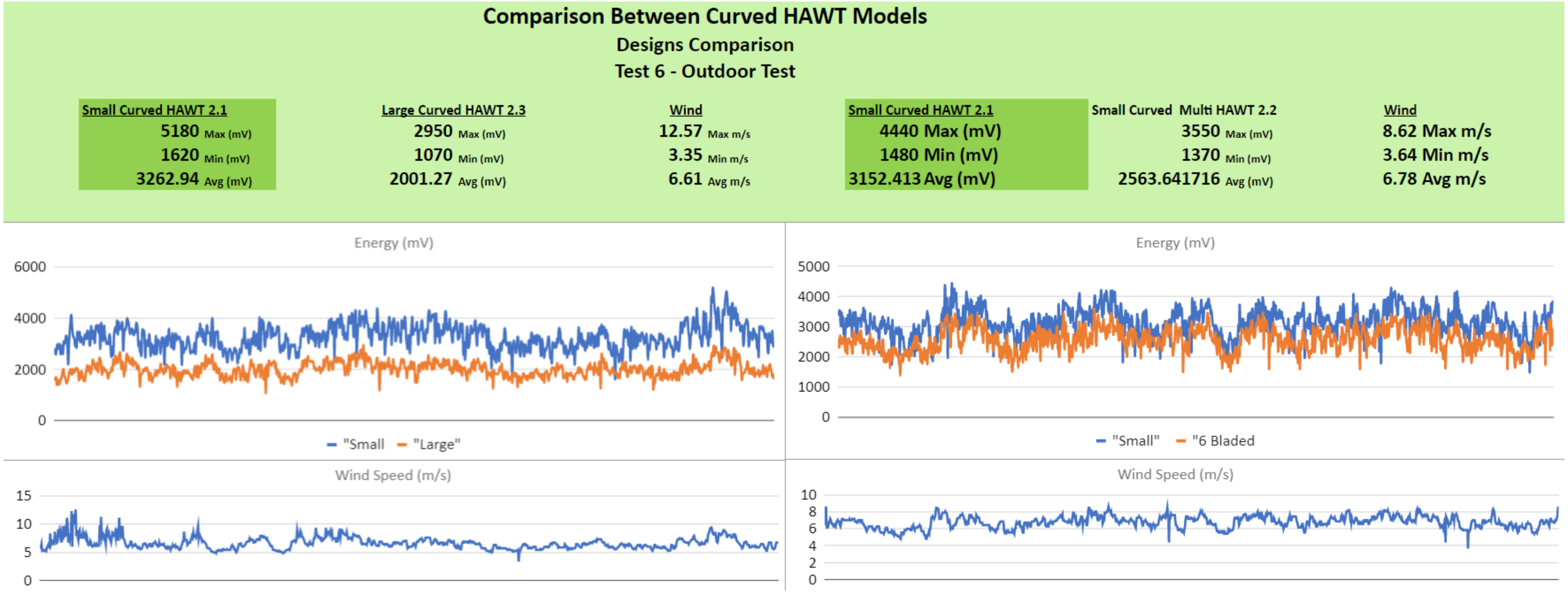
In this quick test I ran a direct comparison test between the top two performing models from each turbine rotor category, 30 mins in duration. Fig 117.



Test Reference: Test 6c - Outdoor Test
Curved Blade Comparison

“Small” Curved HAWT Comparison to Category

In these two tests I ran the “Small” variation of the curved HAWT against each of the other two variations in the Convex Curved Bladed HAWT. Interestingly, at a wind spike of up to10 m/s, the “Small” Curved HAWT spiked up to a peak generation of ~5V. Fig 118.

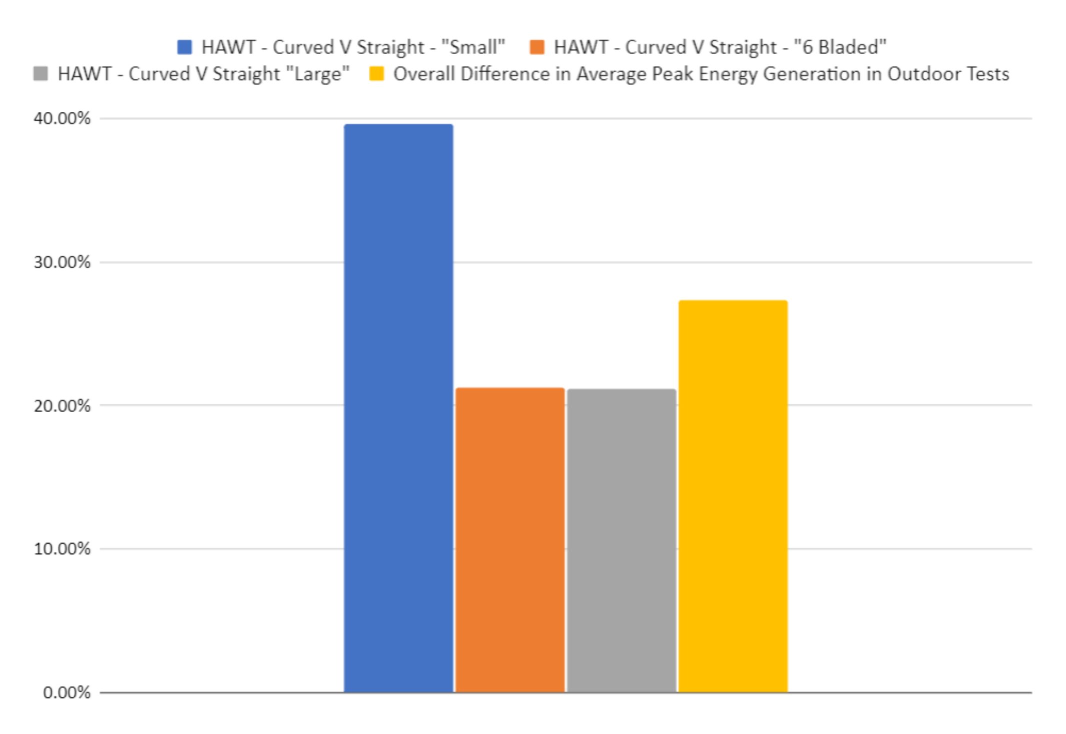


Percentage Difference Curved Bladed HAWT vs Straight Bladed HAWT

In both the Outdoor and Wind Tunnel testing, the Curved Bladed HAWT completely outperformed its Straight Bladed counterpart in each comparison. Most notably this percentage difference, when comparing the average percentage difference between the two in outdoor conditions, in turbulent airflow where the likes of micro-level wind turbines would be mounted; the difference between the energy generated by the two rose from an average of 11.04% to 27.34%. This both suggests the possible viability of Scimitar Blades at a micro-level, and directly aligns with research I found during my background research. Fig 119,120.

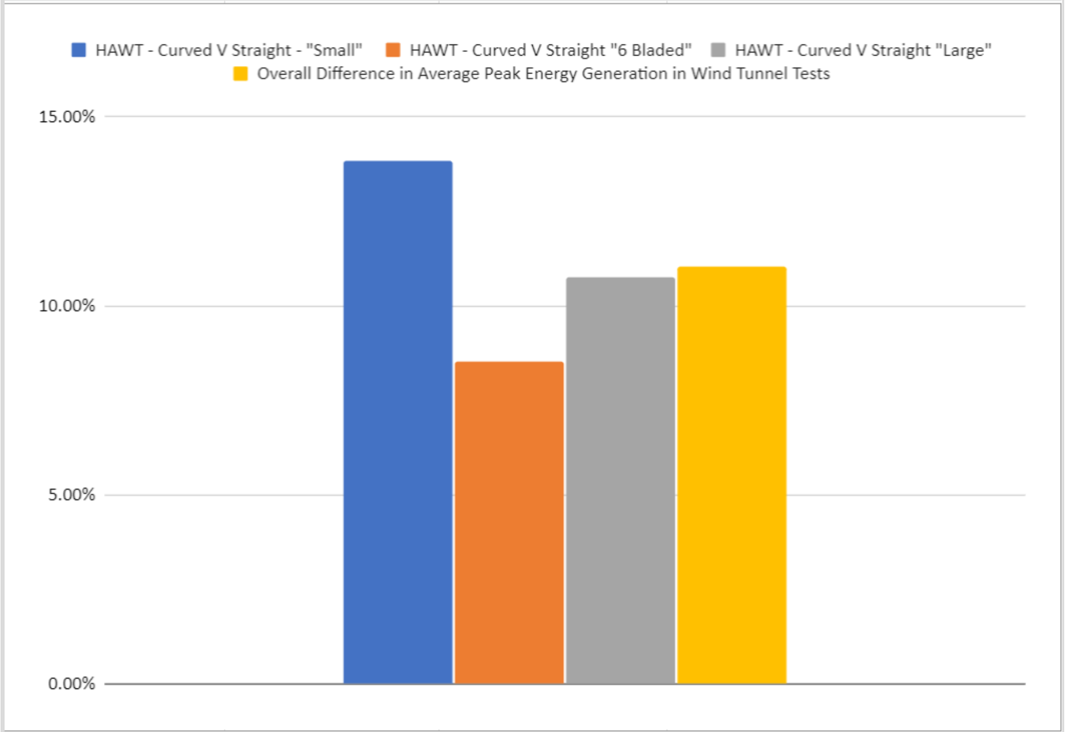
Outdoor Tests

HAWT - Curved V Straight - "Small"	HAWT - Curved V Straight - "6 Bladed"	HAWT - Curved V Straight "Large"	Overall Difference in Average Peak Energy Generation in Outdoor Tests
39.63%	21.25%	21.13%	27.34%



UL Wind Tunnel Tests

HAWT - Curved V Straight - "Small"	HAWT - Curved V Straight "6 Bladed"	HAWT - Curved V Straight "Large"	Overall Difference in Average Peak Energy Generation in Wind Tunnel Tests
13.85%	8.52%	10.76%	11.04%



Overall Ranked Results

Final ranking of all models based on all testing undertaken. Fig 121.

Id	Orientation	Type	Variation		Peak Mv Generation Laminar Flow	Peak Mv Generation Turbulent Flow
2.1	HAWT	Curved Blade	Small	2.1	4340	3600
2.2	HAWT	Curved Blade	6 Bladed	2.2	3560	2900
1.1	HAWT	Straight Blade	Small	1.1	3540	2790
2.3	HAWT	Curved Blade	Large	2.3	3040	3060
1.2	HAWT	Straight Blade	6 Bladed	1.2	3100	2510
1.3	HAWT	Straight Blade	Large	1.3	2680	2490
5.1	VAWT	Alternative Helical Turbine	Small	5.1	720	760
5.3	VAWT	Alternative Helical Turbine	Large	5.3	260	520
5.2	VAWT	Alternative Helical Turbine	6 Bladed	5.2	120	600
3.2	VAWT	Helicoid Turbine 1	6 Bladed	3.2	280	460
3.3	VAWT	Helicoid Turbine 1	Large	3.3	260	300
3.1	VAWT	Helicoid Turbine 1	Small	3.1	0	440
6	VAWT	Symmetrical Airfoil	Small	6	240	0
4.1	VAWT	Darrieus Turbine	Small	4.1	0	0
4.3	VAWT	Darrieus Turbine	Large	4.3	0	0
4.2	VAWT	Darrieus Turbine	6 Bladed	4.2	0	0

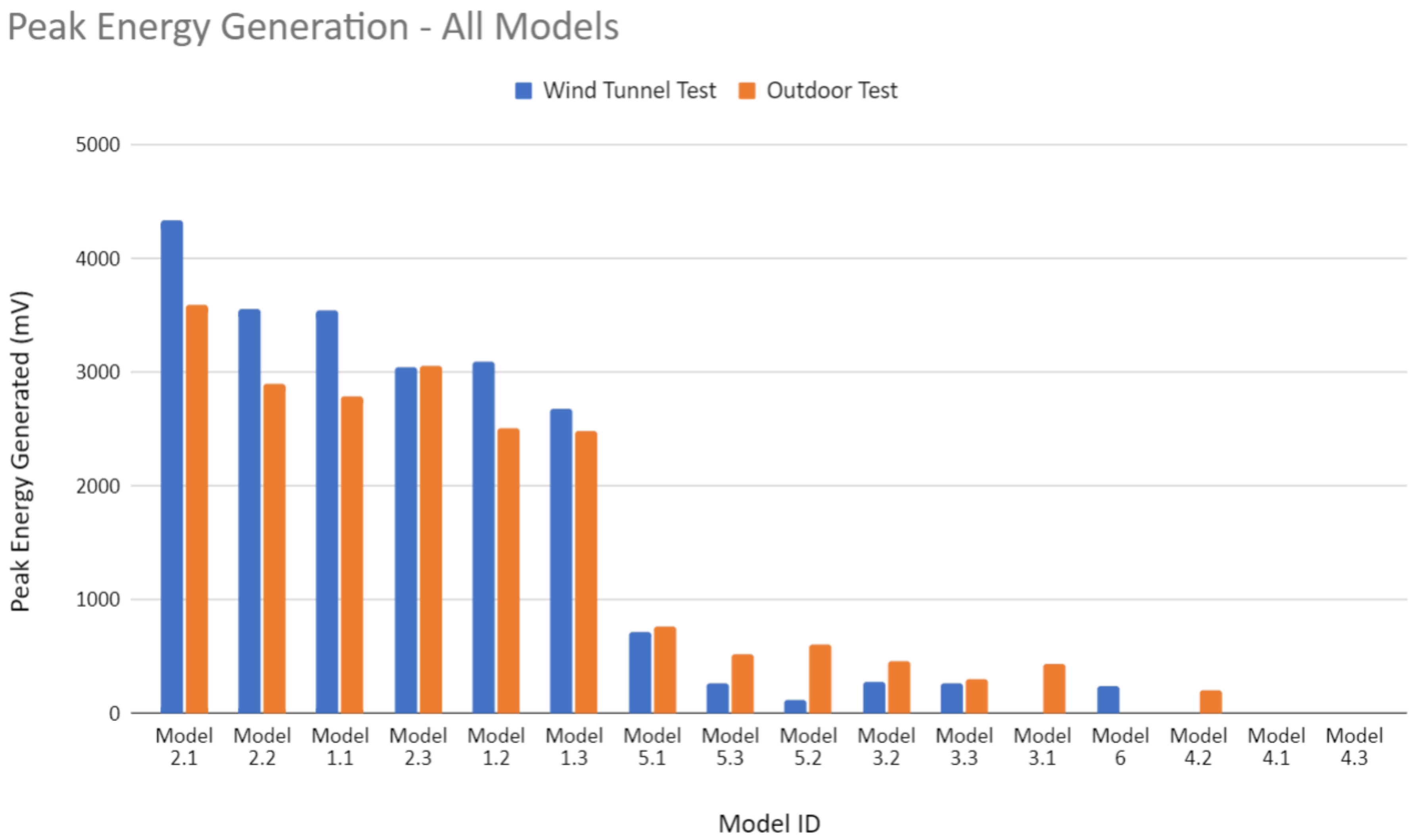

Peak Energy Generation - All Models
Wind Tunnel Test
Outdoor Test
Peak Energy Generated (mV)
5000
4000
3000
2000
1000
0
Model 2.1
Model 2.2
Model 1.1
Model 2.3
Model 1.2
Model 1.3
Model 5.1
Model 5.3
Model 5.2
Model 3.2
Model 3.3
Model 3.1
Model 6
Model 4.2
Model 4.1
Model 4.3
Model ID

Fig 122.

Model ID Legend:

ID	Orientation	Type	Variation	Test 1 - Outdoor	Test 2 - UL 1	Test 3 - UL 2	Test 4 - Outdoor 2	Test 5 - Outdoor 3	Test 6 - Outdoor 4
1.1	HAWT	Sraight Bladed Rotor	Small	n/a		n/a	n/a	n/a	
1.2	HAWT	Sraight Bladed Rotor	6 Bladed	n/a		n/a	n/a	n/a	
1.3	HAWT	Sraight Bladed Rotor	Large			n/a	n/a	n/a	
2.1	HAWT	Curved Bladed Rotor	Small	n/a		n/a	n/a	n/a	
2.2	HAWT	Curved Bladed Rotor	6 Bladed	n/a		n/a	n/a	n/a	
2.3	HAWT	Curved Bladed Rotor	Large			n/a	n/a	n/a	
3.1	VAWT	Helicoid Rotor Turbine	Small	n/a		n/a		n/a	
3.2	VAWT	Helicoid Rotor Turbine	6 Bladed	n/a		n/a		n/a	
3.3	VAWT	Helicoid Rotor Turbine	Large			n/a		n/a	
4.1	VAWT	Darrieus Rotor Turbine	Small	n/a		n/a		n/a	
4.2	VAWT	Darrieus Rotor Turbine	6 Bladed	n/a		n/a		n/a	
4.3	VAWT	Darrieus Rotor Turbine	Large			n/a		n/a	
5.1	VAWT	Alternative Helical Rotor Turbine	Small	n/a	n/a			n/a	
5.2	VAWT	Alternative Helical Rotor Turbine	6 Bladed	n/a	n/a			n/a	
5.3	VAWT	Alternative Helical Rotor Turbine	Large	n/a	n/a			n/a	
6	VAWT	Symmetrical Airfoil Helical Rotor	Small	n/a	n/a			n/a	

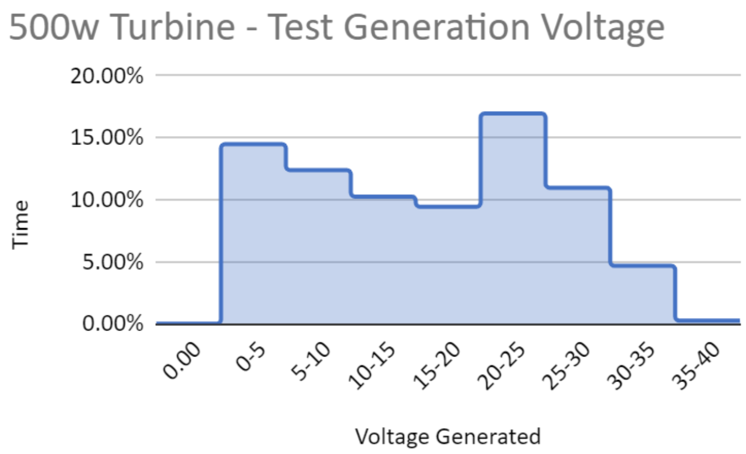
n/a	
	Successful
	Unsuccessful

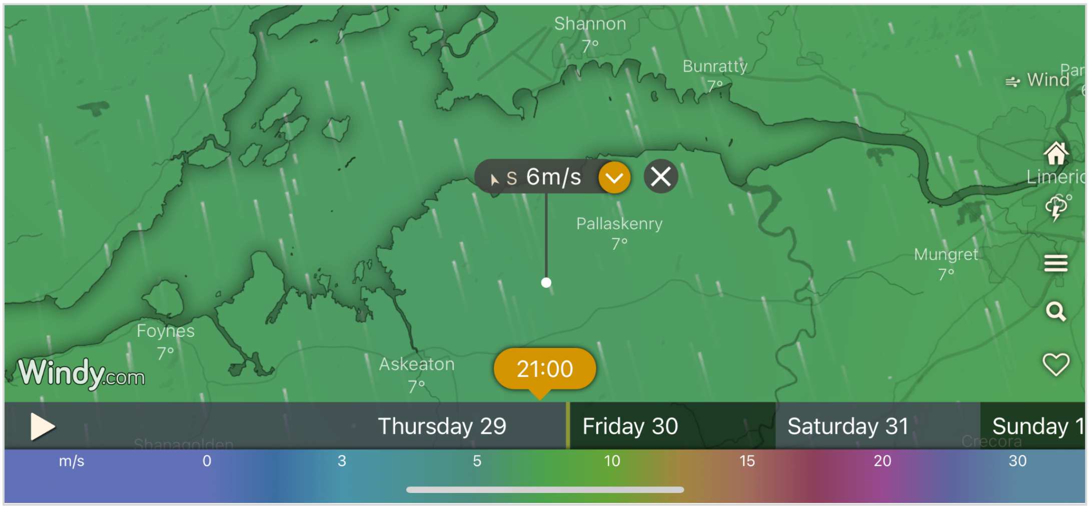
Fig 123, 124.

Test Reference: Test 7 - 24v 500w Production Model 11hr Outdoor Test
Duration - 11 hours

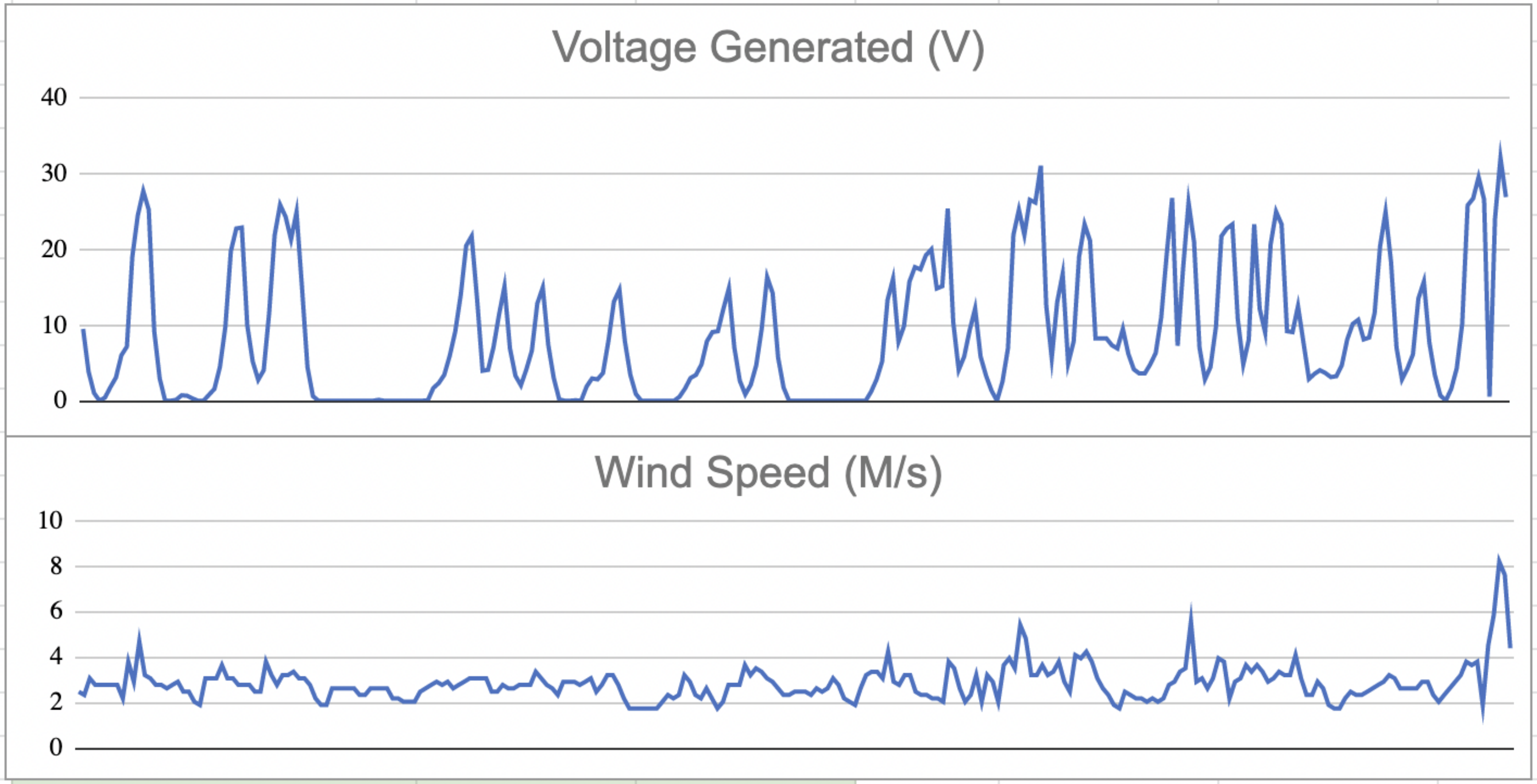
Fig 125, 126.

Total Polling Time (hours)	11
Total Polling (5s intervals)	7143.0
Average Voltage Generated	**12.56**
Maximum Voltage Generated	**38.22**
Minimum Voltage Generated	**0**
Max Wind Speed	10.81
Average Wind Speed	2.75





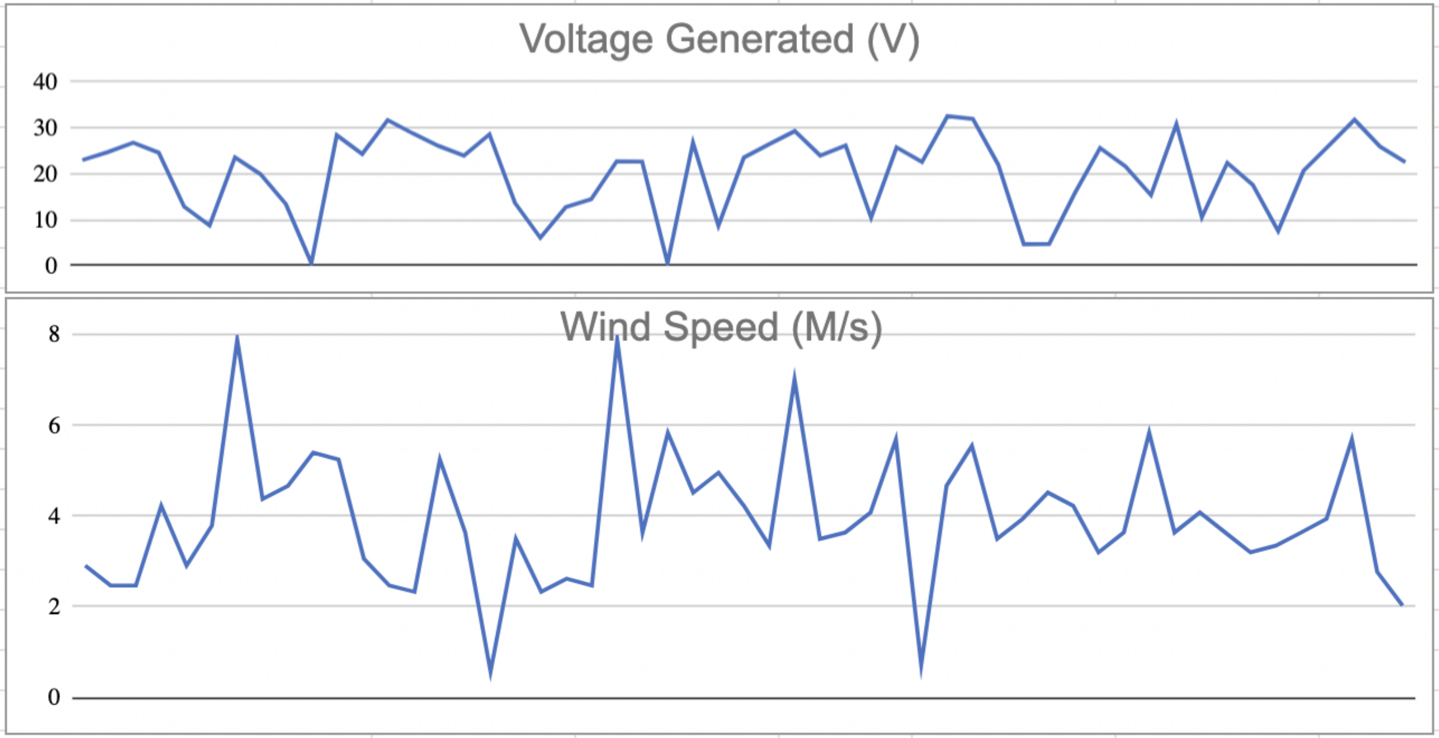
22 Minute Sample Data Capture Showing Average Wind Speed and Voltage Generation



Records (5s interval)	Seconds	Minutes
261	1305	**22**
Average Voltage	8.47	V
Average Windspeed	2.85	M/s

Fig 127.

4-Minute Sample Data Capture Showing Average Wind Speed and Voltage Generation



Records (5s interval)	Seconds	Minutes
53	265	4
Average Voltage	20.30	V
Average Windspeed	3.94	M/s

Fig 128.

Findings

- Overall on average when comparing the highest peak voltages generated the HAWTs performed better than the VAWTs by a factor of 14.36. The average peak HAWT output voltage was ~3377mV and an average peak output of ~235mV for the VAWT. When comparing the average voltages generated in the outdoor test at the same wind speed I found that the HAWTs performed better than the HAWTs by a factor of 7.7. The average energy produced by the HAWT outdoor tests in average turbulent winds of 6 m/s was 2335 mV, and 302 mV was produced by the VAWTs.

- With the highest performing HAWT generating a peak output voltage of approximately 4.34V (in laminar flow winds at 7m/s), and the highest performing VAWT generating a peak output voltage of approximately 0.75V (in turbulent flow winds peaking at 7m/s). These results maintain the same proportions as the results of a research paper I found titled: "Comparison of horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT)" where their HAWT models generated an average peak output of 8.99V and their VAWTs generated 1.4V. Finding that VAWTs are unaffected by wind angle, where wind angle significantly affects the energy generated by and that This speaks to how VAWTs could serve as the safer option for urban and domestic development due to their low operating speeds and also aligns with the accepted belief that it could only do so if it was paired with a gearbox large enough to replicate the electricity produced by the high RPM achieved by the HAWTs.

- The HAWT rotors generated an average peak voltage of approximately 17% more electricity in wind tunnel laminar air flow conditions in comparison to outdoor turbulent air flow conditions of the same wind speed. I also found that when comparing the average energy generated outdoors, and matching that wind speed to it I found that the average percentage improvement was in reality around 34.4%. Confirming that my research results align with the accepted belief that HAWTs are optimised for laminar, regular flowing wind. I also found that the largest increase in average electricity generation was at ~ 57.2% from Model 2.1 ("Small" Straight Bladed HAWT), and the smallest increase was at ~ 16.8% from Model 2.3 ("Large" Curved (Scimitar) Bladed HAWT).

- The VAWT rotors generated an average peak voltage of approximately 38% more electricity in outdoor turbulent airflow conditions than in the wind tunnel at approximately similar wind speeds. Interestingly, two of the VAWT models generated no electricity in the wind tunnel at all but managed to generate more electricity outdoors than two of the other models which worked in the wind tunnel. The largest percentage increase in peak electricity generation when tested outdoors was at ~ 80% from Model 5.2 ("6 Bladed" Helical VAWT), and the smallest percentage increase was at ~5% from Model 5.1 ("Small" Helical VAWT). In comparing the average mV generated by the VAWTs at an average wind speed of 6 m/s in each test, there was an 80% performance increase when tested in turbulent outdoor wind flow, to the wind tunnel test (providing a truer representation of the experimental results). The largest percentage difference was 87%, from Model 5.2 ("6 Bladed" Helical VAWT), and the smallest percentage difference was 9% from Model 5.1 ("Small" Helical VAWT).

- Ultimately I believe that this shows that the testing of VAWT rotors in laminar flow conditions is not representative of actual energy generation in the real-world, turbulent wind outdoors.

- On average I found that the “6 Bladed” variations, when compared to the base “Small” variations, lead to a 15.2% decrease in peak generation in HAWTs outdoors, and a 14.7%% decrease in the wind tunnel; An average overall decrease of 14.9% in the HAWTs. This variation led to a 60.2% decrease in VAWTs outdoors, and a 16.7% decrease in the wind tunnel; An average overall decrease of 38.5% in the VAWTs. It must be understood that rather than simply being weaker overall than the base design, it was as though the graph of the "Small" variation was translated downwards. At every change in wind speed, the percentage performance increases between the two variations from each category remained remarkably consistent.

- On average I found that the “Scaled 1.5/large” variations, when compared to the base “Small” variations, lead to a 27.1% decrease in peak generation in HAWTs outdoors, and a 12.8% decrease in the wind tunnel; An average overall decrease of 27.1% in the HAWTs. This variation led to a 31.6% decrease in VAWTs outdoors, and a 63.8% decrease in the wind tunnel; An average overall decrease of 47.8% in the VAWTs. It must be understood that instead of, just overall being weaker than the base designs, it was like the graph of the “Small” variation was translated downwards, the percentage performance increases remained remarkably consistent between the two variations from each category at each wind speed change.

- Although I wasn’t measuring torque generated in this project, it must be noted that during the testing phases, I observed that the “6 Bladed” and “large” HAWT variations rotated with a significantly higher drive and torque than their “Small” base sizes, and for example in the wind tunnel after I turned off the fan they typically would keep rotating for over double the amount of time it took the “Small” variation to come to a halt. So I would argue that if I paired this variation with a gearbox these designs could serve a fighting chance for the best rotor design.

- In comparing how the HAWTs and VAWTs ran, I found that while the HAWTs ran at a very high RPM but low torque, I believe that the opposite was true for the VAWT and for the sake of micro-level wind generation would not serve as viable solutions alone, but it must be noted that all of the VAWT designs were much less affected by the wind speed and would maintain a steady RPM regardless of the conditions. Not all of the blades produce torque at the same time, which limits the efficiency of vertical systems in producing energy. Other blades are simply pushed along. There is also more drag on the blades when they rotate. This aligns with the research I found in my background research claiming that VAWTs operate with a higher torque but naturally are at a disadvantage to HAWTs in possible energy generation, but are known to maintain a very consistent, safer speed regardless of conditions. Speaking to their possible better-suited nature to city developments, where dangerously fast rotors could serve as a health risk. It’s generally accepted that VAWTs would have to be paired with a gearbox to generate the same levels of electricity as HAWTs, but this leads to consequently higher cut-in speeds at this small scale.

- The best turbine category was the Scimitar “Convex Curved” Shape HAWT. Running at an average peak energy generation that is 11.04% better than the Straight Bladed HAWT outdoors in turbulent air, and 27.34% better in the laminar wind flow tests. With an average overall performance improvement of ~19%.

- From this best rotor category, the base “Small” variation generated the maximum amount of electricity overall, running at a peak mV output of 4340mV in laminar flow and 3600mV in turbulent flow of the same wind speed. In comparison to the “Small”, traditional, “Straight” Bladed HAWT, whose design is in common use in both commercial and domestic models, and generated a peak mV output of ~3540mV in laminar flow and 2790mV in turbulent flow of the same wind speed. That means that in comparing the two best rotor variations from the two HAWT categories, the Scimitar (Curved) rotor variation performed 13.85% better than its Straight Bladed counterpart in laminar airflow, and 39.63% better in turbulent airflow. (These were tested side by side.)

- For context, this “Small” Curved (Scimitar) variation, in the direct comparison test between the top 4 variations from each category, generated a peak energy output approximately 32% better than the “Small” Straight Bladed HAWT rotor, 450% better than the “Small” Helical VAWT rotor and 726% better than the “6 Bladed” Helicoid VAWT rotor.

- One point that must be noted is that the vast majority of the HAWT rotor variations cut in just at approximately 3 m/s during the wind tunnel tests. The “Large” Traditional Bladed HAWT cut in at wind speeds of approximately 2 m/s, and on the opposite end of the spectrum, the “Small” Curved Bladed HAWT also cut in at 3 m/s winds but required about fifteen seconds to get going before rapidly cutting in and surpassing all of the other rotor variations.

- From my 11-hour test of the 500w domestic turbine in wind speeds ranging from 3 m/s to 10 m/s, I found that it generated a maximum voltage of 38V, 20% of the time during this test the turbine generated no electricity, approximately 50% of the time it was generating between 0-20V, and only approximately 30% of the time was it generating between 20-35+ V.

- When calculating the potential annual output of a wind turbine, a capacity factor of 20% in onshore wind farms and 50% in offshore wind farms are generally accepted globally, yet in Ireland, the onshore wind farm average capacity factor as of 2015 was 32.3%. At an annual average wind speed of 6 m/s, this 500w turbine would generate approximately 130 watts, meaning a capacity factor of 26%. Using this average capacity factor of 26%, calculating: $0.26\ capacity\ factor\ \times\ 0.5\ kW\ \times\ 24\ hours\ \times\ 365\ days$I have found that this wind turbine on average could generate 1138.8kW/h in one year.

- By replacing the 500w turbine’s Traditional Blades with Scimitar “Convex Curved” Blades and applying the average potential performance improvement of ~ 19% as observed from the experimental results, a possible annual energy generation of 1355.172 kW/h could be expected. This in theory could mean a potential reduction in payback time by approximately 19%. A possible up to ~19% reduction in rotor size while maintaining the same electricity production. Or the possibility of generating higher levels of electricity in regions with lower average wind speeds.

- Taking a standard 24-hour unit rate of 43.27c kW/h (Electric Ireland as of October 2022, a 124% increase from April 2020) this means that this 500w turbine could generate ~€493 worth of electricity annually. Applying this higher-performing rotor design you could see a potential increase of approximately €93 up to €586 saved each year. Pre-current electricity pricing, the base model above would have generated just €228 worth of electricity (at a unit rate of around 20 c / kW/h, April 2020). I believe this staggering increase in electricity prices serves as one of the core points in favour of the viability of micro-wind generation.

- The best Category 1 rotor variation was Model 1.1, the “Small” Straight Bladed HAWT. Running at a peak mV output of 3540mV in laminar flow and 2790mV in turbulent flow of the same wind speed. In the final outdoor test, this turbine generated an average of 1933mV in average wind speeds of 5.88 m/s. In the wind tunnel at approximately 6 m/s it generated 3040mV, leading to a ~57% increase in energy generation at the same wind speed in the laminar flow of the wind tunnel..

- The best Category 2 rotor variation was Model 2.1, the “Small” Curved Bladed HAWT. Running at a peak mV output of 4340mV in laminar flow and 3600mV in turbulent flow of the same wind speed. In the final outdoor test, this turbine generated an average of 1756mV in average wind speeds of 5.98 m/s. In the wind tunnel at approximately 6 m/s, it generated 3620 mV, leading to a ~34% increase in energy generation from outdoors to the wind tunnel.

- The best Category 3 rotor variation was Model 3.2, the “6 Bladed” Helicoid VAWT. Running at a peak mV output of 280mV in laminar flow and 460mV in turbulent flow of the same wind speed. Interestingly this variation of the Helicoid VAWT, while in the wind tunnel produced practically identical results to the “Large” variation. Outdoors performance improved by 53%, and when compared to the “Small” variation which didn’t generate any electricity in the wind tunnel testing, it only did 4.5% better. When comparing what it generated at an average of 6 m/s in the outdoor experiment to the wind tunnel test, electricity generation increased by 49.4%.

- The Category 4 Darrieus VAWTs, apart from the “6 Bladed” Darrieus, struggled to generate any electricity during any of the tests. I believe that this is due to commercial Darrieus models requiring extremely thin blades and airfoils in contrast to their full assembled height of up to around 10 metres. Alongside this, it must be noted that this variation of a VAWT cannot start itself but rather requires to be coupled with a Savonius turbine or drive itself before it can begin generating electricity. During a lot of the outdoor and wind tunnel testing, I observed this variation getting caught into a form of forced equilibrium due to the size of their airfoils in comparison to the actual size. During the prototyping phase, I found that I wouldn’t be able to reliably manufacture this airfoil at any lower size. Interestingly the “6 Bladed” Darrieus worked very well, generating a peak voltage of 200mv outdoors, despite not moving in the wind tunnel experiment. I think that this could be a result of the lift forces exceeding the minimum required force to start the turbine. In my rudimentary testing before and after the UL Experiments I observed that the odd number of blades would lock the Darrieus model into this form of equilibrium. What I found intriguing was how the ”6 Bladed” variation got started very quickly outdoors, in the chaotic wind flow but not at all in the laminar conditions.

- The best Category 5 rotor variation was Model 5.1, the “Small” Helical VAWT.
  Running at a peak mV output of 720mV in laminar flow and 760mV in turbulent flow of the same wind speed. Generating an average of 575mV in the outdoor test at an average wind speed of 5.69m/s, and a corresponding wind tunnel voltage of 520mV. A total difference of average energy generated of 9% between the wind tunnel and outdoor test.

- The Category 6 Symmetrical Airfoil VAWT interestingly generated a peak of 240mV in the wind tunnel’s laminar flow, yet was unable to generate anything in outdoor winds of the same speed, which is interesting as this type behaved oppositely to all other VAWT variations and which I found in my research. It is generally accepted that VAWTs are designed and geared towards turbulent, chaotic air flow, not laminar and regular flow that can be, and was observed in my wind tunnel experiments.

- The best “Small” HAWT variation wind turbine rotor was the “Small” Curved VAWT generating a peak energy output of 4340 mV in the wind tunnel, in laminar wind flow, and 3600 mV outdoors in turbulent wind flow, cutting in ten seconds later than all other variations, in constant 3m/s laminar wind flow but swiftly surpassing their energy generation after getting started.

- The best “6 Bladed” HAWT variation wind turbine rotor was the “6 Bladed” Curved VAWT generating a peak energy output of 3560mV in the wind tunnel, in laminar wind flow, and 2900mV outdoors in the turbulent wind flow. Generating 18% less energy in laminar flow, and 20% less in outdoor turbulent flow than the “Small” base variation.

- The best “Large” HAWT variation wind turbine rotor was the “Large” Curved VAWT generating a peak energy output of 4340mV in the wind tunnel, in laminar wind flow, and 3600mV outdoors in turbulent wind flow, cutting in at the same wind speed of 3 m/s as nearly all of the other rotors.

- The best “Small” VAWT variation wind turbine rotor was the “Small” Helical VAWT generating a peak energy output of 720mV in the wind tunnel, in laminar wind flow, and 760mV outdoors in the turbulent wind flow.

- The best “6 Bladed” VAWT variation wind turbine rotor was the “6 Bladed” Helical VAWT generating a peak energy output of 120mV in the wind tunnel, in laminar wind flow, and 600mV outdoors in the turbulent wind flow.

- The best “Large” VAWT variation wind turbine rotor was the “Large” Helical VAWT generating a peak energy output of 260mV in the wind tunnel, in laminar wind flow, and 520mV outdoors in the turbulent wind flow. Generating an average of mV.

To conclude here are the main findings of the survey:

- Total Survey Population = 169
- Out of all of the respondents: 82.8% were over 20 years old, 60.9% were over 40 years old, 21.9% were over 20 and less than 40 years old, 13% less than 20 years old.
- 80.5% of respondents think about climate change and its impact on their future.
- 41.4% say that they consistently make climate-positive decisions in their day-to-day life.
- 95.9% believed that in light of the current rises in electricity prices, their behaviours towards conserving electricity had shifted towards maximising energy saved.
- In light of these cost rises 67.5% have thought of investigating renewable energy sources for home electricity generation.
- Only 16% of respondents’ houses had a form of renewable energy supply such as solar PV or wind contributing to powering their home, 97% of these had solar panels, and one respondent had a micro-wind turbine.
- A majority of 71.1% of respondents had very little to no knowledge about micro wind generation.
- 86% of people surveyed see it as a viable option for home energy generation.
- 72.2% wouldn’t object to someone mounting a turbine in their garden, bearing in mind the maximum allowed height without planning permission in Ireland is 13m.
- When provided information about payback times, 78.7% said that in response they would consider installing a wind turbine in their home.
- Initial cost was the highest concern held by the respondents as a possible reason why they couldn't consider getting a micro wind turbine (41.4%).
- When asked, 55% of respondents said that they would be willing to pay between €1000-€2499 for a wind turbine.
- When shown a map and explanation showing how Ireland is one of the best places in Europe for wind generation, and then informed about how the Irish government currently does not offer any grants or incentives for micro wind turbines; when asked if government incentives should be put in place for home micro energy generation 94.1% responded with yes.
- Finally when they were asked if the government grants were put in place, would they be more likely to consider buying a Micro-wind generation unit for their home, 90.5% responded yes.

Conclusion

I have found and confirmed that HAWT rotors see improved performance in laminar airflow conditions than turbulent and that VAWT rotors see increased performance in turbulent airflow environments. Through my research and observations, I have also verified that HAWTs at this scale operate at a significantly higher RPM, with the best design generating a peak voltage of 4.34V (in laminar flowing winds of 7m/s), with the sacrifice of torque and that VAWTs behave oppositely; with the best design generating a peak voltage of 0.76V (in turbulent flowing winds of ~7m/s).

I successfully created 16 turbine rotor models, all but two worked, four operational motor housing assemblies which withstood all of the testings, and 2 Arduino Data Capture Boards, which after plenty of prototyping, worked as intended. Then when comparing the experimental results from the HAWTs and VAWT, I found that the HAWTs generated significantly more electricity across the board regardless of whether in turbulent or laminar airflow, despite them seeing considerable performance increases in laminar flowing winds, and the VAWT performances almost doubling in turbulent flowing winds. I also observed that the HAWTs had a significantly higher RPM, and the VAWTs had a considerably higher torque and aligned with the common belief stating that VAWTs in any form must be paired with a gearbox to match electricity generation.

Finally, out of all of these designs I tested, I found a lesser-known HAWT variation, which experts explained was only applicable in rare specific situations such as small-scale wind generation, and couldn't be used in commercial designs due to it causing dynamic blade instabilities. This HAWT variation was the Scimitar (Convex Curved) Shape Bladed HAWT, performing at an average of 19% better than the Traditional (Straight) Bladed HAWT variation currently in use in practically every micro-level wind turbine I could find (11.04% increase in turbulent airflow, and 27.34% increase in laminar airflow, of ~7m/s).

Applying this performance improvement to the 500W commercially available turbine, I found, could mean a potential reduction in payback time by approximately 19%. A possible up to ~19% reduction in rotor size while maintaining the same electricity production. Or the possibility of generating higher levels of electricity in regions with lower average wind speeds. Taking a standard 24-hour unit rate of 43.27c kW/h (Electric Ireland as of October 2022, a 124% increase from April 2020), this 500w turbine could generate ~€493 worth of electricity annually. Applying this higher-performing rotor model, you could see a potential increase of approximately €98 up to €591 saved each year. Pre-current electricity pricing, the base model above would have generated just €228 worth of electricity (at a unit rate of around 20 c / kW/h, April 2020). I believe this staggering increase in electricity prices serves as one of the core points in favour of the viability of micro-wind generation. This increase in electricity rates within the last two years has essentially halved the payback times of these technologies. Reinforcing the belief that this technology could serve as a means for the Irish people to offset their electricity bills in light of this energy crisis.

Further Work

I plan to continue this project and create a fibreglass version of the Curved Bladed “Scimitar Shape" HAWT large enough to power the 500w Turbine, and let it run over the course of six months alongside another one of the 500w turbines commercially available models. This will allow me to directly show the energy generation difference in real time, measuring wind speed also. They would have all of their data permanently recorded to a website from which I could at any given moment or wind speed or time of day know how they compared against each other. I also plan to investigate creating a larger and more robust way of mounting the VAWTs and from there experimenting with different gearbox variations and how that would affect cut-in speeds, and also overall energy generation changes compared to the HAWT models, and previous VAWT models.

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Stephen Skillington - Gave me a 500w Domestic turbine for my testing, for free.

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Mr Guillfoyle - Woodwork Teacher, who let me use his 3D Printer,

Mr Power - IT Teacher, who let me use his 3D Printer,

All of those who responded to the survey.

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Circuit Simulator Applet (falstad.com)

1M0 / 1M ohm Resisthttp://www.falstad.com/circuit/or Colour Code (petervis.com)

Arduino Ammeter - How to Measure DC Current using Arduino? (mechatrofice.com)

Convert milliamps to amps (unitconverters.net)

Appendix A- Background Research

Fossil Fuel Companies made €4Bn In Profits as the European Energy Crisis Began

In recent years, even before the onset effects of the Russo-Ukrainian War, it had been shown that EU Gas Companies were turning in massively increasing profits year on year. Here's but one example, published in late October of 2021, Global Witness.org posted an article discussing the issue:

" The European gas companies that make up the influential ENTSO-G group, and the fossil fuel giants that own them, made a turnover of at least €4 billion in profits in the first six months of 2021, according to a new Global Witness analysis.

According to the analysis, all 26 of the companies that released financial reports for 2021, including Belgium's Fluxys, Italy's SNAM, and Gasunie - which has operations in the Netherlands and Germany - made a profit just at the time when the European energy crisis was beginning to take shape.

The two companies that released their most recent financial statements (July to September) made big profits as the energy crisis hit consumers. German oil and gas company Wintershall generated 243 million euros in the period, up 245% from the previous year.

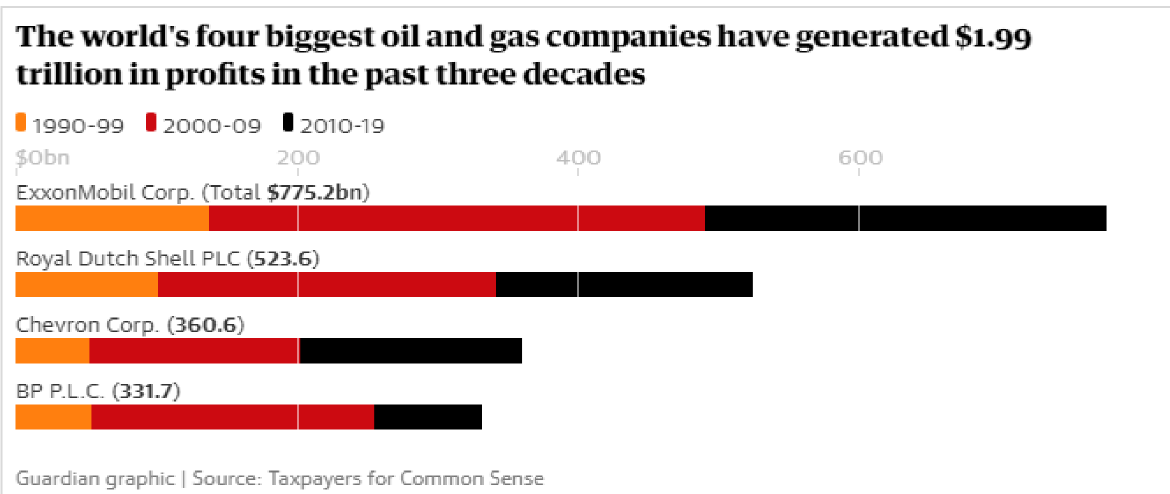
Global Witness Senior Gas Campaigns Jonathan Noronha-Gant said:

"It leaves a sour taste for the same companies to continue to make healthy profits as they passed the massive gas price hikes onto the most vulnerable … "

"It's well known the damage fossil gas does to our climate and with it now proven to be unreliable and volatile, it's time the EU shifts away from all fossil fuels and moves to a genuinely renewable future, as well as protecting the most vulnerable citizens from the rise in gas prices." "

- Source (Global Witness)

Fig. 129. Image Source (The Guardian and Ambrose)



1

Electricity Price Inflation in Europe in First Half of 2022

This year has seen a drastic rise in electricity costs. While this has been brought on and influenced by various factors, at the end of the day, this is directly taking money out of the pockets of European citizens. This is but one article published by Eurostat in October of this year, detailing just how much the EU average domestic electricity cost of electricity increased in the first half of 2022.

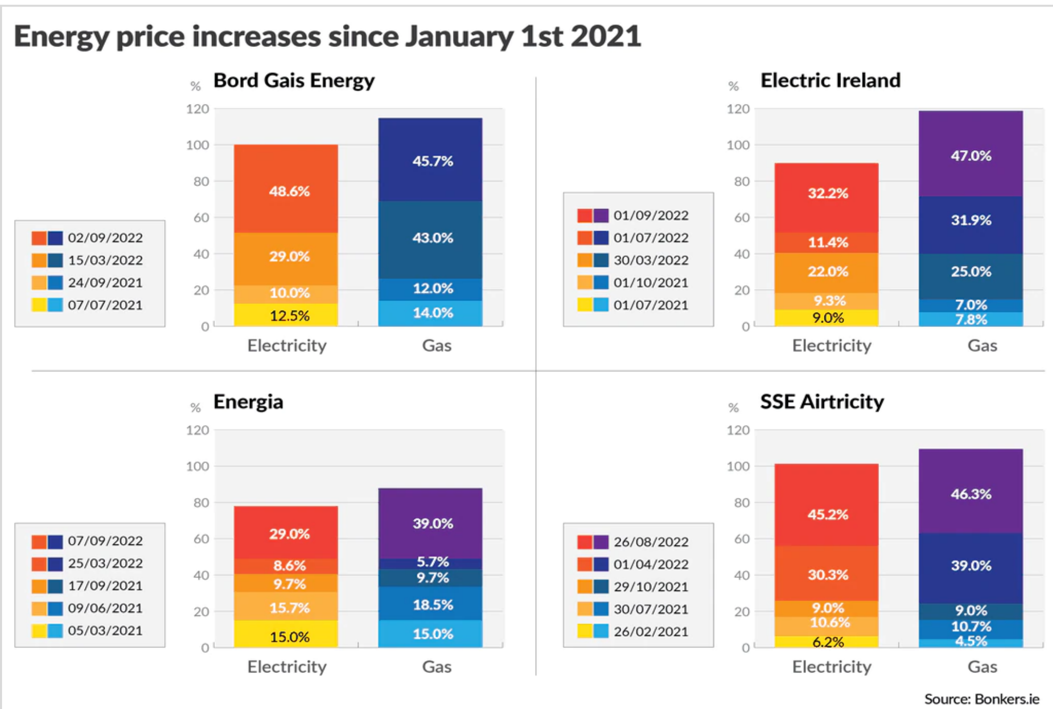
“ In the first half of 2022, the EU average domestic electricity price rose sharply from €22.0/100 kWh to €25.3/100 kWh compared to the same period in 2021. Average gas prices also rose from €6.4 per 100 kWh to €8.6 per 100 kWh in the first half of 2022 compared to the same period in 2021. Recently, wholesale power and gas prices have risen significantly across the EU. The main drivers of the increase are energy and utility costs affected by the current geopolitical situation and the Russian military aggression in Ukraine.

Compared to last year, the weight of taxes and surcharges on the final electricity and gas bills billed to EU households in the first half of 2022 will increase as Member States use government allowances and subsidies to be significantly reduced due to the introduction of mitigation of cost. Compared to the first half of 2021, the tax share on electricity bills has been significantly reduced from 39% to 24% (-15.5%) and the tax rate on gas bills has been significantly reduced from 36% to 27% (-8.6%).

This information is based on recently published electricity and gas price data from Eurostat. This article presents some insights from more detailed statistical explanation articles on electricity and natural gas prices. ”

- Source (Eurostat)

Fig. 130. Image Source (The Irish Times)



EU Approves Emergency Measures To Tackle Energy Costs

In a bid to help the most vulnerable people and companies cope with the surging cost of energy and electricity, EU Energy Ministers decide to approve the first package of emergency measures to tackle rising energy costs. This article published in late September 2022 by EuroNews.com details what exactly was agreed.

“ EU energy ministers on Friday the 25th of September approved the first package of emergency measures to stem rising electricity prices and coordinate member countries' responses to the energy crisis.

Negotiated within one month, the package includes mandatory energy savings, an excess market profit cap and a tax to earn excess corporate profits.

This EU-wide price ceiling for gas imports is now being considered.

Czech Republic Minister of Industry and Trade Josef Sikela said: "The EU has made progress today." The country rotates, he holds the Presidency of the EU Council and is responsible for coordinating internal consultations.

“We have completed another piece of the puzzle, but it is definitely not the last piece,” added Síkela. “This is an immediate patch.”

The deal came at a time when eurozone inflation fell to double digits of 10% for the first time in the history of the single currency.

The EU intends to cut peak power consumption to balance the imbalance between supply and demand, and forfeit some of the revenues from power plants and fossil fuel companies from higher prices. increase.

After a brief discussion that morning, ministers reached agreement, maintaining the core content of the package with changes focused on flexibility and practical implementation.

All three measures are time-limited and cover:

1. An EU-wide plan to introduce power savings: a mandatory 5% target during peak hours, when gas plays a bigger role in price-setting, and a voluntary 10% reduction in overall electricity demand.

2. A cap on the excess revenues made by power plants that do not use gas to produce electricity, such as solar, wind, nuclear, hydropower and lignite. The cap will be uniform and set at €180 per megawatt-hour. All revenues that exceed the barrier will be collected by governments.

3. A solidarity mechanism to partially capture the surplus profits made by fossil fuel companies (crude oil, gas, coal and refinery). Authorities will be able to impose a 33% levy on the profits made by these companies in the 2022 fiscal year – but only if the profits represent a 20% increase compared to the average since 2018.

Additional funds generated by the second and third instruments are diverted to financially stressed households and businesses in the form of subsidies, tariff reductions, or income support.

Countries that have already established similar solutions at national level may continue their programs if they pursue the same goals as the EU package.

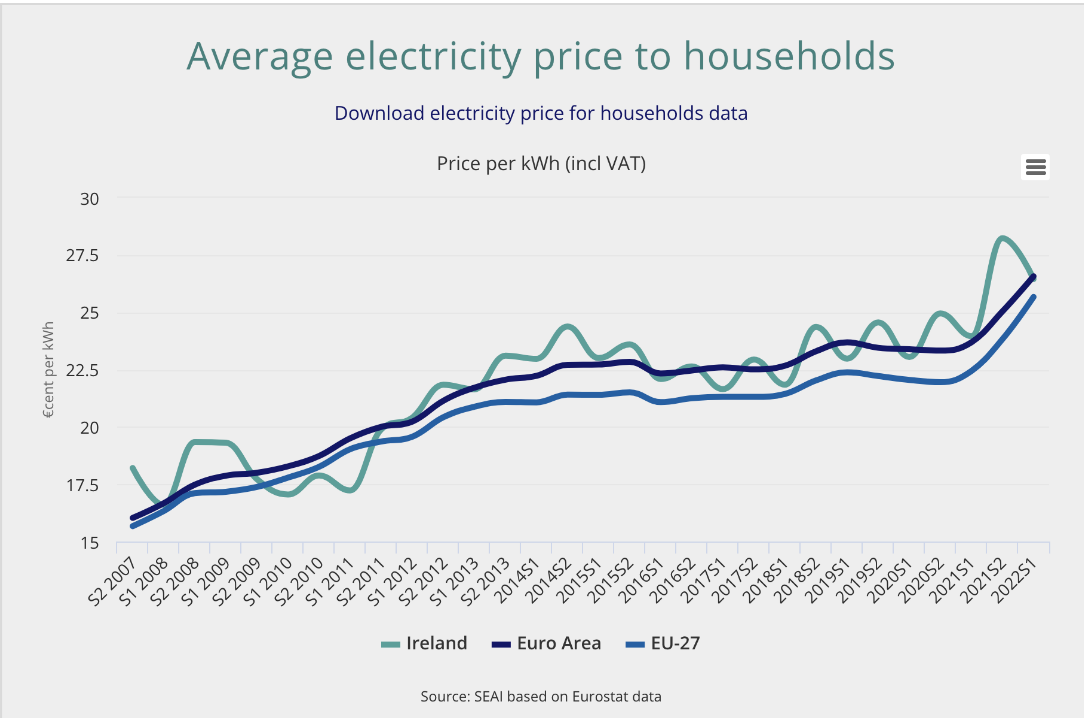
The package represents an important step forward in the EU's response to the energy crisis, but there is broad consensus that more action is needed before the winter season arrives.

"We have to keep working," said Shikera. “We are in an energy war with Russia,”

his French counterpart Agnès Panier-Lunacher repeated the call. "Let me be clear, we need to go faster, farther and make other suggestions," she told reporters Friday morning. ”

- Source (EuroNews and Tidey)

Fig. 131. Image Source (SEAI)

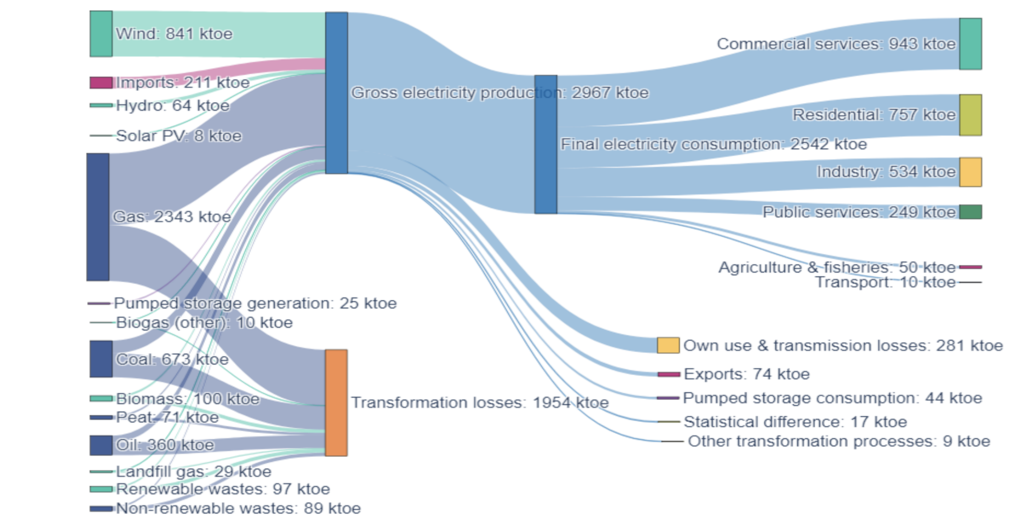


Breakdown of Ireland’s Electricity Production by Sources

Renewable and nonrenewable energy sources are used in combination as Ireland's main energy sources. The Sustainable Energy Authority of the Irish government estimates that about 40% of Ireland's electricity comes from renewable sources, such as wind, hydro, and solar energy. By 2030, the nation aims to produce 70% of its power from renewable sources. Over 25% of Ireland's electricity is produced from wind energy, making it the greatest renewable energy source in the nation. Over 3,000 wind turbines are presently in use throughout Ireland thanks to policies and incentives the Irish government has put in place to promote the growth of wind energy.

Providing 7% and 2%, respectively, of the country's current electricity needs, hydroelectricity and solar power are other existing and expanding sources of renewable-based electricity in Ireland. Ireland still uses a majority of non renewable electricity sources including 40% being provided by gas and 20% by coal.

Figure 29: Flow of energy in electricity generation and consumption



Source: SEAI

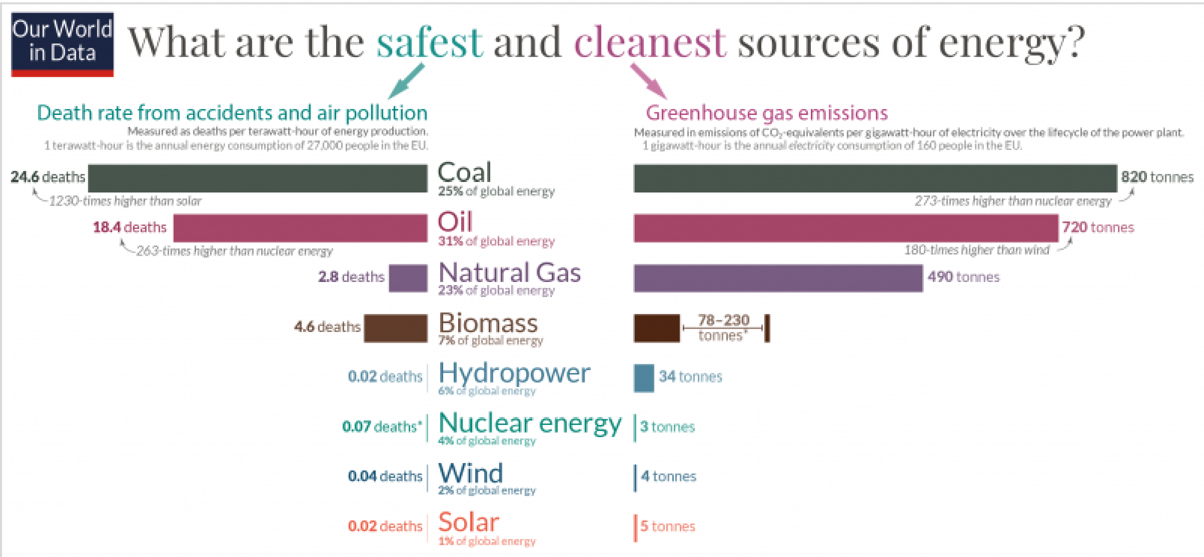
Fig. 132. Image Source (Sustainable Energy Authority Of Ireland)

Power supply that is dependable and secure is critical to contemporary economies and societies. One-third of Ireland's total primary energy supply is utilised as an input to generate electricity. The energy flow from the inputs required to manufacture electricity to the final electricity utilised by the various sectors is depicted by the Sankey diagram in the figure above. According to this diagram, a significant percentage of the energy required to create the electricity is squandered before it reaches the end user owing to a combination of transformation losses, power plant consumption of electricity, pumped hydro storage losses, and transmission losses. The most notable aspect of renewable energy is that there is essentially no, or even negligible quantities of, energy waste.

- Source (Sustainable Energy Authority Of Ireland) (Statista)

What is Currently the Safest Source of Energy

While the discovery of fossil fuels obviously served an integral part of humanities development, the prolonged use of fossil fuels and the avoidance of unestablished and environmentally friendly alternatives has led to us essentially shooting ourselves in the foot. The enormous amounts of greenhouse gases accelerating global warming and subsequently causing climate change. The article 'What Are The Safest And Cleanest Sources of Energy', by Ourworldindata.org covers how although coal, oil and natural gas are the most widely used energy sources currently; they are directly responsible for dramatically more negative impacts apart from permanently changing the Earth's climate, first is air pollution: At least 5 million people die prematurely every year due to air pollution. Fossil fuels and the burning of biomass are responsible for the most deaths, and if eliminated would cut premature deaths from air pollution by about two thirds. Secondly is accidents, these could occur during the mining and extraction of fuels and could happen during the transport of raw materials and infrastructure, the construction of the power plant and even operation. The third negative impact is greenhouse gas emissions: fossil fuels are that main source of greenhouse gases and the primary driver of climate change. In 2018, 87% of global CO2 emissions came from fossil fuels and industry.



Of course, all energy sources must come with negative effects, but to compare the loss of life and quantity CO2 emitted into our atmosphere directly because of fossil fuels to renewable energy is simply wrong. As displayed in this graphic, wind energy, for example, results in 99.998% less accident related deaths than coal; 99.997% fewer than oil and 99.985% fewer than gas. Wind, solar, hydropower and Nuclear based renewable energies I believe are clearly completely incomparable to conventional fossil fuels in terms of preservation of human life, and reduction in greenhouse gas emissions.

- Source (Our World In Data and Ritchie)

Fig. 133. Image Source (Our World In Data and Ritchie)

Average Cost per Mw Produced for all Energy Sources

All renewable energy sources usually have lower average costs per Mw generated than do fossil fuels. This is because the production of electricity from renewable energy sources, such as solar and wind, is generally more efficient and economical than the production of power from fossil fuels, such as coal and natural gas. The levelized cost of electricity (LCOE), sometimes known as the levelized cost of energy, is a measure of a generator's average net present cost of power generation during its lifespan. It is used for investment planning and to consistently evaluate different ways of power generation.

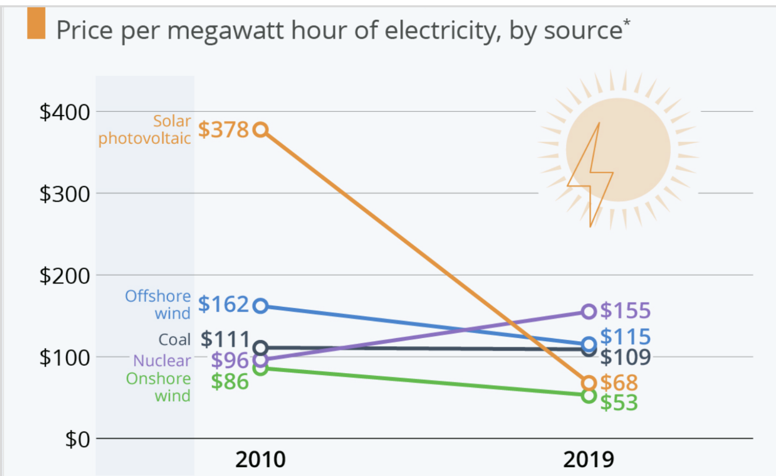
Estimates from a report published by the International Energy Association in 2020 titled “Projected Costs of Generating Electricity 2020” forecasted the average LCOE of wind-based electricity at a median price $50 per MW/h, while the median predicted LCOE of solar-based electricity, at around $56 per MW/h. In comparison to that of coal at $116 and gas at $91 per Mwh. This was verified to be correct by another study published by Lazard in October of 2020 called: “Lazard’s Levelized cost of Energy Analysis 14.0”. In which it was shown that Solar PV (Thin Film Utility Scale) ranged between $29 and $38, and Onshore Wind Power at $26 to $54. Yet again cheaper than conventional fossil fuels like the cheapest of which was Gas at $44 to $73 and in second place Coal at a price of $65 to $159.

Renewable energy offers countless advantages when compared to fossil fuels, only one of which includes cheaper production costs. Renewable energy sources, for example, have been proven to be dramatically more ecologically friendly, sustainable in the long term than fossil fuels, and produce less than one percent of the deaths and greenhouse gas emissions associated with fossil fuels, while still all the while costing less than fossil fuels. Which emit significant volumes of greenhouse gases into the atmosphere that are directly contributing to climate change.

According to these figures, it is clear to see that it’s less expensive to generate energy from renewable resources like solar and wind than it is to generate electricity from fossil fuels like coal and natural gas. However, it should be noted that these figures may change based on factors such as resource availability, location, and technology employed. Renewable energy sources have simply more benefits to provide over fossil fuels than merely being cheaper to produce.

- Source (U.S. Energy Information Administration) (Lazard)

Fig. 134. Image Source (Statista)



Average Irish Household Electricity Consumption and Bill

Energy prices have already risen considerably in 2022, and additional price rises are on the way in the new year. We all need power in our homes, and electricity costs can account for a significant portion of yearly family spending. Overall, as modern appliances become more energy efficient, power consumption per appliance is decreasing. However, the growing number of electrical devices and equipment in our houses contributes to the high average power usage. There are many factors that come into play when trying to understand how much electricity your household consumes annually, only a few include its size, location, and how many people are living there.

According to the most recent energy use numbers for Ireland, provided by the Commission for Regulation of Utilities (CRU), 4200kWh is now the "official" annual power usage for Irish homes. Based on "regular" pricing rates from Electric Ireland, the largest supplier, this would result in an annual electricity bill of €2120. As of October 2022, Electric Ireland's "Standard Rate" is at 43.27c kW/h.

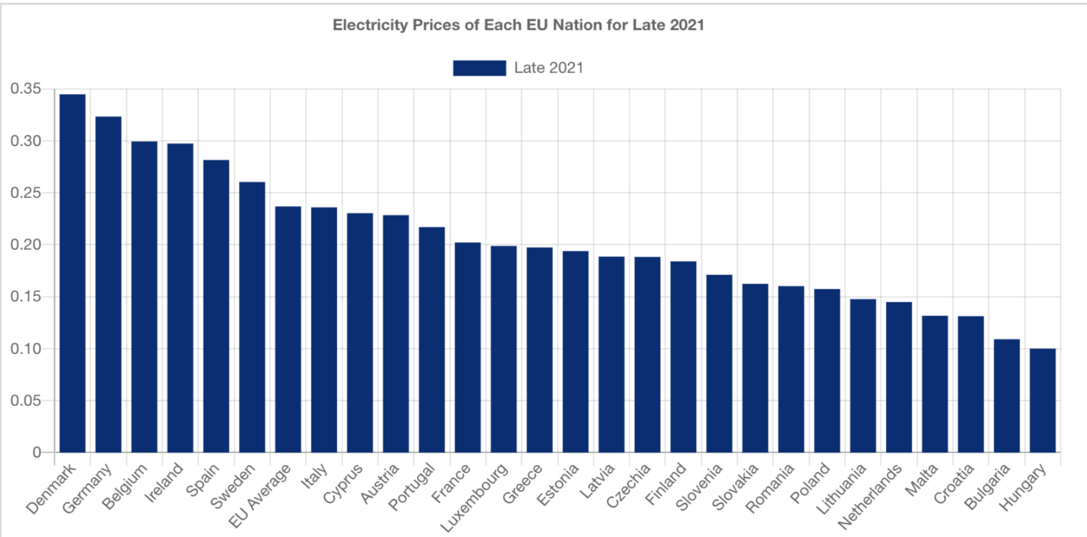
Electricity rates in Ireland increased by 13% in 2020 alone, changing from €0.2616/kWh to €0.2974/kWh, and on the 1st of September (2022), Electric Ireland announced plans to increase residential electricity bills by 26.7% from 1st October 2022. The following table in the second image breaks down the price of energy in Ireland over the last ten years in five-year increments. Based on these costs, we can compute the projected average electricity spend. The calculations are based on an annual use of 4,200 kWh of energy. All taxes, levies, and VAT have been included:

- Sources (Commission For Regulation Of Utilities) (MoneyGuideIreland) (Switcher)

Fig. 135, 136. Image Sources (Selectra)

Electricity Prices in Ireland

Time Period	Electricity Price	Estimated Annual Spend
Late 2021	€0.2974/kWh	€1,249.08
Late 2020	€0.2616/kWh	€1,098.72
Late 2015	€0.2454/kWh	€1,029.84
Late 2010	€0.1874/kWh	€787.50



Ireland’s Potential Wind Energy Output

The island of Ireland produces no nuclear energy, oil or coal, and only enough gas to meet some 30% of its needs. But it has one of the windiest coasts on the planet, and as shown in the graph below, one of the best in Europe. “Wind is Ireland’s oil,” said Micheál Martin, Taoiseach, at Davos this year. “Certainly, by the mid-2030s we want to be exporting energy.” Here is a section of an Economist.com article discussing Ireland’s possible future in exporting renewable energy.

“ Last year 31% of Ireland’s electricity came from wind turbines, according to Wind Europe, an industry group. The share was higher only in Denmark, which managed 44%. Already this year Ireland’s figure has risen to 36%. The Irish government wants to push its renewables share up to 80% by 2030; it even managed to beat this target during one especially stormy weekend in February this year. The hope is that improvements in energy storage, and a new electricity interconnector with France which is due to come online in 2026, will allow Ireland to sell surplus wind power to European countries that are struggling to decarbonise their own energy supplies.

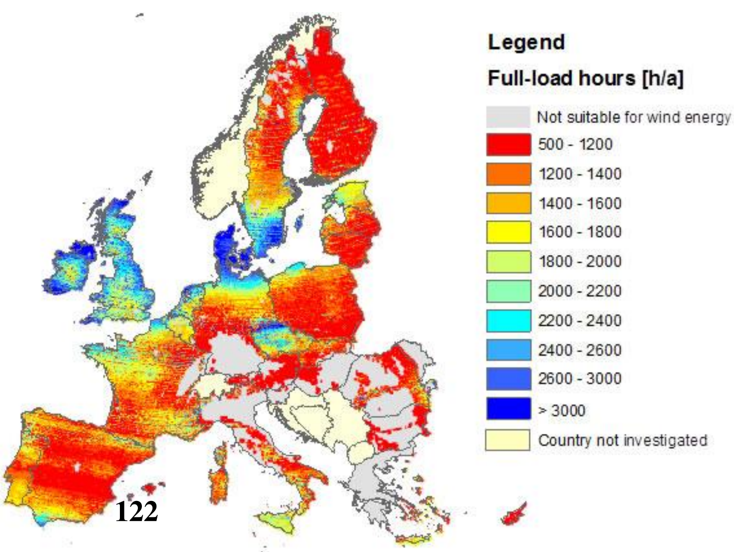
According to WindEnergyIreland.com The Republic of Ireland has built just over 300 wind farms on dry land already, and is running out of places to put new ones. For health and environmental reasons, turbines must be at least 500 metres from existing houses. As of 2022, the Republic of Ireland has 4,309 MW of installed wind power nameplate capacity, the third largest per capita in the world.

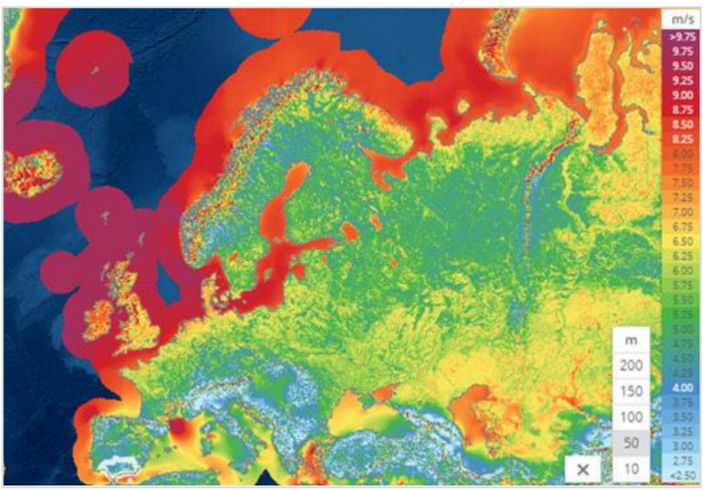
The obvious solution is to move production out to sea. Ireland’s only offshore wind farm, off County Wicklow on the east coast, was the largest in the world when it began spinning in 2004, but has since been dwarfed by newer ones elsewhere in Europe. Noel Cunniffe of Wind Energy Ireland, another industry group, says that in theory Ireland could install offshore turbines with a capacity totalling 80 gigawatts, more than triple Britain’s total current wind capacity, and that this figure will probably increase as turbine technology continues to improve. ”

This estimate can be further supported by the following graph, showing how Ireland boasts one of the highest potential Full-load hours in wind energy in all of Europe.

- Source (Economist.com)

Fig. 137, 138. Image Sources (Held, 2011) (Global Wind Atlas)





Pros and Cons to Wind Energy Generation

The Advantages to Wind Energy

1. Sustainable

One of the most sustainable energy sources is wind power. Wind turbine energy generation produces no greenhouse emissions.

True, some pollution is produced during the production, transporting, and installation of wind turbines. However, it is nowhere near the volume of emissions produced by the combustion of fossil fuels.

Because the actual production of energy produces no greenhouse gas emissions, it is considered a green energy source.

2. Regenerative

Wind energy is a renewable energy resource, which means that it does not diminish the source of energy when used. As a result, as we consume wind energy, we do not reduce the amount of wind available. This is not true of nonrenewable energy sources such as oil and natural gas. As we consume fossil fuels, we diminish the amount accessible for future use.

3. Compact Size

Considering the prominent fact that wind turbines cannot be placed too close together, this would create an argument for the space efficiency of solar farms, although this is not entirely the case. Wind turbines, on the other hand, take up very little space, for the amount of electricity that they generate.

Wind farms are popular in rural areas because the space between each turbine may be used for agriculture. Furthermore, each turbine is capable of producing enough electricity to power roughly 2,500 houses.

4. Encourages Job Growth

Year after year, the wind business expands rapidly. Between 2010 and 2018, the amount of installed wind capacity in the United States more than quadrupled, producing enough wind energy to power more than 30 million households. Thousands of new employment have been generated as a result of this expansion.

Over 120,000 Americans currently work in wind energy, ranging from installers to technicians and manufacturers. In fact, wind turbine technician is the second-fastest expanding employment in the United States.

Wind energy is expected to support more than 600,000 new jobs by 2050 as it grows in popularity.

5. Low-cost Energy Source

Although wind turbines are expensive to install, the electricity they provide is inexpensive. This is due to a number of factors, one of which is that no fuel for the turbines is required. Turbines also have cheap running costs once installed and require little maintenance.

When you factor in the initial investment as well as the cost of operations and maintenance over the life of the turbine, studies suggest that wind energy costs around $0.029 per kilowatt hour.

When you consider the cost of building and operating coal power facilities, that works out to around $0.036 per kilowatt hour.

Disadvantages to Wind Energy:

1. Unpredictability

The most significant drawback of wind energy is that it cannot be generated reliably. Only when there is wind will energy be created, and this can vary significantly based on location.

The quantity of energy produced by turbines is also affected by wind speed. As a result, wind energy is unsuitable as a base load energy source, i.e. our primary source of power generation.

However, if energy storage technology becomes more affordable, it may be conceivable to become increasingly reliant on wind energy. For the time being, however, due to their unreliability, wind turbines must be utilised in conjunction with other energy sources to supply our electrical demands.

2. Wildlife Threat

Wind energy is not harmful to the environment because it does not release greenhouse gases; yet, turbines can have an impact on wildlife.

When birds, bats, and other flying animals are directly struck by a rotating wind turbine blade, their chances of survival are slim. Wind turbines kill between 140,000 and 500,000 birds every year, according to study. Structure collisions, on the other hand, are expected to kill between 365 and 988 million birds every year. The amount of bird crashes can be reduced by carefully planning where wind farms will be developed.

3. Noise

Some residents who live near wind turbines complain about noise. The turbine's generator emits a mechanical hum, and the blades generate a "whooshing" sound as they travel through the air.

The good news is that newer wind turbines make substantially less noise than older turbines, and they will likely become increasingly quieter as technology advances.

4. Appearance

Wind turbines must be erected high up in order to capture adequate wind, making them an eye-catching feature in any landscape. Some individuals regard enormous wind turbines to be an eyesore, however this is a matter of personal choice.

5. Geographical Constraints

Wind turbines must be erected in an area where they will generate enough power to be economically feasible. Wind farms are most suited for coastal locations, hilltops, and open planes - in short, everywhere there is strong, consistent wind.

The majority of these appropriate locations are located in distant areas far from cities and towns, in more rural areas, or offshore. Due to the distance, new infrastructure, such as power lines, must be constructed to link a wind farm to the electricity grid.

This can be expensive and may have an impact on the environment (i.e by tearing down trees to make way for power lines).

Although wind energy has significant drawbacks, such as being an inconsistent energy source and posing a threat to some fauna, the advantages are undeniable. This is why wind farms, both on and offshore, continue to be constructed.

- Sources (EnergyInformative.org) (ConserveEnergyFuture.org) (US Department of Energy) (Energy.gov) (ConserveEnergyFuture.com)

Horizontal Axis Wind Turbines

Horizontal Axis Wind Turbines

Because of their robustness and efficiency, horizontal axis wind turbines are the most popular and most often utilised turbines. The tower bases must be exceedingly robust in order for the rotor shaft to be mounted at the top of the tower, exposing the turbine to harsher winds. When the turbine's blades are perpendicular to the wind, the spinning of the blades can create more power than a vertical axis wind turbine. The building of this sort of turbine, however, necessitates a substantial tower support to hold the weight of the blades, gearbox, and generator, as well as the need of a large crane to carry the components to the top of the tower. When the wind blows downhill, the turbine structure may experience metal fatigue, which might lead to structural failure. This is handled by designing the turbines to face upwind. To monitor the direction of the wind and avoid damaging the turbine, horizontal axis wind turbines require additional yaw control.

Examples of Horizontal Axis Wind Turbines:


Fig. 139, 140. Image Sources (Pixabay.com)

Horizontal axis wind turbines are often built with capacities ranging from 2 to 8 MW, depending on the application. While wind turbine production varies depending on turbine size and wind speed, an average onshore wind turbine with a capacity of 2.5 - 3.0 MW may produce more than 6 million kWh per year, which is enough to power 1,500 ordinary EU dwellings.

For any type of energy conversion, there is always energy lost. How to improve energy conversion efficiency is one of the biggest focuses of product development in the wind energy industry. Currently, horizontal axis wind turbines have the highest efficiency. They can transform 40 to 50 % of received wind power into electricity, whereas vertical axis wind turbines on average have an efficiency of 10-17%.

Horizontal axis wind turbines have been the main wind turbine model for decades, therefore research and development are well advanced. Not only are present market items dependable, but the application and utilisation of horizontal axis wind turbines is also fully investigated.

- Article Source (Luvside.de) (EnergyFollower.com)

Vertical Axis Wind Turbines

Vertical Axis Wind Turbines

Vertical axis wind turbines are less impacted by frequent wind direction changes than horizontal axis wind turbines because the blades are spun perpendicular to the ground on the rotor shaft. The turbine does not need to revolve to follow wind direction with the blades and shaft arranged in this manner. Due to the challenges in placing the shaft and its components atop the tower, the shaft is installed near ground level. The advantage of mounting the turbine at ground level is that it is easy to maintain and may be positioned in sites such as roofs.

VAWTs are reportedly much more efficient in turbulent winds, enabling rooftop and urban installations, and they turn at comparatively lower revolutions per minute, thus producing less vibration and noise. Most VAWT manufacturers quote noise levels of less than 40 dB at a distance of less than 20 ft/6m, while the few HAWT builders that offer such measurements often report 50 to 60 dB or more at much greater distances. VAWTs are typically more compact and operate at lower elevations, making them less visually intrusive.

Fig. 141. Image Source (Wikipedia.org)

The disadvantages of this turbine installation include decreased efficiency owing to air drag and lower wind speeds compared to higher elevation wind speeds. When the wind blows on the blades of a HAWT, all of them contribute to energy production. When wind blows on a VAWT, only a fraction of the blades generate torque while the other parts merely 'go along for the ride', or even cause drag or push the turbine in the opposite direction. The result is comparably reduced efficiency in power generation.

The most popular VAWTs are lift based designs, such as the French "eggbeater" Darrieus (first patented in 1927.) Each blade experiences maximum lift (torque) just twice each rotation, resulting in a massive torque (and power) sinusoidal output – similar to cranking a bicycle – that is not present in HAWTs. Furthermore, the lengthy VAWT blades have various natural vibration frequencies that must be avoided during operation. For example, a 500-kW two-bladed vertical-axis turbine on site has two or three rotating speeds that must be swiftly passed through to reach working speed, as well as numerous modes inside the operational range that the control must avoid. These issues do not exist in a well-designed HAWT.

However, VAWTs might have issues, some say, with reliable self-start in low wind speeds and also with less efficient power production than HAWTs (the low rotation speeds are quiet but not necessarily efficient). This issue is discussed in a paper by Jacken Chen, founder and general manager of Hi-VAWT Technology Corp., a Taiwan-based manufacturer of a combined Savonius/Darrieus VAWT. The Savonius unit provides a more reliable self-start, but the Darrieus components provide efficient power. Meanwhile, other sources claim that simply modifying Darrieus designs via optimal turbine sizing and higher-performance blade shapes will do the same. Savonius based VAWTs do not use any airfoils but are rather purely drag based rotors. It has been shown that Darrieus VAWTs boast an overall efficiency of about 40%-50% in drastic comparison to Savonius VAWTs 10%-17%.

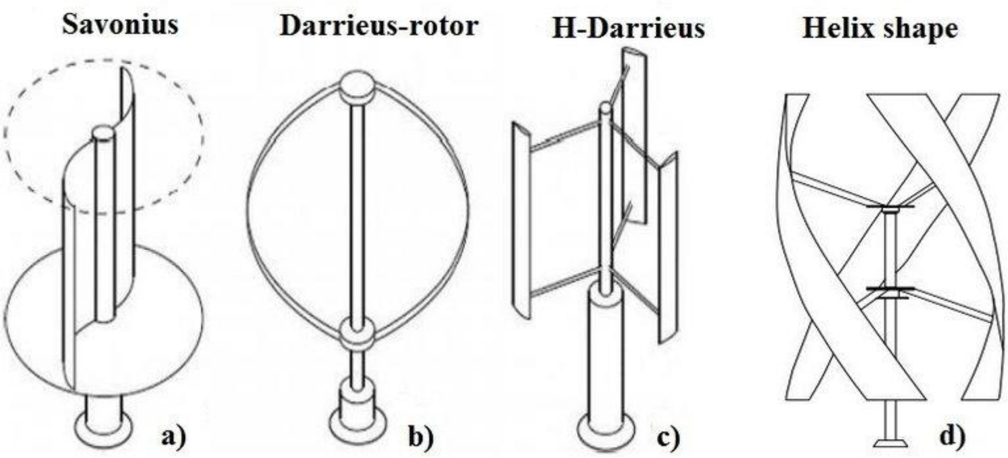
HAWTs have a greater efficiency then VAWT when extracting energy from the wind force due to its design that allows it to transfer energy through the full rotation of the blades when placed under consistent wind flow. HAWTs are also immune to the backtracking effect.

- Source (EnergyEducation.ca) (Researchgate)

  Fig. 142, 143, 144. Image Sources (Gil et al.) (Townsville.org)

Image "a" depicts a Helix Shape variation, Darrieus rotor VAWT

Image "b" depicts a Darrieus-rotor variation, VAWT.



General Overview of Micro-Wind Generation

Micro-wind generation, also known as small-scale wind energy, is the use of wind turbines with a capacity of less than 100 kW to generate power for homes, companies, and communities. The practicality of micro-wind energy generation can be determined by various criteria, including location, wind resource availability, system cost, and planned use of the power generated.

In general, micro-wind generation can be a viable option in areas with good wind resources, where the wind speed is consistently high enough to generate electricity efficiently, such as Ireland. The cost, specifications and intended usage of each individual system can and will naturally play a sizable role in determining the viability of micro-wind generation. For example, if the electricity generated is intended to offset a high electricity bill, the cost of the system may be justified if it can produce enough electricity to make a significant dent in the bill over its lifetime. On the other hand, if the primary goal is to reduce carbon emissions, the cost of the system may be justified even if it only makes a small contribution to reducing electricity use.

So considering this and going down the route of saving money, following the Irish Government's 2022 Microgeneration Scheme, customers from Electric Ireland when availing of this scheme could be paid 21c Per kW/h put back into the grid. If you compare this to the current "Standard" electricity rate in Ireland, that being 43.27c per kW/h from Electric Ireland. It is clear that putting the energy you generate directly into powering your home or business and offsetting your electricity costs is the correct, and cost effective use of Micro-wind generation.

According to Energy.gov: "Installing micro-wind generation systems can lower your electricity bills by between 50%–90%." Small wind electric systems can also be used for a variety of other applications, including storing the energy into deep cycle batteries and pumping water on farms, to powering lights and appliances or your washing machine in the evening. Typically in order to set up a Micro-Wind generation unit, you would firstly need a turbine and a way of mounting it safely within your property. According to the Office of Public Regulations, domestic wind turbines in Ireland can be installed up to a maximum height of 13m without planning permission, but cannot be mounted to any house or building and instead must be freestanding, and the supporting tower must be a distance of not less than the total structure height (including the blade of the turbine at the highest point of its arc) plus one metre from any part of the property boundary (,in case of it collapsing). Another fact to be noted is that although Ireland has been shown to be one of the best locations in Europe for wind generation; there are currently no government grants or incentives available for citizens considering installing their own domestic micro-wind generation systems.

If you are considering buying your own Micro-Wind Generation system, you can buy the actual turbine from the likes of Amazon.co.uk or Alibaba.com, prices of the units can range from €500 to €30,000+. This isn't including the installation costs involved, although it is absolutely possible to do it yourself, purchasing the poles, making the concrete foundations and electrical wiring, assuming you have the facilities and experience required. Below is a table displaying the system cost and approximate yearly system output of each system size.

System size	Indicative system cost (incl. VAT @5%)	Approx. yearly system output*
1kW (roof-mounted)	£1,500	1,750kWh
1.5kW (pole-mounted)	£7,000	2,600kWh
2.5kW (pole-mounted)	£12,500	4,400kWh
5kW (pole-mounted)	£23,500	8,900kWh
10kW (pole-mounted)	£45,000	21,500kWh
15kW (pole-mounted)	£70,000	36,000kWh

Fig. 145. Image Source (RenewableEnergyHub.co.uk)

The following figures were made assuming the average UK wind speed of 5.6m/s for the sake of illustration. The actual system output is predicated upon a large range of factors. Larger, higher output turbines also tend to be mounted at greater heights, where wind speeds are higher.

Depending on the type and size of the turbine, there are also annual system maintenance costs which one must bear in mind, though these tend to be relatively small. Since they rely on relatively simple mechanical processes, the turbines themselves tend to have a long life, and typically come with a service warranty period of 10-20 years. If the wind turbine system contains batteries for the storage of the electricity generated, these will probably need to be replaced around every 5 to 10 years.

As I have covered towards the beginning of this background research, the average Irish household annual electricity consumption is said to be 4200 kW/h, and an average electricity bill of €2120. Considering this, if someone purchased a 1kW wind turbine, for about €1500, that would account for approximately 42% of their electricity consumption, saving the equivalent of €757 (as of October 2022, standard 24h unit rate of 43.27c kW/h, a 124% increase from April 2020), and pay itself back in less than two years (not including battery of installation costs). [Now as you will see later, in the survey I sent out to parents and teachers in my school with 169 responses, the largest portion of respondents (at 20%) said that they would be willing to pay over double the amount of this turbine in the example if it could provide for their home electricity demands.]

- Article Source ("Energy Payback & Return on Energy") ("WINDExchange: Small Wind Guidebook") ("How Much is the Average Electricity Bill in Ireland ?") ("Planning Permission for wind turbines - exemptions") ("How Much a Wind Turbine Costs") ("Markets and applications for small wind turbines")

Appendix B - Survey Results

Question 1.

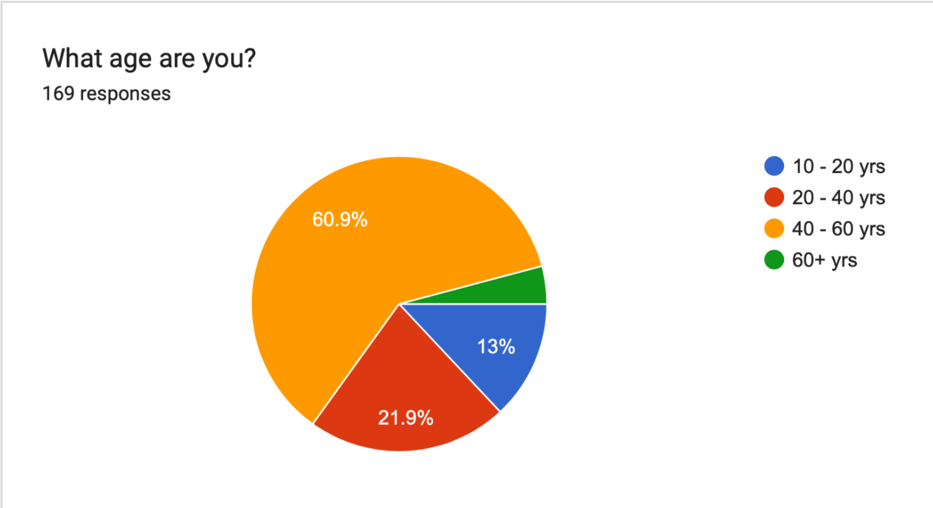


Fig. 146.

I had intended for this survey to be taken by parents and teachers, and from this graph it is clear to see that I have achieved the majority of responses from this demographic.

Question 2.

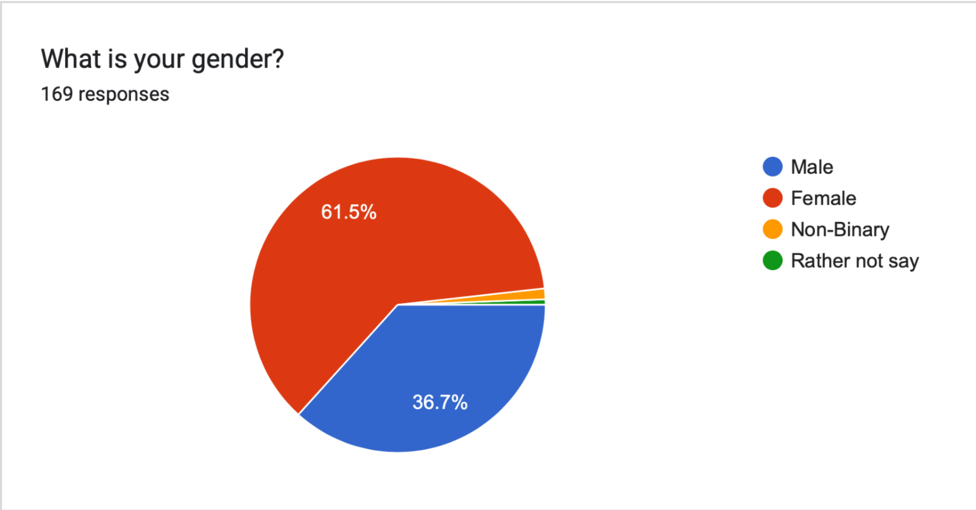


Fig. 147.

From this we can see that there was a majority of female respondents at 61.5%, male respondents at 36.7%. This I believe is to be expected when sending a survey out to staff and parents, the likelihood of an even gender mix reduces when it turns to voluntary participation. It has been proven that women are more likely to respond to women than men. As shown in this snippet:

"Notably, some researchers maintain that females are more likely to engage in online activity characterised by communication and exchanging of information whereas males are more likely to engage in online activity characterised by seeking of information (Jackson et al., 2001)."

Although I don't think that this small difference will make much of a difference overall. As I don't plan on comparing between genders, and this survey is more for understanding the overall opinions.

- Sources (Smith) (Royall)

Question 3.

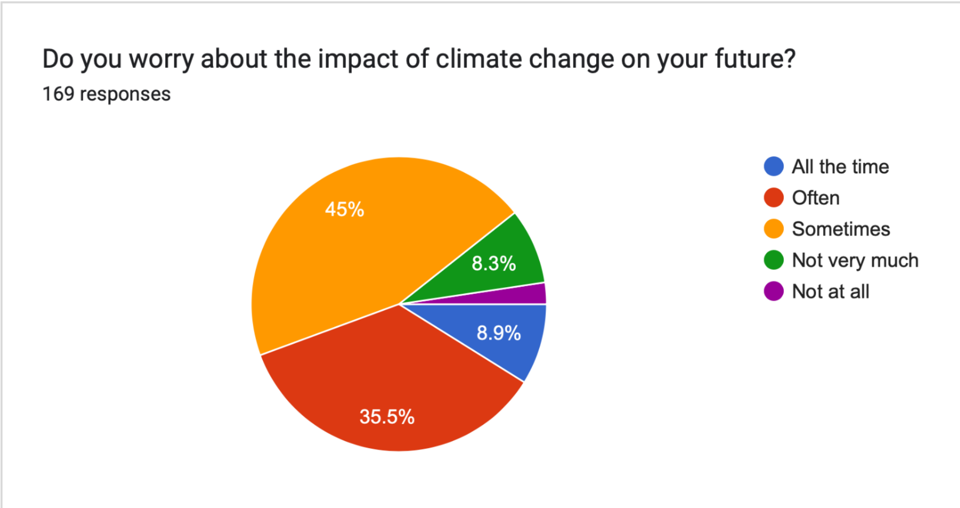


Fig. 148.

This served as an introductory question for the respondents and to get a better understanding of people's opinions towards climate change, and how it's directly affecting their future. As can be seen, the majority of respondents (45%) chose the middle option saying that they sometimes think about climate change's impact on their future, but in close second at 35.5% was the second to most extreme option 'Often'. Essentially, 80.5% of respondents said that they do think about climate change and how it will affect them later on in life, and nearly half of them said that they think about it often. The next question is fairly similar to

Question 4.

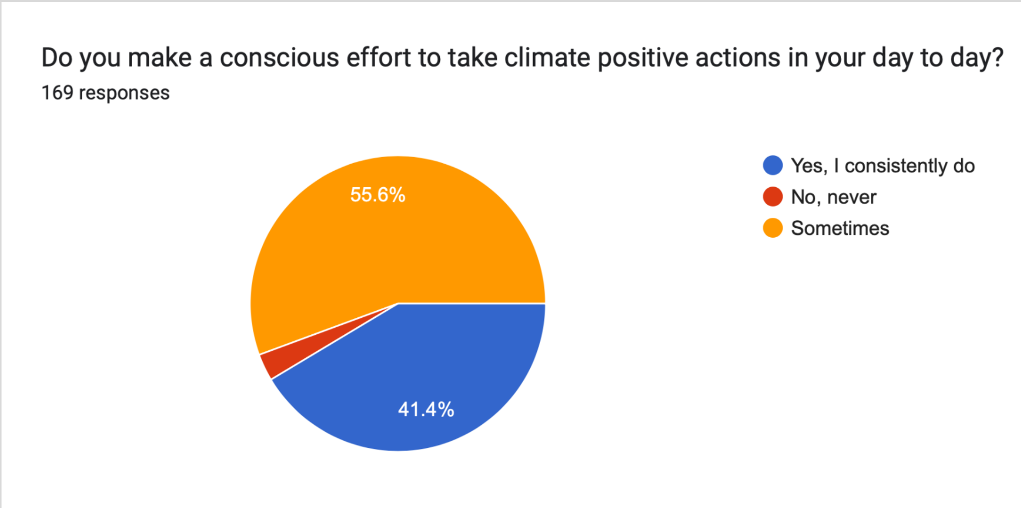


Fig. 149.

This question more than anything, once again served as a form of introductory question in order to help the respondents get into the flow of completing the survey. It shows how while over 41.4% of respondents say that they made a conscious effort to take climate positive actions in their day to day, 55.6% also responded saying that they don't necessarily make these actions daily but certainly sometimes. Whether this reflects reality or not is another question, but what this does show is that how while the overwhelming majority of people (80.5%) responded in Question 3 saying that they do worry about how climate change will affect their futures, this belief is also represented in the actions they take to help make a positive impact in their day to day.

Question 5.

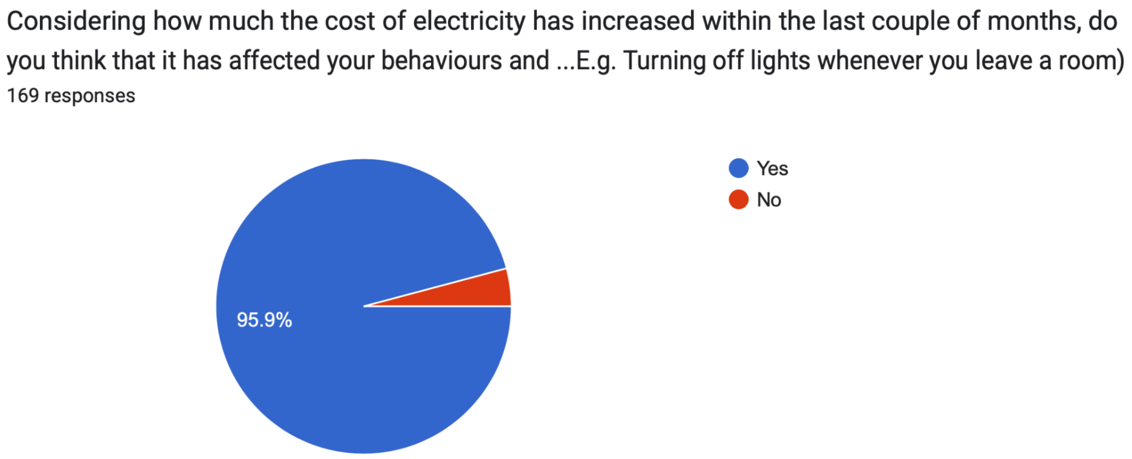


Fig. 150.

This question acted as a simple segway for the respondent to begin thinking about the current cost of living crisis and how it had affected their own patterns and behaviours of living, and in response an overwhelming majority of 95.9% of respondents believed that the current climate had influenced their behaviours towards saving electricity and money. This points towards, how in Question 4 when asked whether people make a conscious decision to take actions that will better the environment, only 41.4% people were as positively engaged than in comparison to taking actions that will ultimately save them money and time.

Question 6.

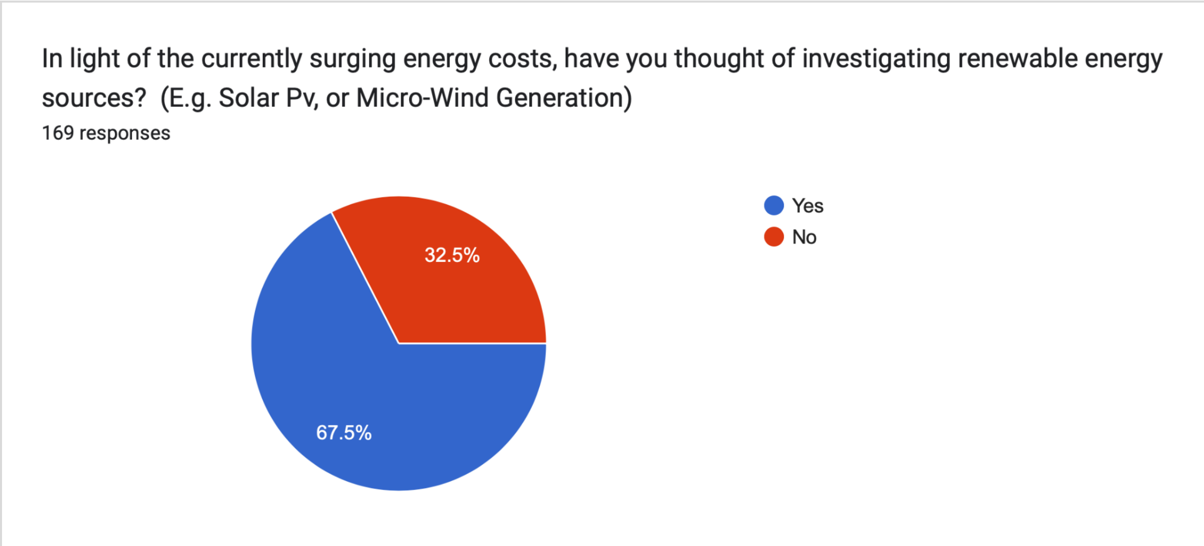


Fig. 151.

In this question respondents, the majority of which at ~84% were above 20 years old, were asked to consider whether the current climate and cost of living crisis had driven them to consider or investigate renewable energy sources as a solution for their homes. With 67.5% of respondents saying that they have, in light of the currently surging energy costs, thought of investigating other renewable alternatives for powering their homes. This really drives home the point that this is really a crisis, and it’s forcing people to look into other ways of keeping the lights on at home.

Question 7.

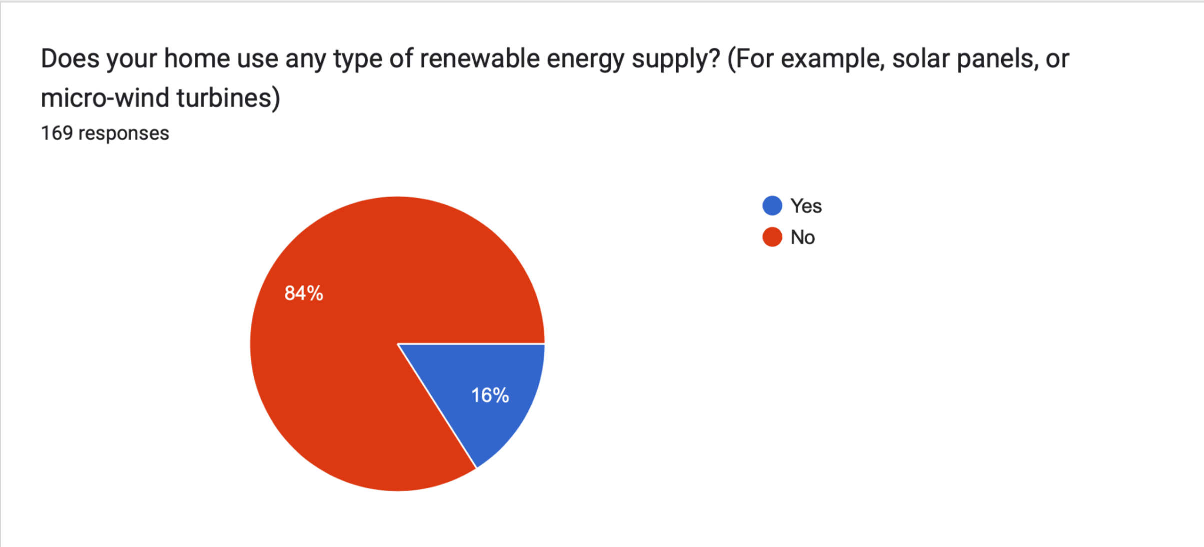


Fig. 152.

This question was made to be a followup to Question 6, where through comparing the two I could get a better idea of how many of these people already had some renewable source of energy powering their homes. As we can see 84% did not, and only 16% said that they did, comparing this to the 67.5% of respondents who did say that the current situation has forced them to think about other renewable sources of energy for their homes. That means, assuming that only people who didn't at the time of the survey have any source of renewable energy powering their homes, that approximately 80% of these people in light of the current crisis have been forced to consider these alternative energy sources.

Question 8.

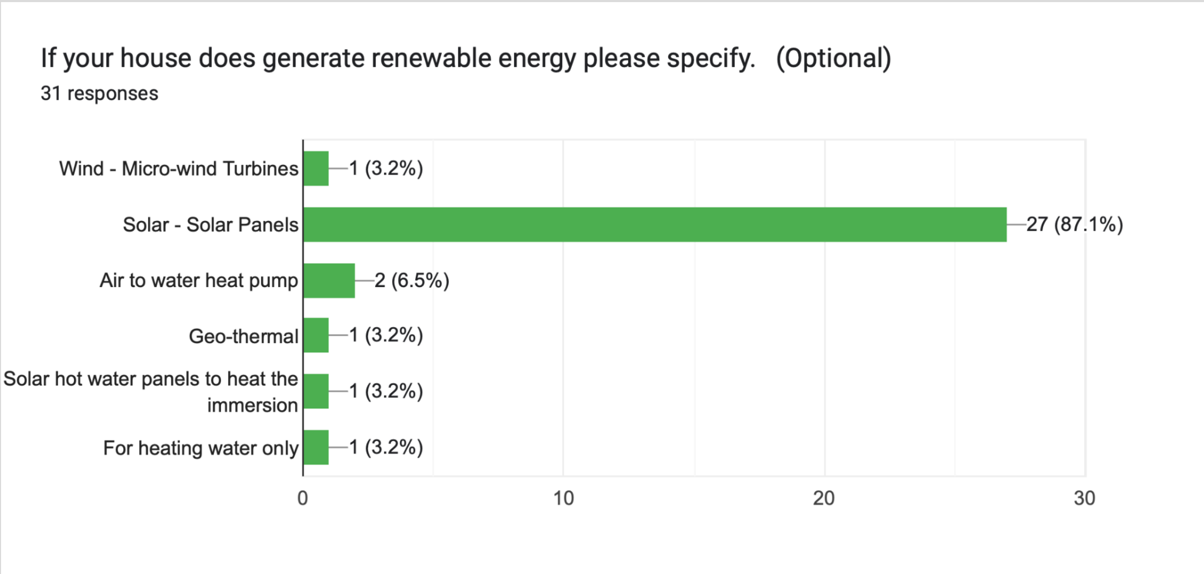


Fig. 153.

In this followup question for those who responded to Question 7 saying that their house does have a renewable source of energy, I asked them to simply specify what type of energy generation technology they have? As we can see, the overwhelming majority at 27 answers, or 87.1% was Solar PV Panels, then after that we had a small spread of many other energy sources. Interestingly only one person who responded to this survey had a micro-wind turbine, where 27 had Solar PV. Even though Ireland, as I have shown in my background research, is one of the best places in Europe for wind energy generation, but then again, there are no government grants or incentives currently available and it isn't something that's altogether getting talked about and learned about nowadays. As we will see in the next question.

Question 9.

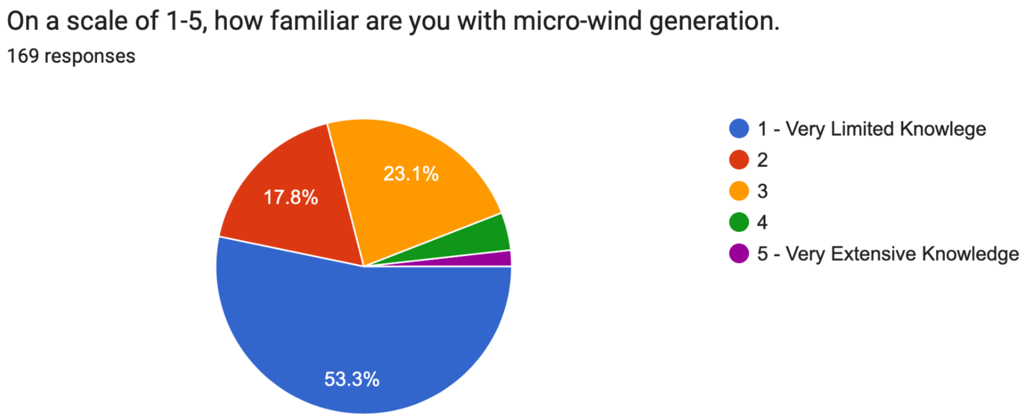


Fig. 154.

I included this question to create a segway from talking about the very broad topic of renewable energy generation to a focused point on micro-wind generation. This I believed was the simplest and most straightforward method, it isn't included in the question here, but in the survey I had included a brief explanation of what micro-wind generation is and possible applications. With 53.3% of respondents having said that they had "very little knowledge" of micro-wind generation, and another 17.8% having selected the second to most extreme option, it is evident that a majority (71.1%) of participants in the survey had little to no knowledge about micro-scale wind generation. Yet again, 23.1% of respondents selected the middle option, suggesting that they were somewhat familiar with it; and it should be noted that there was a very small portion (5.8%) of respondents who claimed that they had "very extensive knowledge" around micro-wind generation.

Question 10.

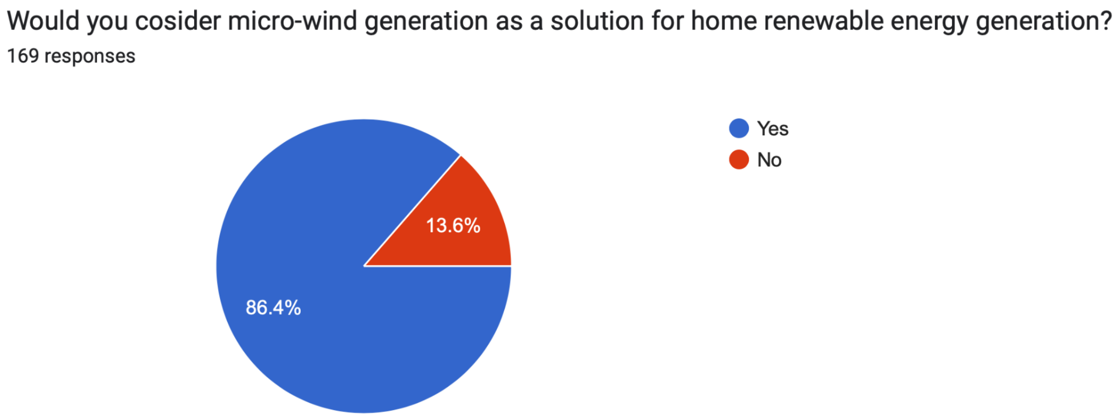


Fig. 155.

I included this question to try to understand whether the respondents would consider micro-wind generation as an alternative renewable energy source for their home. As shown in the graph, 86.4% of respondents responded saying that, yes they would consider micro-wind generation as a possible solution for home renewable energy generation.

Question 11.

Currently, a domestic wind turbine in Ireland can can stand up to 13m tall without planning permission. Would you object if your neighbour decided to mount one in their back garden?
169 responses

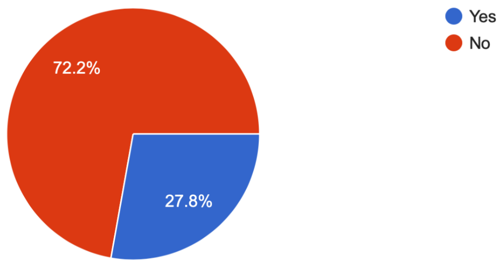


Fig. 156.

I decided to include this question to gauge whether respondents would say whether or not they would object to their neighbour installing a wind turbine, because currently Irish planning regulations state that you do not require planning permission to mount a wind turbine assuming that its total height is no more than 13m. Now 72.2% of respondents said no they would not, but it should be taken into account that over a quarter (27.8%) said yes they would object. Ireland is very well known for its NIMByism and I'm not sure how these figures would stack up against reality, but regardless, assuming that the majority of respondents are being truthful, these are good results.

Question 12.

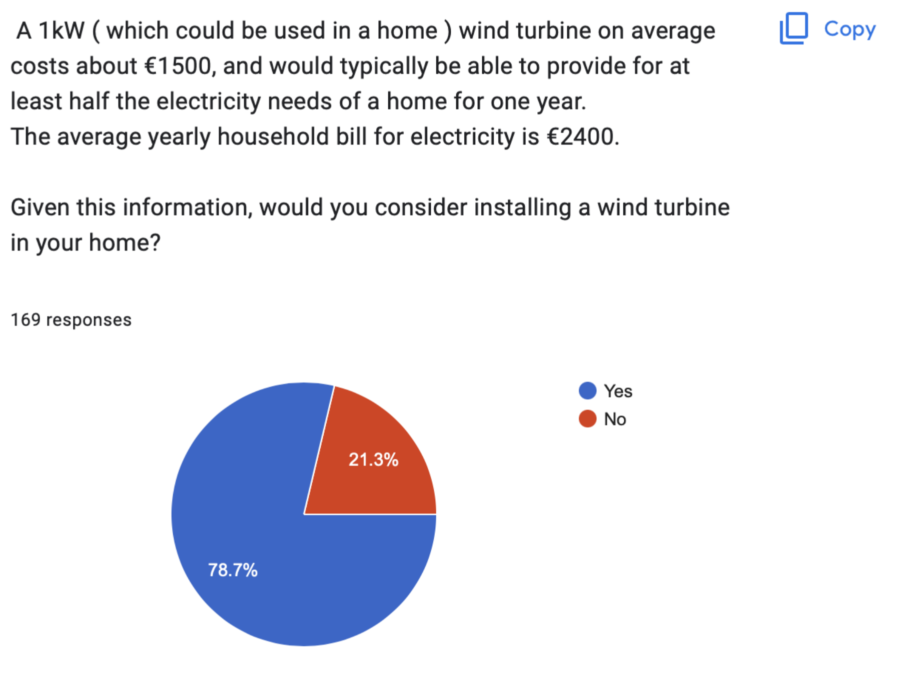


Fig. 157.

In including this question I thought that through providing some basic information and the expected payback time of a 1kW wind turbine, I could inform the respondents about the appeal of micro-wind generation, and gauge how that affects whether they would consider installing a wind turbine at their home. Interestingly, while in Question 10, 86.4% of respondents said that they considered small scale wind energy as a possible solution for alternative home energy generation, 78.7% of respondents for Question 12, after being provided with this background information, said that given this information, they would consider installing a wind turbine at their home. Which is a great figure considering how 71.1% of respondents in Question 9 said that they have “very limited knowledge” regarding micro-wind generation.

Question 13.

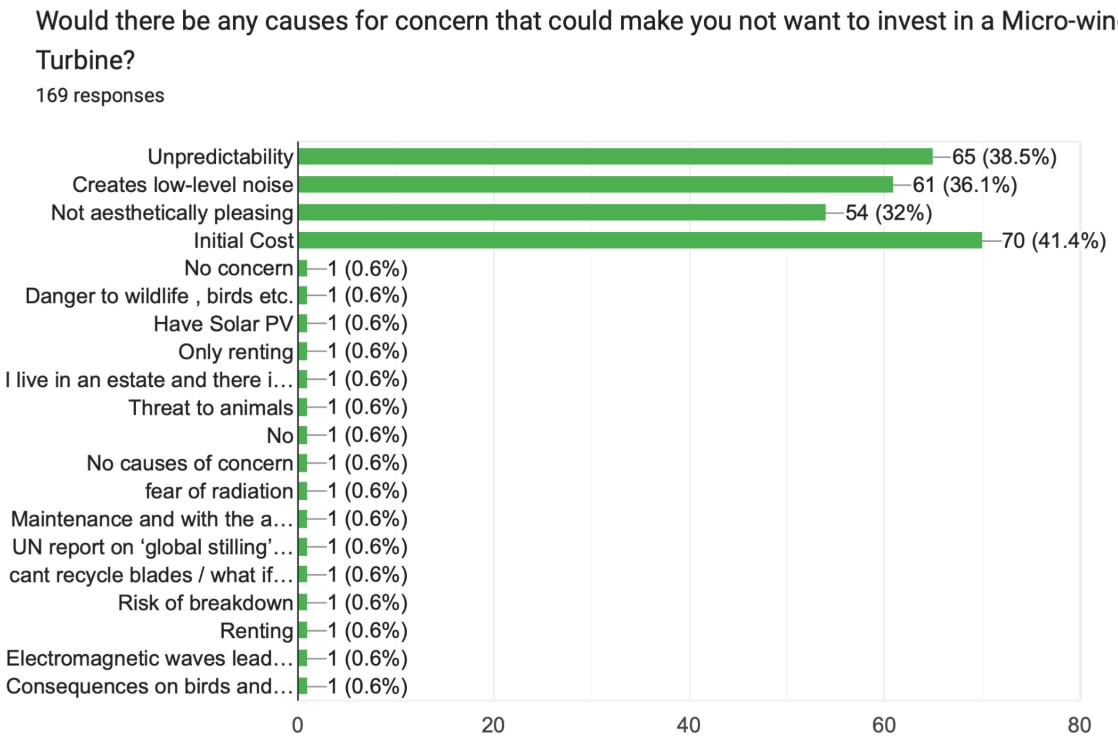
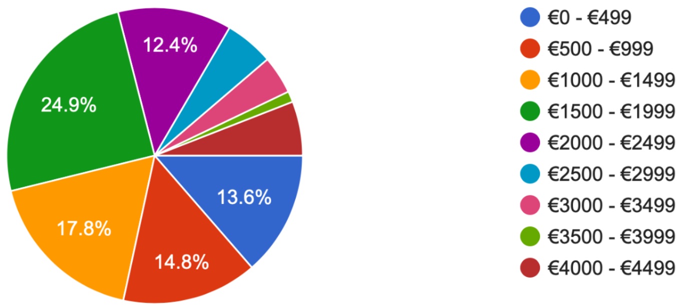


Fig. 158.

I included this multiple choice question so that I could understand exactly what issues with Micro-level wind generation could be putting people off of getting a turbine installed for their home. While four of the options were widely selected, there were various "Others…" responses that were very interesting. Like one talking about a UN report on global stilling, a recently observed phenomena where wind speeds at around 10m high are steadily decreasing year on year. The top sources of concern people selected were Initial Cost at 41.1%, Unpredictability at 38.5%, Creates Low Level Noise at 36.1% and Not Aesthetically Pleasing at 32%.

Question 14.

What would be the maximum price you would be willing to pay for a Micro-wind Turbine that was able to provide for your energy needs in the home?
169 responses



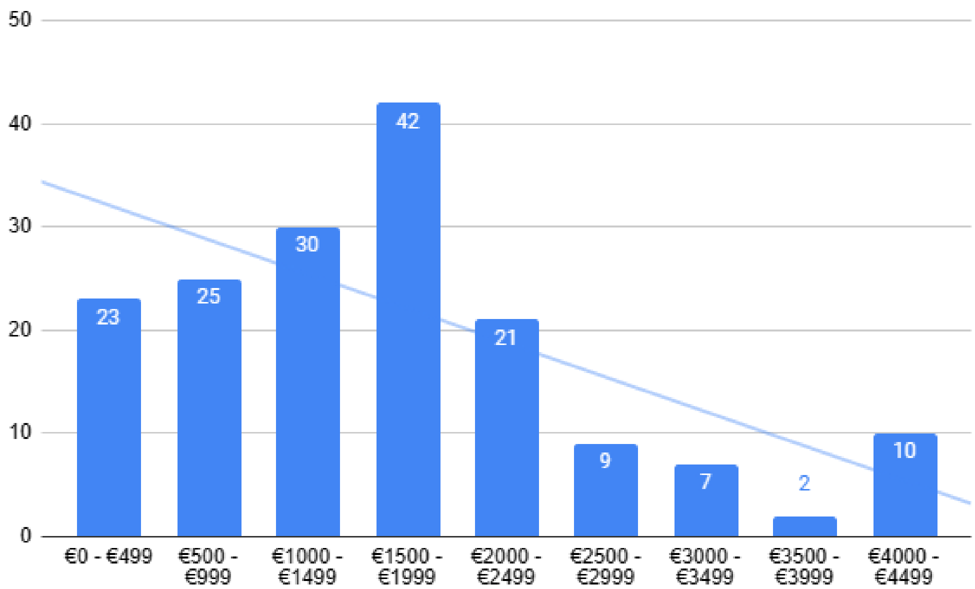
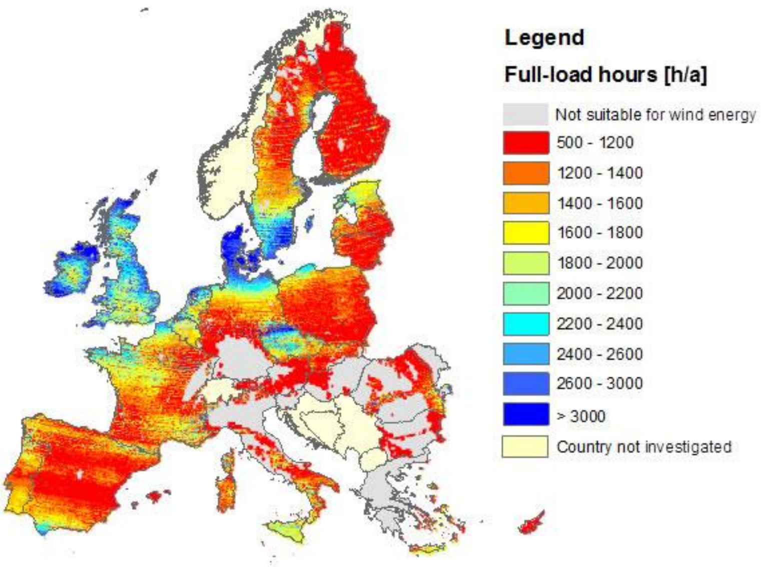


Fig. 159, 160.

Following on from Question 13, I figured that it would be best to try and understand around what price range would the respondents of this survey be willing to pay for a micro-wind turbine. As we can see the majority of respondents selected the €1500-€1999 price bracket, and 55% of the respondents chose between €1000 - €2499. This would buy you the equivalent of a 1.5kW wind turbine unit.

Question 15.



The best places for micro-wind generation are typically areas with strong, consistent wind. These areas may include coastal regions, hilly areas, and open plains.

As shown in this map, Ireland is the ideal location for wind generation.

There are currently no grants available for domestic wind turbine installations.

Do you think that more government incentives should be put in place for home micro-wind energy generation?

Image Source: [*https://green-x.at/RS-potdb/potdb-long_term_potentials.php*](https://green-x.at/RS-potdb/potdb-long_term_potentials.php)

169 responses

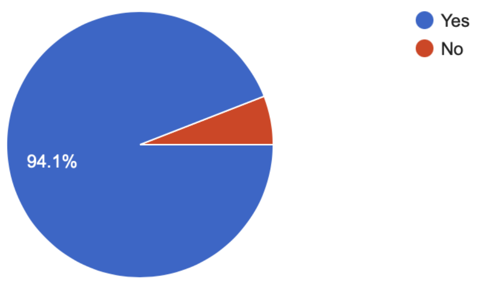


Fig. 161, 162.

For this question I decided that I wanted to try something different. I wasn't entirely sure if people knew just how much usable wind resources Ireland had in comparison to the rest of Europe, and alongside this, currently the Irish government provides no grants or incentives for domestic wind turbines, despite Ireland being one of the best places for wind in the Euro area alongside the UK and Denmark. So for this question I decided to try introducing a graph and also a brief description to inform the reader, and then point out how the Irish government offers no grants for domestic wind turbines. Finally asking, considering this information, should the Irish government be offering grants for domestic, micro-level wind turbines. From this question 94.1% of respondents said yes. Considering their answers from Question 13 with 41.4% of all respondents saying that a reason why they wouldn't invest in wind turbines is the initial cost, I believe that if the incentives were in place micro wind generation would absolutely be a strong source of renewable energy used by the Irish people. To question my assumption I asked just that in the next question.

Question 16.

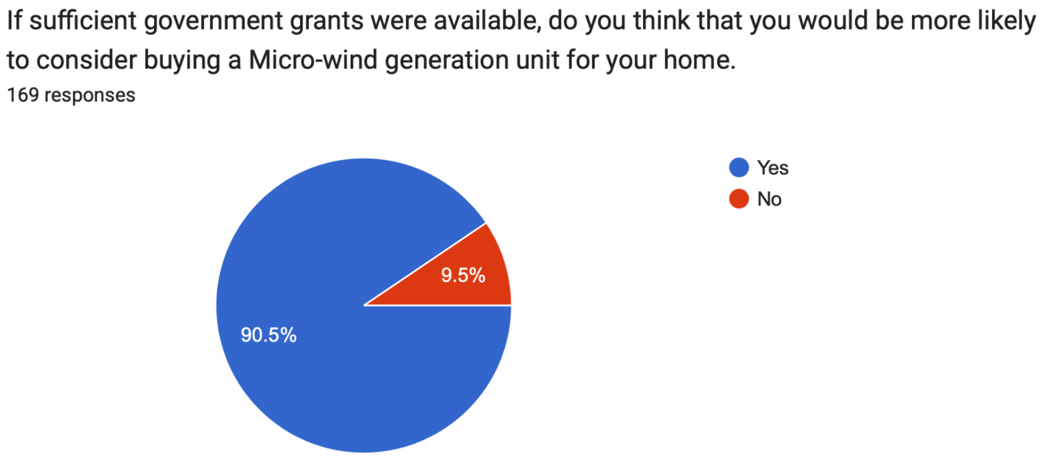


Fig. 163.

As I discussed in the last question. When provided with information and maps explaining just how fortunate Ireland is when it comes to wind resources, yet the Irish government currently don't offer any government grants; and were asked if there should be grant's put in place to incentivize micro scale wind generation 94.1% responded with yes, this is following on from Question 13 where 41.4% of all respondents said that the initial cost of investing in wind energy is a factor which would discourage them from buying a micro-wind system. So for this final question I decided to ask that if government grants were put in place and made available for domestic wind generation, do they think that they would be more likely to consider buying a Micro-wind generation system for their home, and 90.5% said yes.

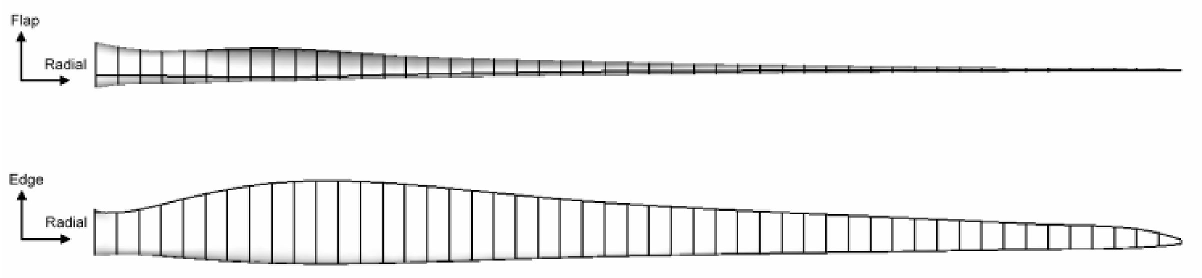
Appendix C - Turbine Rotor Designs

Designing Model Category 1 - Traditional (Straight Bladed) HAWT

Introduction:

In comparing the efficiencies of HAWT rotor designs, informed from my background research and previous knowledge regarding wind rotors, I thought that it was absolutely necessary to compare the most popular HAWT blade design, used in commercial and domestic wind turbine rotors, to all other variations that I will test. From this rotor design I, as you will see, was able to directly compare its performance to others and from there roughly estimate potential percentage performance increases on the 500w Turbine that was sponsored to me, if alternative variations were used.

Example Photograph:



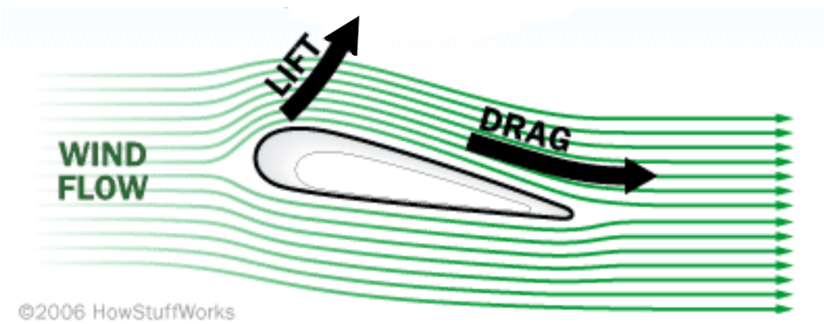


Fig 164, 166. Image Sources (Pirrera) (“Wind Turbine Blade Design, Flat, Bent or Curved”) (Pixabay.com)

Applications and Tools Used

Fusion 360 - Student Licence - 3D Modeling Software
Ultimaker Cura 4.2 - 3D Printer Slicer
Ender 3 Pro - 3D Printer
PLA Filament 1.75mm
2 Part Epoxy Resin

Procedures:

This style of wind turbine rotor design most commonly features three curved blades radiating out from the centre of the rotor in a straight line; with an airfoil which initially, when moving outwards from the centre, initially widens and then progressively reduces in width until the blade nearly reaches a point. This blade operates on the principle of lift, as the airfoil creates a longer path for the air to flow along on one side of the blade, creating a region of low pressure and a lift force which drives the rotor. This style of rotor design is one of the easiest to produce at large scales.

To simplify and remove the possibility of different airfoil designs between the models interfering with the validity of my experimental results, I decided that all of my rotor designs would use the same airfoil design. After some research and finding a publication by NREL titled: “NREL Airfoil Families for HAWTs”, I considered using NREL’s S804 Airfoil for the root of the blade, S801 primary for the and S803 airfoil for the tip, after further research I came to understand that NREL no longer recommends these airfoil section designs.

So after some more looking I decided to use the S835 root airfoil, S833 primary airfoil and the S835 tip airfoil, as these are the designs recommended for use in 1-3m rotor diameter wind turbines on wind.nrel.gov. Then for the VAWT models I would use the S833 airfoil throughout.

- Source (“NREL Airfoil Families for HAWTs”) (“Wind Turbine Airfoil List”)

10. Firstly to design the rotor I opened Fusion 360, created a new design and imported the images of the airfoils that I planned on using.

11. Next I created a sketch plane and traced the outline of each airfoil using the “Fit Point Spline” tool. Then I extruded each at 5mm thickness and created a new component for each.

12. Then after I made the airfoil sections I first rotated each of them 90° clockwise on the Z axis about their centres, making it so that when looking down at the model the airfoils were standing as if they had been sections taken out of a whole rotor that was just sitting there. Then I created another sketch and drew a line 150mm long from the centre point of the tip airfoil perpendicular to its surface.

13. Then along this line I began marking with sketch points and moving the components to, where the root, and primary airfoils of the wind turbine blade would be. After some investigation online I concluded that the middle, or widest section of the airfoil should be no more than 15mm from the root. The root airfoil naturally will go to the end of the 150mm line, and at the opposite end would be the tip airfoil. For this design I decided not to introduce any rotation in the blade from root to tip as this from my understanding strayed into other variations like “Scimitar-Shape” or “Swept Bladed” rotors and was adding another layer of complexity which I didn’t think would have made my design still be a direct model of the standard “Straight Bladed” HAWT.

14. Next I created a centre line guided loft from the tip airfoil, to middle, to root, guided by the 150mm centre line. Now at this point I had the first blade.

15. Then I set out to make the centre hub which the blades would meet at and directly drive the shaft of the motor. To do this I first created a 15mm diameter two point circle from the ‘root-end’ of the 150mm sketch line that I used to make the blade, then I extruded it upwards another 15mm and finally I used the fillet command to round the top and create a nice cone at the centre of the rotor.

16. Before combining the blade component of the centre hub, I decided to investigate what was the best suited angle of attack for blades of this size and scaling, from these quick searches I was able to find sources pointing towards an angle of attack of around 5° was best for small scale turbines. So I next selected the blade component and rotated it 5° clockwise along the axis of the original 150 mm guideline.

    Source (Voelker)

17. Next after applying the angle of attack to the blade, I first created a new sketch and drew a circle of diameter 150 mm, on the same plane as the blade was lying. Then I used the “circular pattern” command to create two copies of the blade and combined all three of them to the centre motor hub using the “combine” command.

18. To complete the design I finally extruded a cylinder at the base of the rotor 10 mm high with a hole of diameter 2.25 mm that the motor shaft could fit directly onto.This model served as the base design from which I modified to create the 3 final variations which I used for testing.

Fig 167.

Model 1.1 - Small

Introduction:

The base design at its current dimensions as I described in the last set of procedures represents the sizing of the “Small” variation of the Straight HAWT design category. The only modifications I had to make to the design were that I had planned on printing the rotor in its whole form sitting flat down on the bed of my 3D Printer, but the 10mm base for mounting the rotor to the motor shaft would have meant that I’d have had to waste a lot of material on support structures and even at the end of this the motor hole might end up not fitting correctly; and then I would have to redo the entire rotor. My solution was (for this smallest size) to make the motor connection cylinder separate from the actual rotor itself and print them in two parts. Then design it so that they could fit and be glued together via a standardised connector.

Modifications:

1. To modify the design all I had to do was firstly use the “cut plane” command to separate the base cylinder from the rotor, then create a new sketch on the top facing surface of the cylinder and make a centre aligned square at the middle of the cylinder with side lengths of 7.5mm.

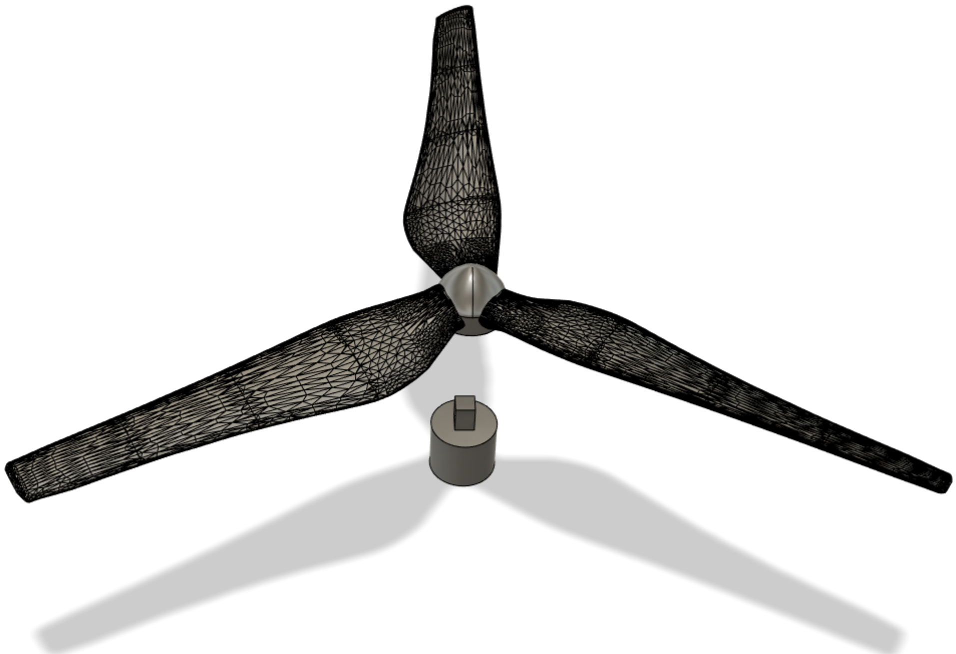
2. Then I extruded the square up 7.5mm, combined it with the cylinder and then used a feature of the “combine” tool, subtracting the square connector from the rotor hub.

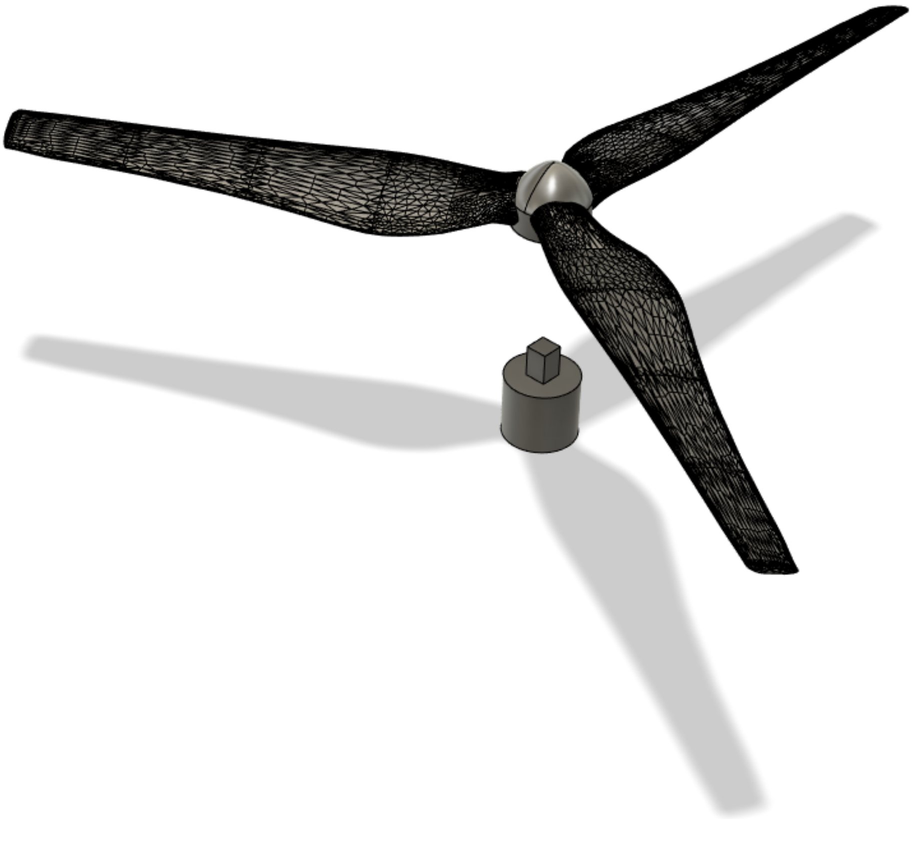
3. Next I applied offsets of -0.1mm to the square cut out of the rotor so that they would fit snugly (as 3D Printing is usually out in dimensions by ±0.2 mm).

Finally I set them off to print on my Ender 3 Pro using Cura’s tree support feature to help print the angled rotor blades and then sanded, cleaned and glued them together once everything was fitting properly.

Fig 168.

Final Design Photograph:
Fig 169, 170.





Model 1.2 - 6 Bladed

Introduction:

The dimensions of the “6 Bladed” variation of the “Straight Bladed” HAWT are the same as the “Small” variation. I decided to make this comparison as when looking online at micro-level wind generation systems I came across a large number of turbine rotors which had over 3 blades, when I researched this the most promising reason as to why I was met with was that the increased blades increased torque which in certain situations would prove to be beneficial. When researching commercial systems with more than 3 blades I came across virtually none (in fact 97% of commercially available HAWTs use 3 blades). One of the largest reasons why there aren’t commercially available models with over 3 blades is due to the unnecessary added cost, compounded with more blades equating to less speed and more torque, and 3 bladed variations being extremely self stabilising. As said in this piece from electrical4u.net:

“Three bladed turbine rotors produce very little vibration or chatter. This is because when one blade is in the horizontal position, its resistance to the yaw force is counterbalanced by the two other blades. So, a three-bladed turbine represents the best combination of high rotational speed and minimum stress…”

Sources (Ayothi) (Wind Energy Solutions)

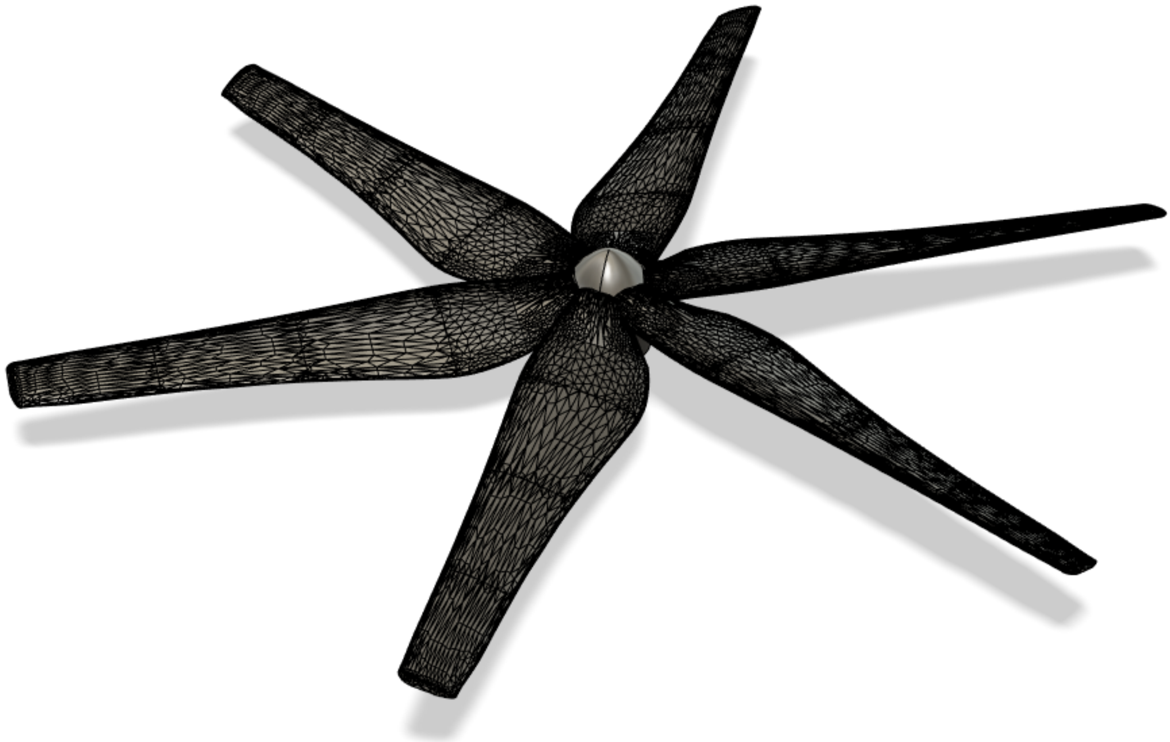
Modifications:

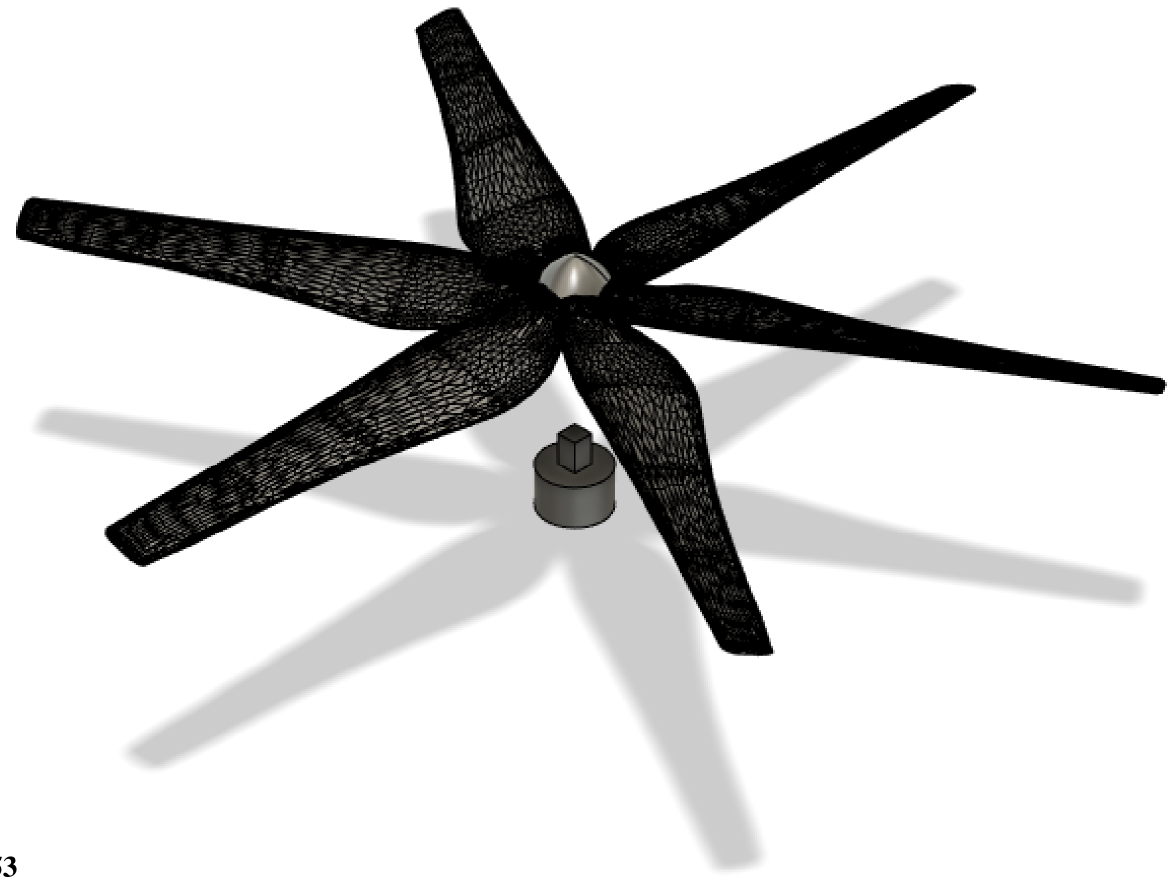
1. The only modifications I had to make with this design was to use the “circular pattern” command to double the amount of blades on the rotor.

2. After completing this circular pattern command, the base socket of the rotor body had to be redone, and I once again subtracted the two bodies and applied the necessary offsets. 3D Printing and manufacturing followed the exact same format as the “Small” variation.

Fig 171.

Final Design Photographs:
Fig 172, 173.





Model 1.3 - Large

Introduction:

For the “Large” variation of the “Straight Bladed” HAWT I planned on scaling all of the dimensions uniformly by 1.5. By doing this I was able to get a direct understanding of how much the energy generated by the wind turbines would change. Naturally this would generate higher levels of torque and require higher wind speeds to rotate at the same rpm as the smallest variations but I thought that these served as an important way of understanding how increasing the size of the rotor would affect the required wind speeds to generate the same amount of energy compared to the smallest variation.

Modifications:

1. To make this design first I had to use Fusion 360’s “capture design history” feature to go back to before I combined the three blades with the central hub of the “Small” wind turbine.

2. Firstly I made a copy of the blade and motor hub and then returned to the “present” in the design history. I then used the “uniform scaling” function and scaled them by 1.5 and after doing this instead of combining the blades with the hub I subtracted them, but ensured to select “keep tools” and keep the turbine blades. I then combined the base cylinder to the central hub so that both would now print in place.

3. Finally I applied offsets of -0.1 mm to the holes cut into the rotor centre hub. Now instead of one combined unit I had 3 blades and one central motor hub which I could all print separately.

4. Once again I loaded all of the models into Cura and sliced them for my Ender 3, the models would print with the 3 rotor blades standing upright on the build plate alongside the centre motor hub. After printing the blades slotted snugly into the sockets and I then used epoxy resin to secure them into place.

Fig 174.

Final Design Photograph:
Fig 175, 176.

Designing Model Category 2 - Scimitar (Convex Curved) Shape Blade HAWT

Introduction:

In comparing different variations in HAWT designs, I wanted the investigation to compare completely alternative turbine rotor variations instead of minute changes of the same overall design. I decided that the primary objective of my project was not to develop the most perfected wind rotor design, but rather to compare distinctly different blade designs at micro-scale wind generation. The majority of said variations I found online were only separated by different airfoil, less or more blades, pitch angle and twisted blades; but after a while I came across an interesting form of rotor design which I had not once seen in any commercial model, and struggled to find any studies investigating its effectiveness. A convex curved blade wind turbine, also known as a scimitar shape bladed HAWT, where instead of the blades radiating outwards from the centre of the rotor in a straight line, this variation had the airfoil follow the path of an arc after halfway up the blade. Supposedly increasing surface area and blade stability, while not changing the operational sweep area, but only making sense to use under very rare specific cases, and unusable at a commercial scale due to it causing dynamic instabilities in the blades. I concluded that this would have been an excellent opportunity to investigate how HAWT performance would differ from the ubiquitous straight bladed variation at a micro-scale to one which is known to be more efficient at smaller scales, but not at a commercial level, and as such had little experimental data.

According to a Former Mechanical Engineer: "

Under rare specific cases blades are bent sideways (i.e., scimitar shape) but that technique comes handy only for smaller turbines. Large MW range turbines have blade lengths from 50–100m. A scimitar shape bend in such blades would increase the participation factor of torsion vibration modes of the blade structure. Torsion modes are known to have significant influence in dynamic instabilities like flutter of blade structures.

Advantages include:

4. Increased surface area without increasing blade length. This results in a larger area exposed to wind flow thereby improving the capacity of the turbine.
5. Improves blade stability.
6. Increases distance between blade tip and tower" - Source (Voelker)

When discussing this turbine blade category or any of its respective variations, as a form of shorthand I referred to it as the "Curved Bladed HAWT".

Example Photograph:

Fig 177, 178. Image Sources ("White Curved Fan Wind Turbine | 3D model" (NREL)

Applications and Tools Used

Fusion 360 - Student Licence - 3D Modeling Software
Ultimaker Cura 4.2 - 3D Printer Slicer
Ender 3 Pro - 3D Printer
PLA Filament 1.75mm
2 Part Epoxy Resin
Electrical Tape

Procedures:

1. In designing this rotor variation I leaned heavily upon my first “Straight Bladed” HAWT design. Using the “capture design history” feature which Fusion 360 offers I was able to essentially go back to the beginning where I had the root, primary and tip airfoils ready to be lofted and create the first blade. Then I made a copy of all three and translated them far enough away from the other models so that they wouldn’t interfere.

2. Next in order to create the arc sweep in the blade I created a sketch looking down on what would have been the top face of the blade (if the airfoils had been lofted to create a new body), and created a line radiating from the root airfoil of the blade outwards at an angle of 10°, I drew a sketch circle of radius 150 mm starting from the centre of the rotor, and then drew a 3 point circle attached to where the line intersects the outer circle, and the start of the line at the root airfoil. Finally I set the diameter of the circle to be 150 mm.

3. Now I had the curving path on which I could move the airfoil sections, so I next applied the measurements I had initially used to space out the airfoil sections on the “Straight Bladed” HAWT. Moving and rotating the primary and root section airfoils so that they were placed at the correct point on the line and perpendicular to the curve line.

4. Next to create the first blade I lofted the surface of the root airfoil to the primary and then the tip, and used the arc line as a centreline for the volume of the airfoil.

5. Next, after applying the 5° angle of attack to the blade, I used the “circular pattern” feature to create the remainder.

6. Then, using the same central motor hub as the “Straight Bladed” HAWT, I combined the blades to the motor hub using the “combine” feature. Now the base size rotor was complete.

Fig 179.

Model 2.1 - Small

Introduction:

This variation of the “Curved Bladed” HAWT rotor design was to serve as the base model from which I could compare the performance of the other two variations. The dimensions of the standard model I described in the piece above represented those of this variation. So no size modifications were needed. I had planned out that this variation would be printed in the same way as the previous “Small” variation of the Category 1 HAWT rotor design, lying flat and to assemble and glue the motor connection later on, so I will need to change the base size to create this.

Modifications:

1. For this variation of the Category 2 HAWT I had planned on printing it in two parts, one being the actual rotor and the other being the motor connection. Then assembling them using the socket design and glueing them later, after I got the tolerances of the motor shaft hole as best as I could. To modify the base design, I first had to separate the motor connection part of the model from the actual rotor using the “split body” command.

2. After this I created a sketch plane on the top of the “motor-shaft-connector” cylinder and drew a centre fixed square, and extruded it up 15 mm.

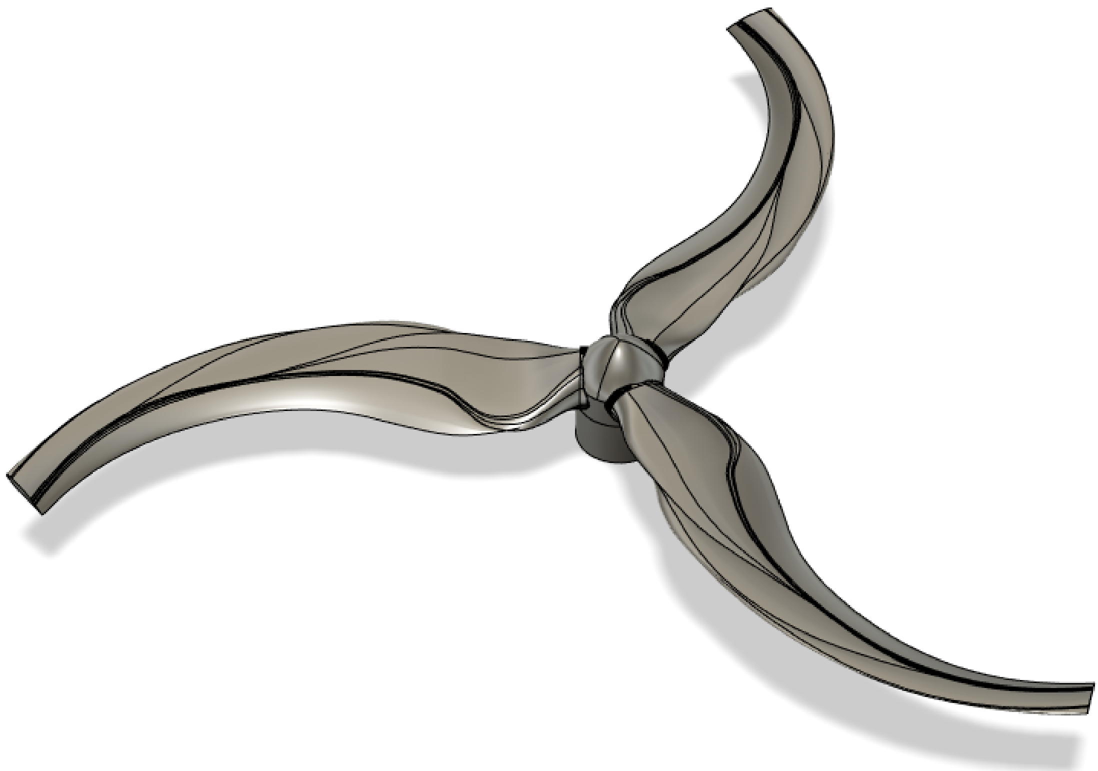
3. I then subtracted the two bodies, still keeping the “motor connection” part, and applied the necessary -0.1 mm offsets to the newly created socket in the rotor body.

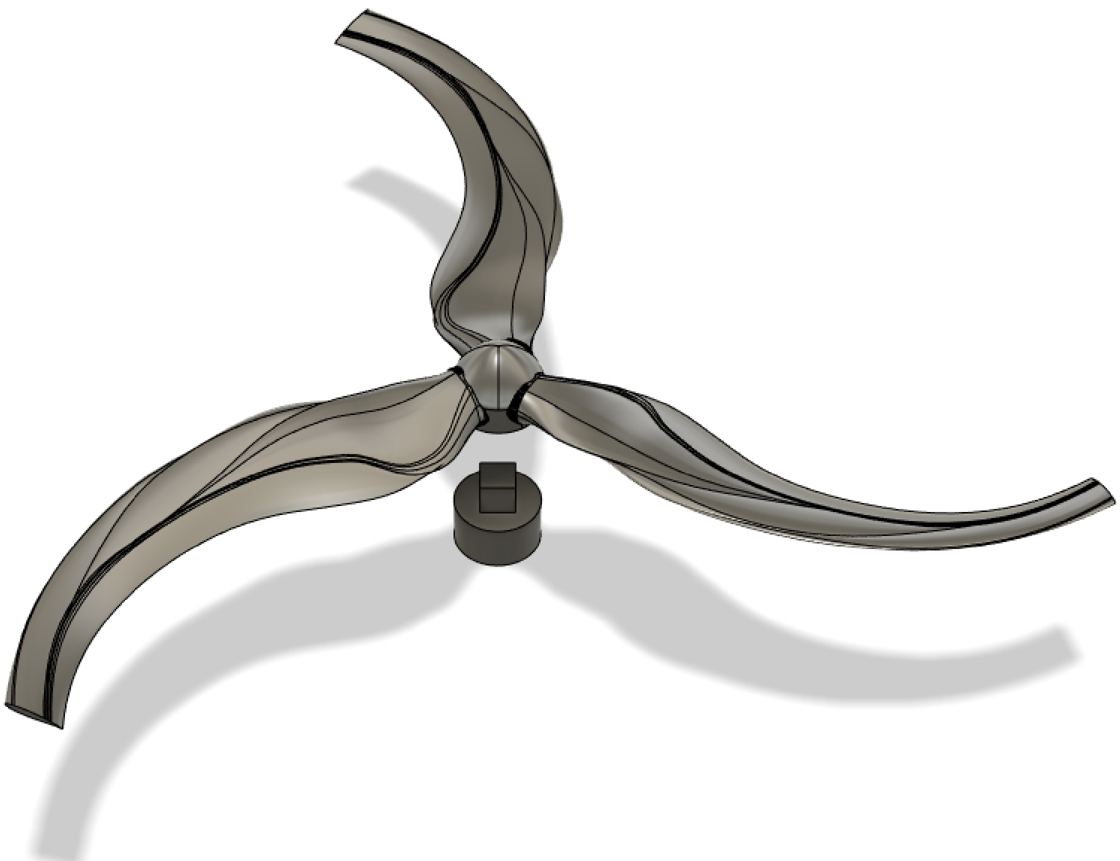
4. I then put them on to print on my Eneder 3 Pro, and then sanded, assembled and prepared them to the same quality as all other models.

Final Design Photograph:

Fig 180.

Final Design Photographs:
Fig 181, 182.





Model 2.2 - 6 Bladed

Introduction:

This variation once again was created with the intention of understanding how electricity generated was affected by doubling the amount of blades on the rotor. It also served as a point of comparison between all of the final rotor models and overarching categories that I came up with.

Modifications:

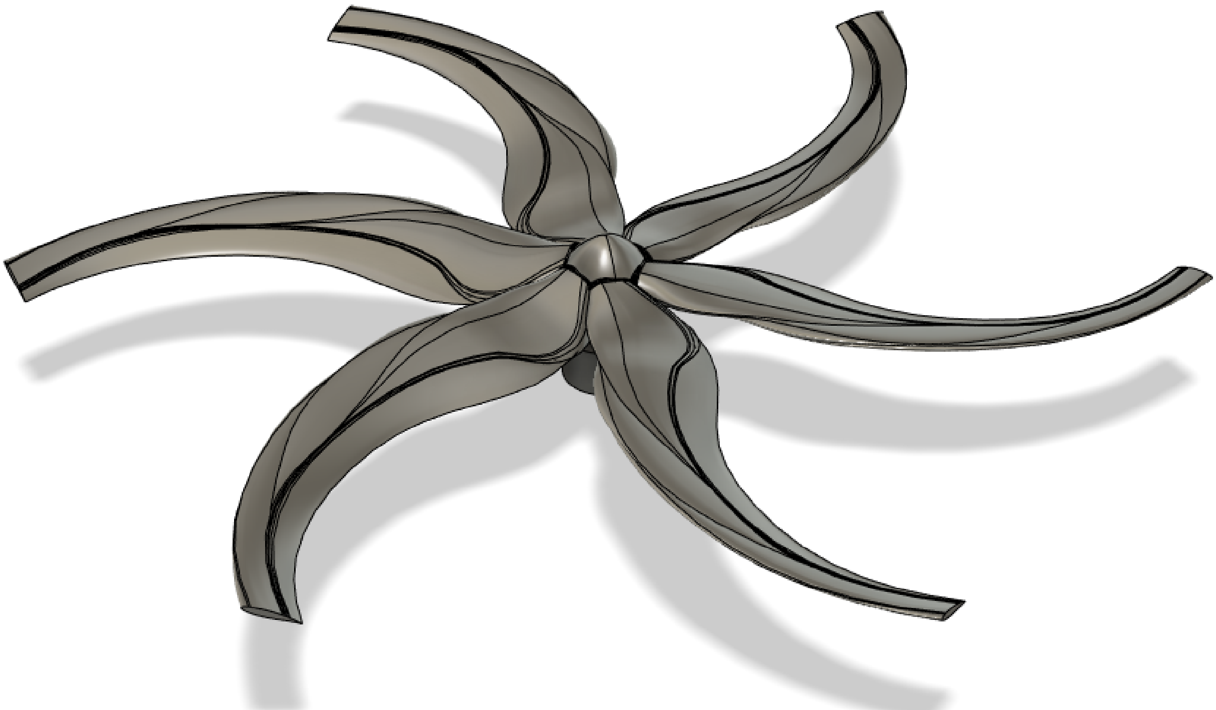
1. For this variation, just like the last “6 Bladed Straight” HAWT model, also known as Model 1.2, I just had to use the “circular pattern” command to double the amount of blades.

2. After doing this, the socket connection at the bottom of the turbine hub was unusable, so I then had to once again subtract the two bodies and apply the necessary offsets. 3D Printing settings were the same as Model 2.1.

Final Design Photograph:

Fig 183.

Final Design Photographs:
Fig 184, 185.



Model 2.3 - Large

Introduction:

For the “Large” size variation rotor, once again just like Model 2.2, I could use this as a source of direct comparison between the smallest size and itself scaled by 1.5, but alongside this, I could also use it to compare how performances between all of the blade designs changed and shifted when they were scaled upwards to 1.5.

Modifications:

1. Just like Model 1.3, due to its size I was unable to print it all fully assembled flat on my 3D Printer’s build plate. Instead I needed to modify the base design so that all of the rotor blades could print vertically and slot into the central hub when assembled. To do this I first made use of Fusion 360’s “capture design history” feature to go back in the design history until where I hadn’t yet combined the rotor blades with the central hub.

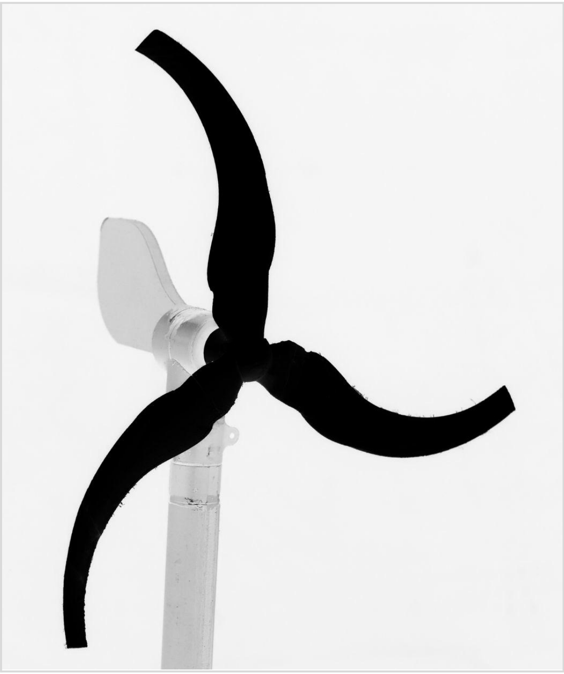
2. After this I created a copy of the four bodies and translated them well away from the other working models and then returned to the present in the design history.

3. Next I subtracted the rotor blades from the central hub unit and applied the necessary offsets.

4. I then prepared the files for printing using Cura and set them off, finally I sanded, assembled, and glued all of the blades to the hub using two part epoxy resin.

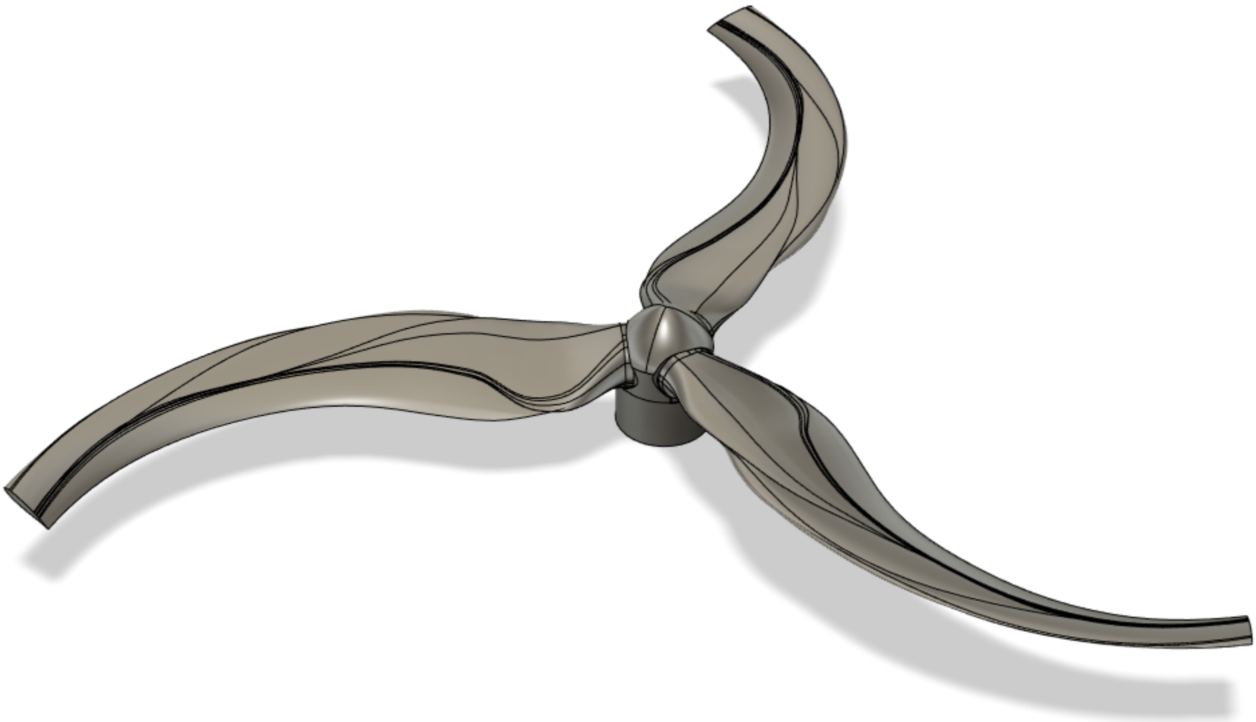
Final Design Photograph:

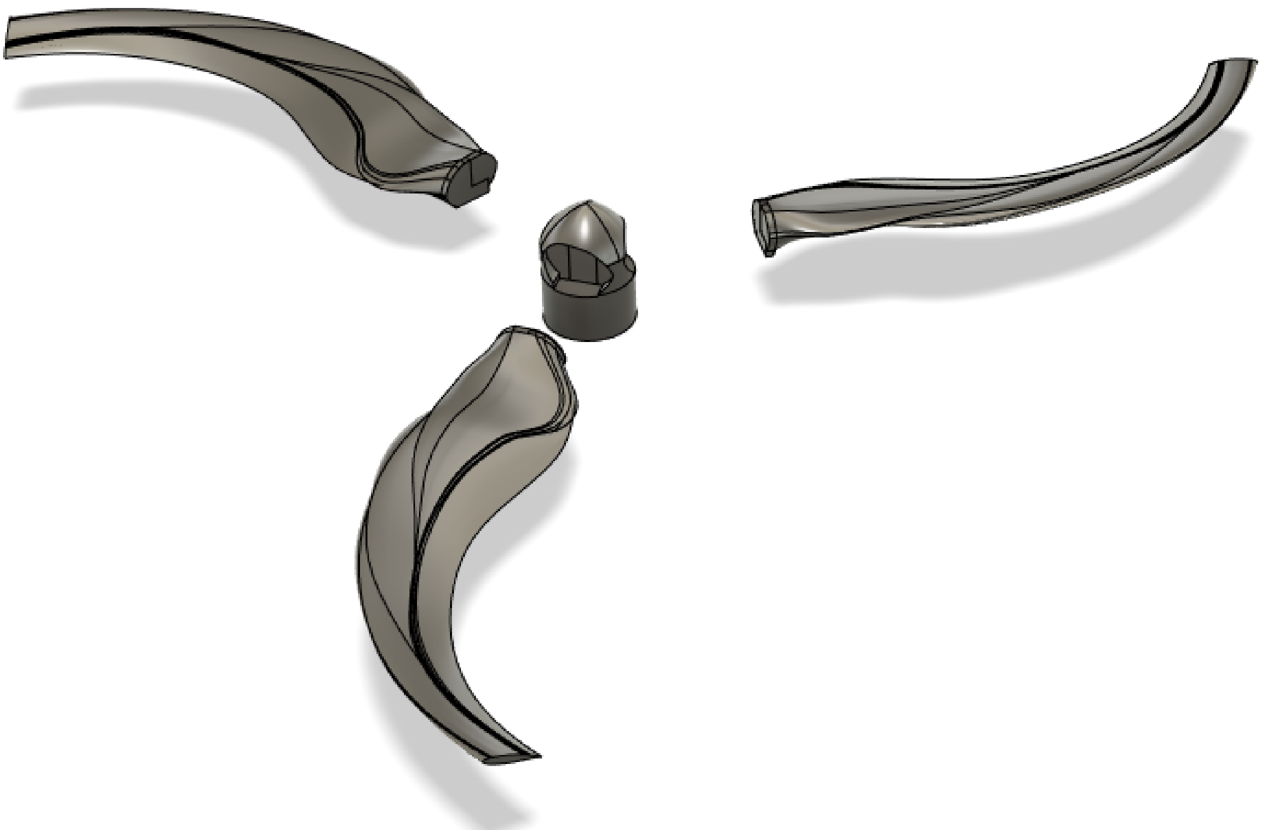
Fig 186.



Final Design Photographs:

Fig 187, 188.





Designing Model Category 3 - Helicoid VAWT

Introduction:

Category 3 was the first “final" VAWT blade design I made in this project. As I have covered in my background research, initially when I was considering this project, and thinking about, and researching the whole topic of investigating the viability of micro-level wind generation. I came across a huge discussion split between whether VAWTs or HAWTs were the better choice for small scale wind generation, and when I looked into studies investigating it there were some results saying that VAWTs were better suited for smaller scale generation in the likes urban applications due to their “preferred” windflow being turbulent wind; but then on the other hand other studies flat out saying that HAWTs were the best at, and that commercial level VAWTs naturally run at low RPMs but high torque, but as a product produce no noise and significantly reduced safety concerns. Where they would then have to be paired with a gearbox in order to generate the same levels of electricity as that of the HAWTs. From said studies I also found that VAWTs were supposedly less affected by outdoor increases in wind speed and after cutting in would maintain a very consistent RPM, in comparison to HAWTs which when operating are very responsive to changes in wind speed and turbulence.

As explained in “A critical review of vertical axis wind turbines for urban applications” by Rakesh Kumar from Sciencedirect.com:

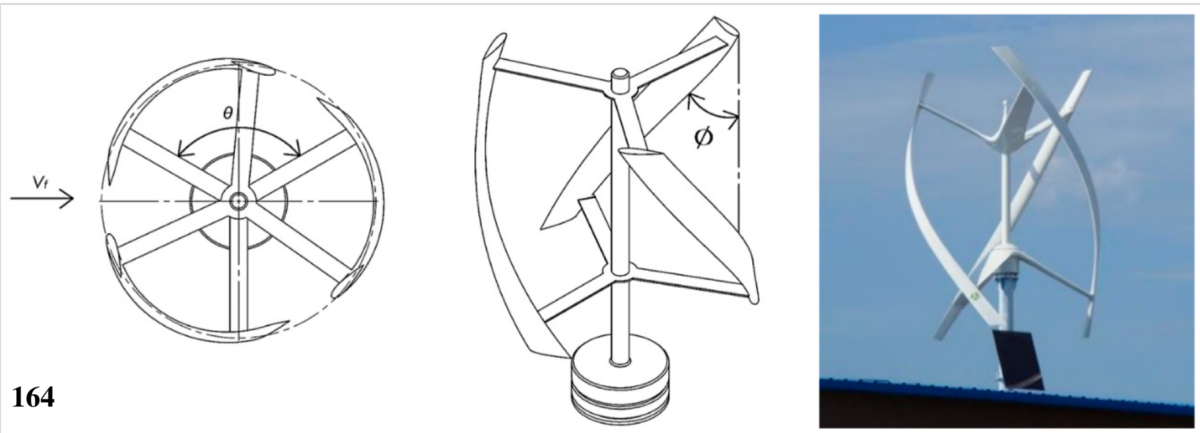
“HAWTs are used in many countries for medium-to-large scale power projects, and most commercial installations around the globe are solely based on these turbines. On the other hand, HAWTs are not recognized as a viable option to harness the energy of the wind in urban areas, where the wind is less intense, much more chaotic and turbulent.”

This first design is what is called a “Helicoid Darrieus VAWT ", most commonly used variations use three blades, each rotor blade is of constant airfoil thickness and follows a path lifted up the height of the rotor while also rotated ninety degrees clockwise. Operating on the lift principle this rotor design is driven through the asymmetrical surfaces of the blades, and where all HAWTs

- Sources (“Strategies for Enhancing the Low Wind Speed Performance of H-Darrieus Wind Turbine—Part 1”) (Trepka) (Kumar 281-291)

Example Photograph:

Fig 189. Image Source (“Strategies for Enhancing the Low Wind Speed Performance of H-Darrieus Wind Turbine—Part 1”)



(a) (b) (c)

Applications and Tools Used

Fusion 360 - Student Licence - 3D Modeling Software
Ultimaker Cura 4.2 - 3D Printer Slicer
Ender 3 Pro - 3D Printer
PLA Filament 1.75mm
2 Part Epoxy Resin

Procedures:

1. In designing this rotor I focused heavily on following all of the core principles of the Helicoid Darrieus VAWT, which can be observed in the schematics above. In making this I first had to ensure that I was using the exact same airfoil section as the HAWTs. For the VAWTs I planned on making in this project, I decided that I would use the mid blade section airfoil NREL S081 I used in the HAWTs. I ensured to have the longest side of the airfoil facing outwards, as this is how functional models are designed, I also made sure when making it that it had the same diameter as the HAWTs and that its vertical height represented the blade length of the HAWTs. Another detail which I had to note was that the airfoil follows a lofted path which rotates upwards along the circumference of the rotor having rotated 90° clockwise by the time it reaches the top of the rotor. To make this rotor I first had to design the base blade, and then from there I could create the other two, and finally design the motor connector and top cover. So to begin with I created a new design and imported an svg of the airfoil, created a sketch plane and using the "fit point spline" tool trace the outline of the airfoil. Then I extruded it up 5 mm.

2. Next I had to begin creating the path that the blade would sweep out in 3D. So to begin with I created a circle of diameter 150 mm and made two lines perpendicular to each other radiating from the centre and stopping when they touch the circumference.

3. I then changed my perspective on the sketch to isometric rather than top down and changed it to "3D Sketch" meaning that I could change the sketch plane each time I drew a new line or feature. Next, if you were to imagine you were looking down at the sketch with two lines coming out from the centre of the circle, then moving clockwise along the circle I selected the line which would mark the end of the 90° arc between the two lines and drew a line perpendicular to where it met the circumference of the circle. I set this vertical line to be 150 mm high. Next, back to the circle with the 90° lines, I created a line dividing the 90° into two 45° angles. Then from where this line hit the circumference I drew a new line perpendicular to the plane of the circle, and at a vertical height of 75 mm. Finally I selected the top point of the tallest line, then the one coming from the 45° line of half the height and lastly where the first line which marked the beginning of the 90° arc met the circumference of the 150 mm circle. Then I created a fit point spline along these points, this would serve as the path that the airfoil would follow.

4. Now having made the path that the airfoil of the blade would follow I took the airfoil section and moved it towards the base sketch circle. I moved the airfoil section so that its centre of mass was directly in line with the base of the fit point spline path of the blade. Next I rotated it so that the longest side of the airfoil was facing outwards, and the airfoil had an angle of attack of 5°. Then I translated and made a copy of the airfoil and rotated it 90° about the circumference of the 150 mm circle, then I moved it up 150mm. With the second airfoil section now at the opposite end of the blade path I lastly made another copy of the airfoil section and rotated and translated it so that it represented if we took a section out of the blade at exactly halfway. Finally I lofted the surface of the end of the blade, through the primary airfoil and all the way to the end airfoil, and using the fit point spline as a centre guideline. With that the blade is done.

5. Now with the blade done, using the “circular pattern” command I made the other two blades and then designed a standard connector to connect the three at the base. I made a copy of the standard connector and translated and rotated it so that it fit on the other end of the blades. I then used the “combine” tool to combine the 3 blades with the standard connector at the bottom, so that it could print flat. I put the motor shaft hole in and then subtracted the top standard connector from the rest of the rotor, and made sure to keep tools. Now I had two components, one which was the base and 3 blades spiralling up and then another connector to join the blades at the top. I finally prepared the file for printing and printed the two components separately and glued them together later.

Fig 190.

Model 3.1 - Small

Introduction:

The “Small” variation of this rotor served as the core link of comparison between all of the variations, and other “Small” variations of other rotors. The design as I have described it above doesn’t need to be altered in any way.

Modifications:

No modifications Required.

Final Design Photograph:

Fig 191.

Final Design Photograph:

Fig 192,193.

Model 3.2 - 6 Bladed

Introduction:

The sizing of the “6 Bladed” variation of the Helicoid VAWT was no different to Model 3.1, all I had to change was double the amount of blades. As the report book continues this will to a certain extent become fairly repetitive, but in designing the blades these were all important moments. As I did have to modify the base models for each variation.

Modifications:

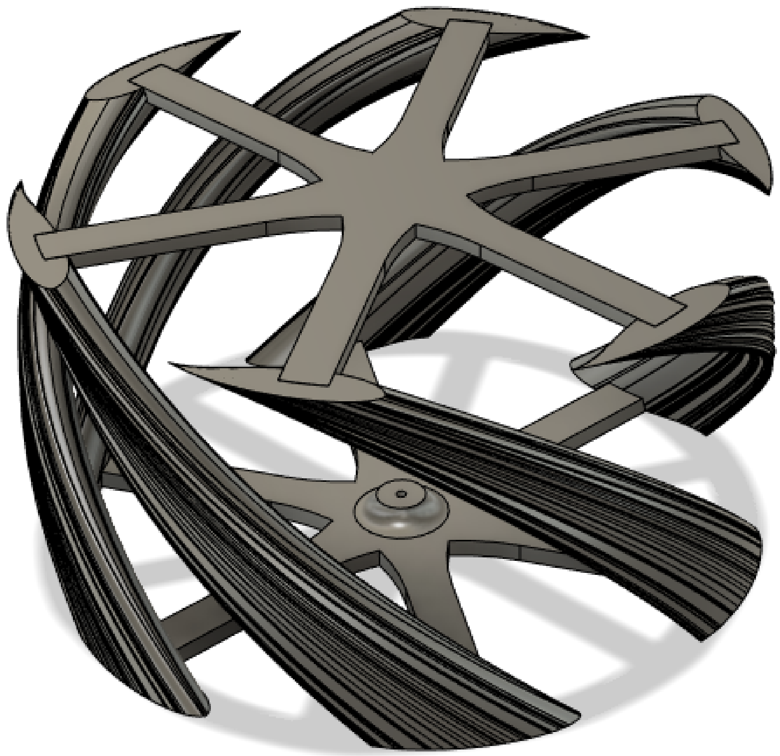
1. To make Model 3.2 I took the base model and using the “circular pattern” feature, selected both components from the base model and doubled their features. Printing and preparation went the same as Model 3.1, and after printing the two components and finishing sanding, I assembled it and glued it together.

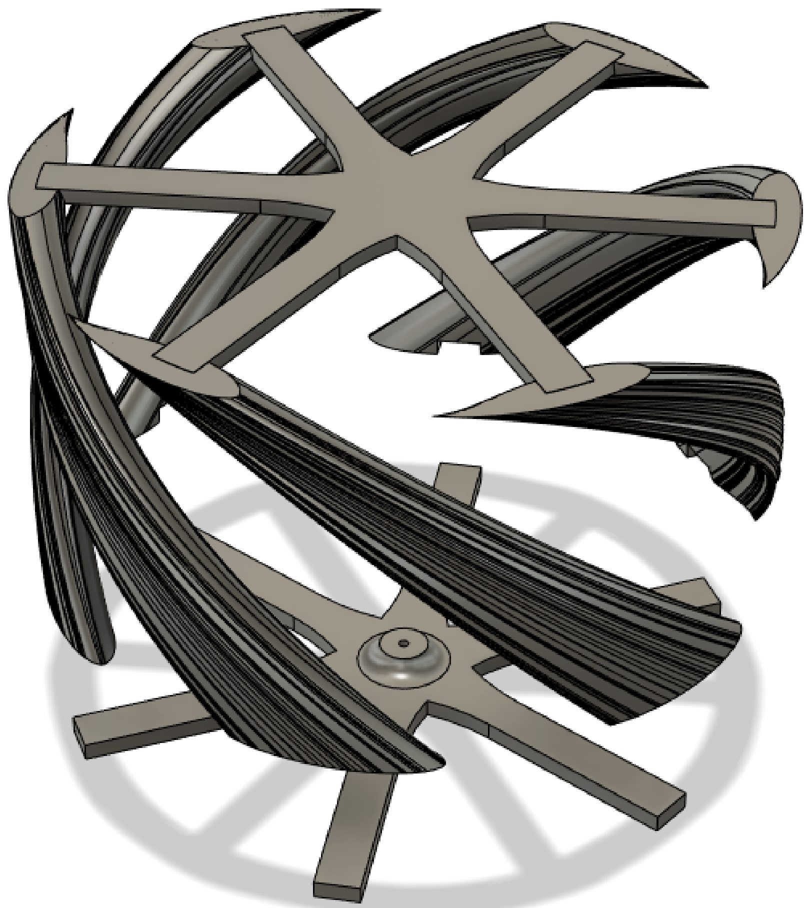
Final Design Photograph:

Fig 194.

Final Design Photographs:

Fig 195, 196.





Model 3.3 - Large

Introduction:

For the “large” variation of the Category 3 rotor I did have to make some modifications. As it couldn't fit onto the build plate after being scaled, I had to divide the component which had the 3 blades spiralling up into 3 bodies that join together, fortunately I didn’t need to change the top connector body.

Modifications:

1. To make this rotor I first selected the two components that made Model 3.1, and then made a copy of each and translated them well away from the other working models.

2. Next I scaled the two by 1.5 and created a sketch plane on the top face of the base component (the one with the 3 blades), in this sketch I made a set of three symmetrical interlocking dovetail connections and split the component into 3 bodies using the “split body” tool.

3. I designed it so that each of the 3 divided bodies were identical and the connections and sockets when all connected had 3 axes of symmetry. This meant that when printing the base component of Model 3.3 I only had to use one file prepared for the 3D Printer and print it three times and then wedge the bodies together and glue in the end. This model took a total of 4 prints and was one of the most time consuming so far.

Finished Photograph:

Fig 197.

Final Design Photographs:
Fig 198, 199.

Designing Model Category 4 - Darrieus VAWT

Introduction:

In researching VAWT variations and designs, I soon came to understand, like with the HAWTs, there was one category that made use of airfoils in every way that they could: Darrieus types, and then many others also very popular designs which didn't use any airfoils, such as Savonius and other drag based systems. I chose not to investigate the effectiveness of these drag-based VAWT rotors, as I felt that if I did I would be straying out of the realms of equal comparison, as with both all of my VAWT and HAWT designs, I aimed to keep as much about their design as common as I could, that being airfoil, sweep area blade length. In this initial research, I discovered that there was a selection of VAWT types that held the highest popularity among all others, these being the Darrieus VAWTs. One of the most notable types of this wind turbine known as the "egg-beater" was first designed by Georges Jean Marie Darrieus, a French aeronautical engineer; filing for a patent in 1926. Darrieus-type VAWTs are symmetrical,

It must be noted that while I use "Darrieus" to describe this turbine style specifically, there are various other models (for example Helical Darrieus, H-Type, and Helicoid Darrieus rotors) that all fall under the umbrella term of "Darrieus VAWT".

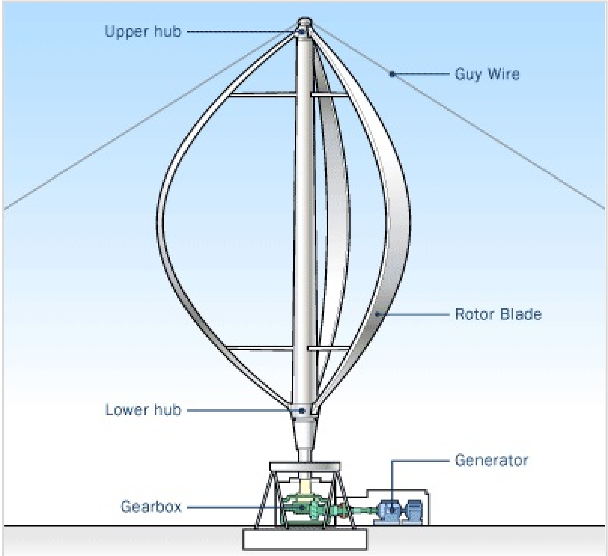
This variation of a wind turbine is known to be the most popular VAWT style and naturally replaces the trade-offs from HAWTs bringing its own to the table. Darrieus-based wind turbines do not have a high operational RPM but rather provide high torque and commercial models are designed to drive a gearbox. Naturally, this style of a wind turbine can be driven by wind flowing from any direction, but it cannot be mounted on a tower and harness the same level of wind that HAWTs have to use, but this also means that maintenance is significantly more straightforward. This type of turbine design has been proven to be more effective in turbulent wind flow than HAWTs, and various studies have been published investigating the viability of Darrieus wind turbines in urban settings. Despite this, Darrieus VAWTs have not been nearly as successful commercially as HAWTs. It must be noted that Darrieus turbines alone generate very low levels of torque at the beginning of their generation curve, meaning they aren't self-starting and are usually paired with a Savonius turbine rotor, or forced to use electricity to get themselves started, but it's commonly thought that at small scales the wind turbulence can provide enough energy to start them. There are also major difficulties in protecting the Darrieus turbines from extreme wind conditions, despite this, Darrieus model wind turbines are significantly safer than conventional HAWTs and still offer the potential for Micro-scale wind generation, due to their preference for turbulent wind flow and low to the ground design.

- Sources (Khudri et al.) ("EXPERIMENTAL STUDY OF DARRIEUS WIND TURBINE- A Detail Review") ("Darrieus Wind Turbines – Turbines Info") ("Darrieus wind turbine") (Voneschen)

Example Photographs:

Fig 200-202. Image Sources ("Dornier Darrieus 55 - 55,00 kW - Wind turbine") ("The Main Types Of Wind Turbines Being Used Today") ("Vertical-Axis Wind Turbine (VAWT): Working, Types, Advantages & Disadvantages") (Stroski)

Applications and Tools Used



Fusion 360 - Student Licence - 3D Modeling Software
Ultimaker Cura 4.2 - 3D Printer Slicer
Ender 3 Pro - 3D Printer
PLA Filament 1.75mm
2 Part Epoxy Resin
Electrical Tape

Fig 203.

Procedures:

This style of wind rotor design that I plan on designing features three blades on opposite sides of the rotor, each lofting outwards on a plane parallel to the axis of rotation following an arc of a circle, where the blade starts its path connected to the centre cylinder of the rotor, peaks outwards at its largest distance from the centre axis of rotation of the rotor at about half the total vertical height, with the distance from that peak and the axis of rotation equalling approximately half the total vertical height and then finally following the exact same path back to the top end of the centre cylinder. Each blade is of constant airfoil thickness throughout and follows the same path, and as such the rotor is symmetrical.

1. To begin designing this turbine I first created a new design and imported a SVG image of the NREL S833 primary airfoil used in the HAWTs and my previous VAWT design. Next I created a sketch plane and drew the outline of the airfoil using the “fit point spline” tool, then I extruded it 5 mm.

2. Next I created a cylinder of diameter 35 mm and extruded it to a vertical height of 150mm. This would serve as the centre cylinder from which the three blades would sweep out from at the base and return again to at the top.

3. Next I moved the cylinder so that its base circle’s centre point was placed on the design origin, and I then created a sketch on the YX plane and drew a vertical line coming from the origin and up 150 mm. Next I marked halfway on that line and from there I measured out 75 mm. Then I created a fit point spline between the base of the vertical line, the end point of the line at half the vertical elevation of the centre line and perpendicular going out 75 mm, and finally the end of the centre line at the top of the cylinder.

4. Now that I had made the centre guide rail for creating the blade complete I next had to make the first blade. So firstly what I did was take the primary airfoil section that I had made earlier and using the “move/copy” command I translated it so that it’s centre point was in line with the cylinder’s, and then rotated it so that it was facing the correct direction relative to the

centre guide rail, and then rotated it on the X-axis so that its top face was perpendicular to the guide rail. Next, I created a “midplane”, a construction plane, and using the mirror command I mirrored the primary airfoil section component at the bottom of the cylinder and created a new airfoil section at the top of the cylinder. Lastly, using the “move/copy” command I made a new airfoil section and translated it so that its centre point was in line with the midpoint of the guide rail, and then I rotated it on the X-axis so that it was horizontal. Finally, to make the first blade, using the loft command I selected the surfaces of the three airfoil sections and then selected the fit point spline as a “centre guide rail”. Now I have completed the first blade.

5. Now having made the first blade the rest of the steps were to be considerably easier and more straightforward. To make the other two blades I used the “circular pattern” command, using the axis of the circle as the axis of rotation. Then I combined all of the bodies, the three blades and the centre cylinder, finally creating a new cylinder of diameter 60 mm at the base and top of the cylinder extruded 15 mm in thickness. Then making the 2.25 mm diameter hole for the motor shaft at the base and lastly I added some fillets for aesthetics. Then designing was done.

Final Design Photograph:

Fig 204.

Model 4.1 -Small

Introduction:

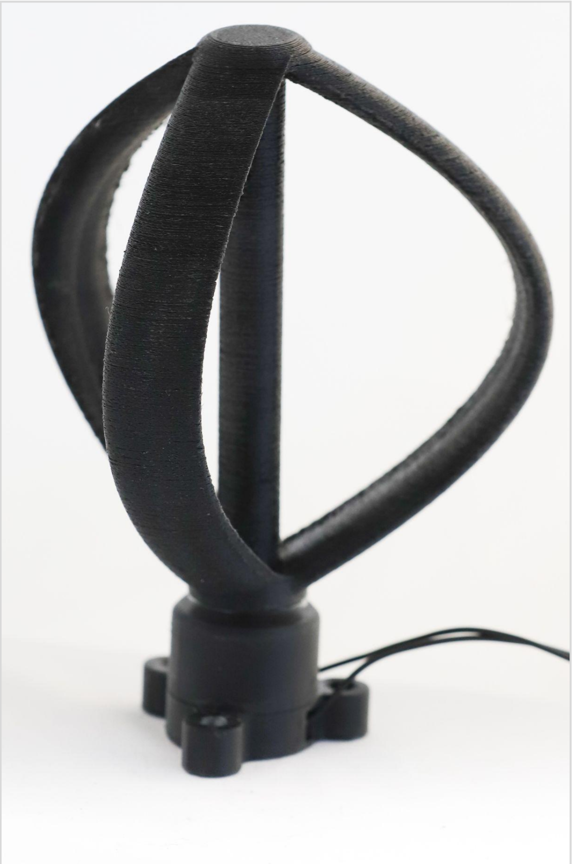
The “Small” size variation of the Darrieus wind turbine rotor was the exact same dimensions as the design described when making the standard Category 4 VAWT, because of this I had to make no modifications to the design for this variation of the rotor.

Modifications:

No additional modifications were required for this model.

Final Design Photographs:

Fig 205, 206.



Final Design Photographs:

Fig 207, 208.

Model 4.2 - 6 Bladed

Introduction:

The only modification needed to create the “6 Bladed” rotor variation of the Darrieus wind turbine rotor was doubling the number of blades. This model had the same height, airfoil and radius sweep area and I intended to use it to compare performance and energy generated depending on whether you doubled the number of blades of a rotor. On one hand, you could argue that it’s double the lift, but then on the other, it’s double the weight and mass to rotate, displacing practically double the amount of wind the other version would. Hence is why I chose to explore this question.

Modifications:

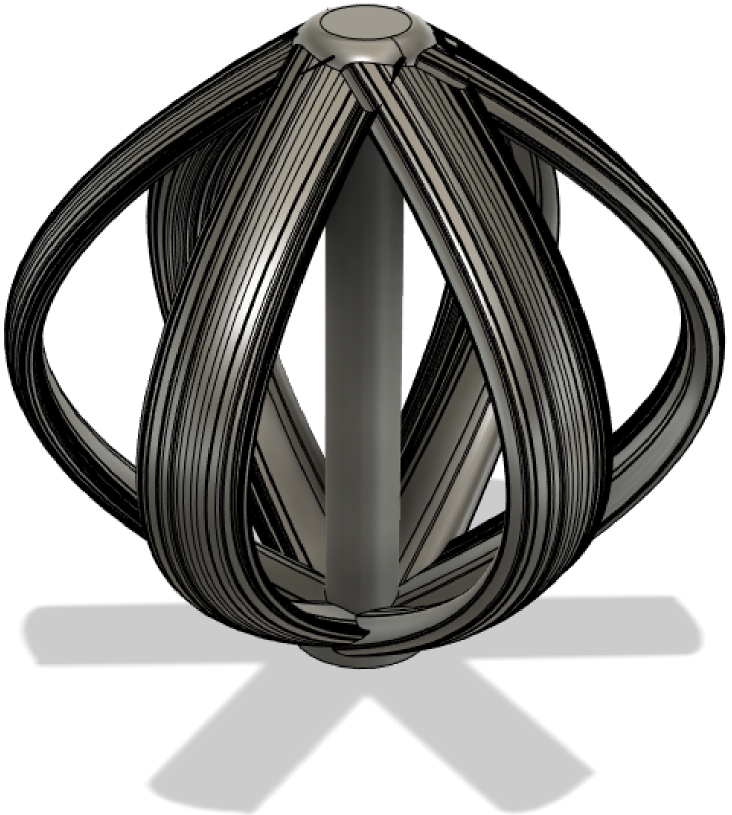
The only modification required to create this design variation was to use the “circular pattern” command to double the number of blades on the rotor. The motor shaft hole nor any other elements of the design were affected by this.

Final Design Photograph:

Fig 209.

Final Design Photographs:

Fig 210, 211.



Model 4.3 - Large

Introduction:

Considering the current scale I am operating at with my project, and how initially I had planned on making all of my designs at a scale usable by a domestic 500w wind turbine 24V 20A AC generator, I was curious to investigate how even just scaling my designs by 1.5 would affect their efficiency, performances and cut in wind speeds. Fortunately, I could do so, as scaling my designs by any partially larger figure would have forced me to buy larger motors and redesign significant elements of my project.

Modifications:

To design this variation of the Darrieus VAWT, I just had to make a copy of the design using the "move/copy" feature and then select the component and use the "scale" tool to uniformly scale it by 1.5. To complete the model I just had to redo the motor shaft hole at the base of the centre cylinder.

Final Design Photograph:

Fig 212.

Final Design Photograph:

Fig 213, 214.

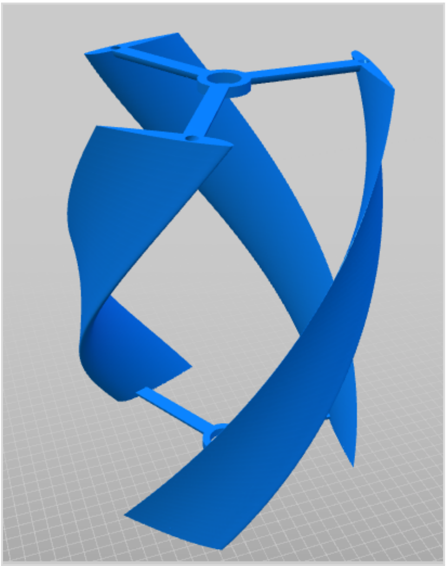
Designing Model Category 5 - Helical VAWT

Introduction:

In light of the UL Testing and the abrupt unsuccessful results from all of my VAWT designs across the board. I discussed the issue with Ardian, the professor who helped me with all of the wind tunnel tests, and came to the conclusion that VAWTs tend to only work (in wind tunnels) when their designs are highly optimised, so I decided to take another working design and use it's blade design and apply it to my previous model in a new category of VAWT and try to see if that made any difference to performance. After further research, I came to the conclusion that HAWTs require less fine-tuning and optimisation to generate higher levels of electricity because when operating all blades are contributing to generating electricity. With VAWTs because of their "Yaw-less" design only a fraction of the blades are helping to push the turbine at any given time, the rest are dragged around and in some cases can push the turbine backwards and create a state of equilibrium. It should be noted that regardless of how optimised VAWTs are, they still lag far behind the efficiencies of their HAWT counterparts.

Here is the source of the blade design that I referenced:
Customizable Vertical Axis Wind Turbine by B3rn475 - Thingiverse

Example Photographs:



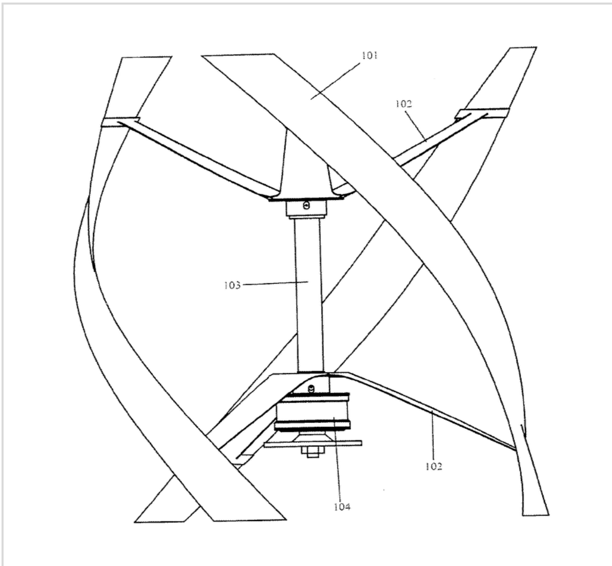


Fig 215, 216. Image Sources ("Vertical Axis Wind Turbines") ("Customizable Vertical Axis Wind Turbine by B3rn475")

Applications and Tools Used

Fusion 360 - Student Licence - 3D Modeling Software
Ultimaker Cura 4.2 - 3D Printer Slicer
Ender 3 Pro - 3D Printer
PLA Filament 1.75mm
2 Part Epoxy Resin
Electrical Tape

Procedures:

1. This style of Helical turbine initially when I found the design was about double the height of my other VAWT variations, so I was forced to scale it down to the dimensions that I had previously been using to compare between all of my designs, I used Fusion 360's, "scale" tool to uniformly scale the design so that its diameter matched the other designs and after that a non uniform scale reducing its height until it matched my other designs (multiplying its vertical height by 0.6).

2. After this I took my primary section airfoil slice and translated and rotated it so that it sat at the bottom of one of the turbine blades, oriented the same way and centred on the airfoil. After this I created a sketch and drew a circle of diameter 150 mm and a line extending out to the base of the blade where I had positioned the primary airfoil.

3. Next I created a sketch on the XZ plane where I created four rectangles of height 30 mm and each separated by a 2 mm high spacer rectangle, starting at the base of the rotor, these rectangles completely covered the design from top to bottom. Then what I did was extrude and cut out all of the 20 mm high rectangles from the rotor design model, leaving just the 3 mm slices.

4. After this I could trace a 3D Sketch "fit point spline" from all of the airfoil sections left of the blade that my primary airfoil was placed under, and then make a new guide rail from which I could remake the rotor using my airfoil.

5. Then I took the primary airfoil slice component, and using the "move/copy" tool I translated and rotated a total of seven sections to their respective locations on what used to be the blade of the Helical VAWT. Then using the "loft" tool I selected the surfaces of all of the new airfoil sections and selected the fit point spline as the centre line. Then I created the first blade, using the "circular pattern" command I was able to make the other two blades and finally I recycled the centre blade connector from my first Helicoid VAWT design to connect all other blades. Except this time instead of creating a slot for the connector I just, using an offset plane cut the whole top off and during assembly glued them back together.

Model 5.1 - Small

Introduction:

For the "Small" variation of this alternative Helical VAWT, I didn't need to make any variations or modifications to the base design. I planned on using this model as an example of illustrating where the possible peak output of VAWT generation lied

Modifications:

No design modifications were required to make this turbine, the only change required was strengthening the base motor shaft connector with a new printed base, as I had printed this design at a slightly lower infill percentage than the others and because of this the base wasn't prepared to withstand the speeds this turbine runs at. Apart from this, all 3D Printed and glued together with no problems.

Final Design Photograph:

Fig 217.

Final Design Photograph:

Fig 218, 201.

Model 5.2 - 6 Bladed

Introduction:

Just like all of the other “6 Bladed” turbine variations, this rotor design only required me to use the circular pattern command and double the number of blades on the turbine. This turbine rotor variation had very consistent print quality and I believe that it can be seen in the photograph example at the bottom of the page.

Modifications:

For this rotor variation all that I had to alter was the number of blades on the rotor, using the circular pattern command to essentially multiply all of its features by 2. 3D Printing, preparation, and glueing still went the same as previous designs.

Final Design Photograph:

Fig 202.

Final Design Photograph:

Fig 203-206.

Model 5.3 - Large

Introduction:

The “Large” size variation of this wind Helical VAWT took a total of two 3D Prints and a total print time of about 24 hours, in comparison to the “Large” (Scaled 1.5) variation of the Helicoid wind turbine with a total of four 3D Prints and a total print time of about 36 hours. As can be seen from the model photographs, the Helix VAWT is made out of a different colour filament to the other designs, just for clarification, these designs are also made out of PLA and were printed at the same infill percentages, print speeds and on the same 3D Printers as the other models.

Modifications:

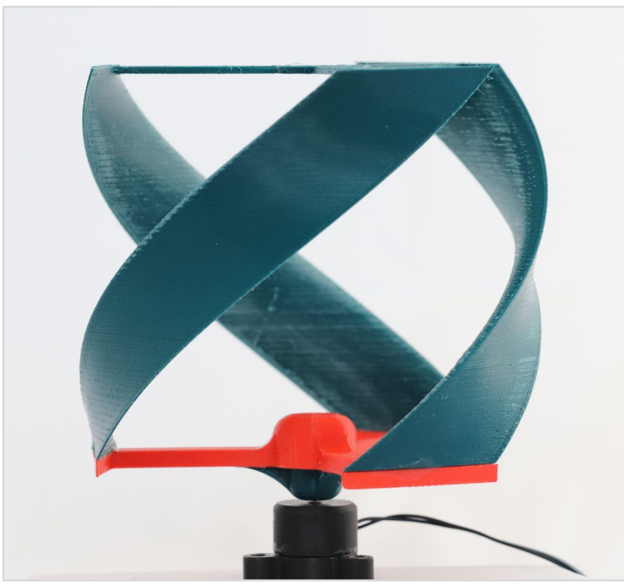
For the “Large” size variation of this wind turbine rotor, the only modifications required were scaling the base size components by 1.5 using the “uniform scaling” tool, lastly redoing the 2.25 mm motor shaft hole at the base of the model.

Final Design Photograph:

Fig 207.

Final Design Photograph:

Fig 208-210.



Designing Model Category 6 - Symmetrical Airfoil Helical VAWT

Model 6.1

Introduction:

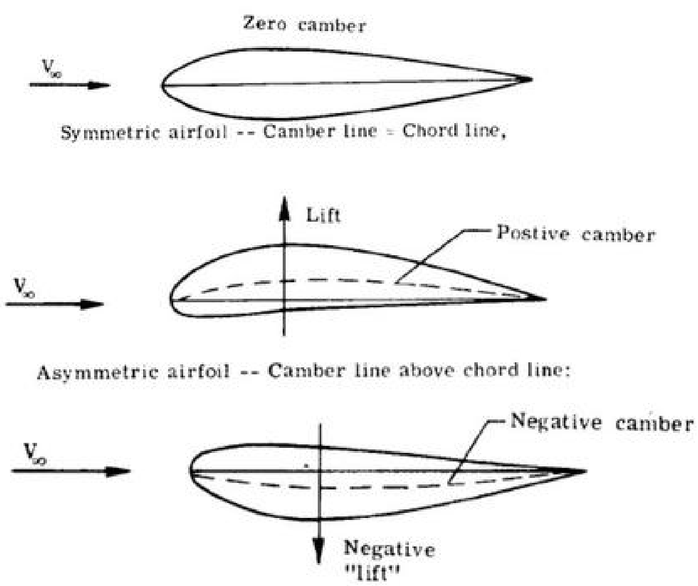
An interesting discussion which I came across when researching what airfoil design was considered the best airfoil for VAWTs be that laminar flow airfoil, cambered, or symmetrical. As explained in the 2018 study “Performance assessment of Darrieus wind turbines with symmetric and cambered airfoils”

“Where NACA’s symmetrical airfoils family are predominant in VAWT development for their good efficiency within a wide range of operating conditions, cambered (asymmetrical) airfoils can tend to produce higher maximum torque and power coefficients.

The laminar airfoil lift-to-drag ratio at a low angle of attack and appropriate Reynolds number gives better efficiency than a conventional symmetrical airfoil at highTSRs; the high static stall angle of the cambered airfoil allows higher power production than a symmetrical airfoil, but at high wind speeds.”

- Source (“Performance assessment of Darrieus wind turbines with symmetric and cambered airfoils”)

Example Photographs:



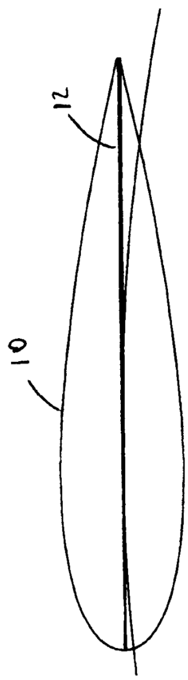


Fig 211. Image Source (“What is a symmetrical airfoil?”) (“US20080256795A1”)

Applications and Tools Used

Fusion 360 - Student Licence - 3D Modeling Software
Ultimaker Cura 4.2 - 3D Printer Slicer
Ender 3 Pro - 3D Printer
PLA Filament 1.75mm
2 Part Epoxy Resin
Electrical Tape

Procedures:

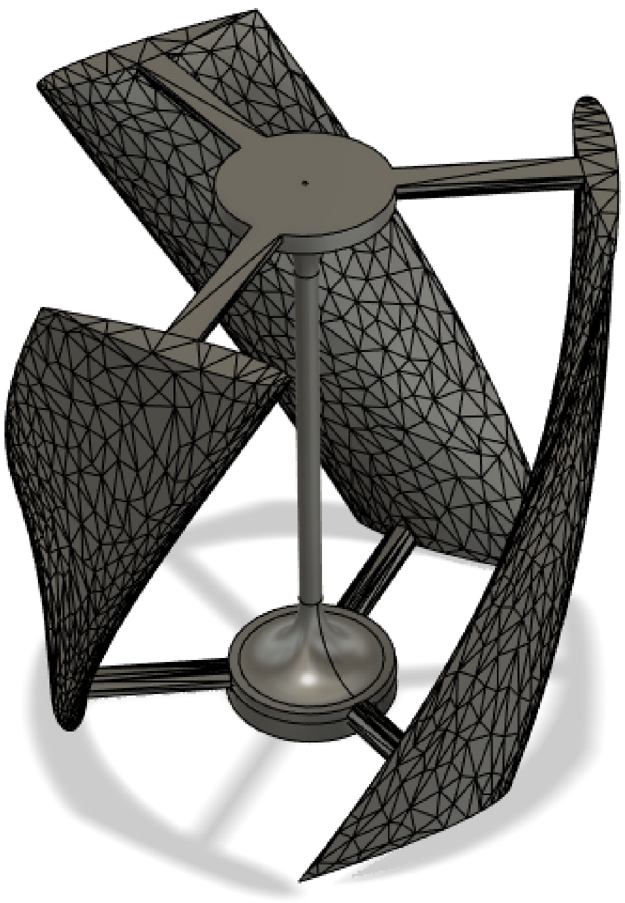
1. To make this VAWT allI had to do was follow the same steps I used for the first Helicoid VAWT but just having swapped out the cambered airfoil for a symmetrical type. After printing and testing the design outdoors I quickly realised that the motor shaft detail of the design had to be reinforced. After making that adjustment, assembling and glueing it together this rotor was prepared for use.

Final Design Photograph:

Fig 212.

Final Design Photograph:

Fig 213, 214.



By
Seán O’Sullivan

Coláiste Chiaráin