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DESIGN OF A VERTICAL AXIS WIND TURBINE (VAWT) FOR ROOFTOP APPLICATIONS



DESIGN PROJECT REPORT REV. C

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Executive Summary

In collaboration with 99P Labs at Honda Research Institute (HRI), we explored rooftop applicable vertical axis wind turbines (VAWTs) as an emergent technology related to urban renewable energy generation. While VAWTs are well-suited for low-speed, turbulent, and multidirectional wind conditions, they remain underdeveloped in power generation and efficiency compared to horizontal axis wind turbines (HAWTs).

Our project represents phase 1 of a multiphase effort to design a rooftop-compatible VAWT. This phase focused on concept development, small-scale prototyping, and preliminary performance evaluation to establish a foundation for future design and implementation.

Our design process began with the exploration of over 200 VAWT concepts from commercial technologies, academic literature, and original ideation. Through structured screening and evaluation, we narrowed this to four concepts, which we modeled, 3D printed, and tested in a 12 in $\times$ 12 in wind tunnel. Based on our experimental results and iterative refinement, we selected a helical hybrid configuration that combines a helical Darrieus rotor with an internal Savonius rotor.

To evaluate the performance of our selected prototype, we integrated wind tunnel testing, rooftop wind data analysis, computational fluid dynamics (CFD), wake comparison, and scaling. These methods provided insight into turbine behavior while highlighting key limitations. Challenges in CFD verification and discrepancies between modeled and experimental behavior revealed the need for future higher-fidelity analysis, and scaling results emphasized the difficulty of translating small-scale testing to real-world urban environments.

We performed an initial economic analysis, which showed that the current design is not viable for low-wind speed rooftop energy generation due to low predicted power output and an impractical breakeven period. Despite this, our project establishes a foundation for future development through a structured design process, validated experimental and computational workflows, and identification of key challenges in efficiency, startup behavior, scaling, and validation. Recommended next steps include improving the wind tunnel setup to allow for more in-depth data collection and further optimizing turbine performance, exploring alternative application environments with higher wind speeds, or advancing CFD toward a high-fidelity digital replica.

This project contributes to the early-stage development of VAWTs as a distributed energy technology and supports HRI/99P Labs' broader mission to explore innovative, sustainability-driven solutions.

Acknowledgements

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Glossary and Abbreviations

Glossary

- **Arbitrary Mesh Interface (AMI)**: A technique in computational modeling that allows simulation across adjacent meshes, even if their mesh grids do not align. The domains can be stationary or move relative to each other.
- **Capacity Factor (CF)**: A ratio that estimates how often within a timeframe the turbine is operating at its rated power conditions.
- **Coefficient of Power (C_p)**: A common measure of wind turbine efficiency defined as the ratio between the power delivered by the turbine (P_T) and the total power available in the wind (P_w).
- **Computational Fluid Dynamics (CFD)**: A branch of fluid dynamics that numerically solves conservation of mass, momentum, and energy equations to analyze systems involving fluid flow.
- **Cut-in Speed**: The wind speed at which the turbine begins spinning.
- **Cut-out Speed**: The wind speed at which the turbine is shut down to prevent damage.
- **Multiple Reference Frames (MRF)**: A steady state simulation technique that acts like a frozen snapshot to model rotating parts without physically rotating the domain.
- **Nominal Capacity (CN)**: The rated capacity of a wind turbine at the beginning of its life.
- **Rated Power**: The maximum power output of a turbine.
- **Rated Speed**: The wind speed at which the maximum power output is reached.
- **Reynolds Number**: A formula/value used to predict if fluid flow will be smooth (laminar) or chaotic (turbulent).
- **Starting Torque**: The torque generated by the turbine before it begins rotating.
- **Swept Area (S)**: The product of the height and diameter of the turbine.
- **Tip Speed Ratio (TSR)**: The ratio between the tip speed to the turbine and the free stream velocity.
- **Torque Coefficient/Moment Coefficient (C_T)/(C_M)**: A nondimensional measure of the torque produced by a turbine.
- **Yaw System**: The mechanism that rotates the turbine's top housing to align the rotor blades directly into the wind.

Abbreviations

- HAWT: Horizontal Axis Wind Turbine
- VAWT: Vertical Axis Wind Turbine

Variables

- P_T : power produced by turbine
- P_W : power available in the wind
- D : diameter of turbine
- R : radius of turbine
- H : height of turbine
- T : torque on blades
- ρ : density of air
- S : swept area
- U : x-component of wind velocity
- ω : angular velocity
- V : wind velocity

1 Introduction

Our Design Clinic team, VAWT Ventures, collaborated with Honda Research Institute (HRI)/99P Labs on the exploration, preliminary design, testing, and performance evaluation of a vertical axis wind turbine for low wind speed campus applications. Honda 99P Labs is the Ohio office of Honda Research Institute, USA that focuses on investigating sustainable technologies and innovative approaches to global challenges with applications beyond Honda's current products. Their research is guided by four key research pillars: sustainable materials and energy, computational design and digital twins, joint cognitive systems, and software-defined intelligence [1]. This project on vertical axis wind turbines (VAWTs) aligns with the two key pillars of sustainability and computational design and digital twins. VAWTs are an emerging renewable energy technology that could be used to take advantage of wind resources in urban areas. However, they have yet to achieve mainstream adoption due to challenges related to urban wind conditions and efficiency. These factors make them naturally align with 99P Labs' focus on investigating pioneering technologies that support a sustainable future [1]. In addition, the initial design work, testing, and computational modeling we did will provide the foundation for a future digital twin that could serve as a virtual replica of a physical turbine, aligning with 99P Lab's broader goal to utilize simulation to analyze and predict performance of physical systems in real-time.

The first academic semester consisted mostly of background research, concept generation and compilation, concept elimination, and finally the selection of four concepts to pursue. During the second academic semester, we began by narrowing the scope of the project and then optimized the chosen concepts in Fusion, tested small-scale prototypes in the wind tunnel, and evaluated their performance using computational fluid dynamics (CFD) and scaling studies to assess power output. Our final deliverables include a CAD model of our selected design, initial testing and performance evaluation results, and a series of recommendations for future work on the project. This report documents background information, project scope, design considerations, design development, design selection, performance evaluation including an economic analysis, and finally our recommendations for future work.

2 Sponsor, Motivation, and Scope

This section provides context for the project by outlining the role of HRI/99P Labs as the sponsor, the broader motivation for exploring wind energy, and the specific scope of work undertaken within this initial phase of a multiphase project.

2.1 HRI/99P Labs

Honda Research Institute, USA (HRI) is Honda's North American research arm, focused on developing forward-looking technologies beyond current products. Within HRI, Honda 99P Labs conducts exploratory research guided by four pillars: sustainable materials and energy, computational design and digital twins, joint cognitive systems, and software-defined intelligence.

This project aligns most directly with the two pillars of sustainable materials and energy and computational design and digital twins. 99P Labs investigates technologies such as advanced batteries and materials to improve efficiency and scalability of energy systems as part of their sustainable energy research. While much of this work focuses on energy storage, it reflects a broader goal of enabling sustainable energy solutions. Our exploration of VAWTs contributes to this objective by investigating renewable energy generation in urban environments.

The project also connects to 99P Labs' work in computational design and digital twins, where virtual models are used to simulate and optimize complex systems in areas such as product design and smart city infrastructure. Similarly, this project uses CAD modeling, wind tunnel testing, and computational fluid dynamics (CFD) to evaluate turbine performance. These efforts establish a foundation for a multiphase design process that could evolve into a digital twin for a rooftop VAWT.

Overall, this project reflects 99P Labs' focus on exploring emerging technologies with high potential impact. By combining physical prototyping with computational analysis, this project contributes to early-stage investigation of VAWTs as a viable urban renewable energy solution.

2.2 Why Wind Turbines

To avert the worst impact of climate change, global temperature increase should be limited to 1.5°C above pre-industrial levels. To achieve this goal, net zero carbon dioxide emissions should be reached by the year 2050, as was decided upon in the Paris Agreement [2]. One of the largest contributors to greenhouse gas emissions in the United States is electricity and heat generation for buildings [3]. The United States runs on a centralized energy system, where electricity is generated in large-scale central facilities and then distributed to people around the country via transmission lines [4]. While renewables constitute increasing shares of the centralized energy

system (or “grid”), much of the power is still produced from fossil fuels. In addition to being reliant on fossil fuels, the current centralized grid system can be vulnerable to natural disasters, which can lead to widespread blackouts. Distributed and renewable energy can increase energy independence, decrease strain on the grid, and provide greater reliability in the event of a power outage.

Wind energy has strong potential to contribute to reducing fossil fuel usage, with most current contributions coming from horizontal axis wind turbines (HAWTs). VAWTs have received increasing attention in recent years, though they remain less extensively studied and implemented. As an emerging technology, VAWTs are being explored as a possible option for distributed sustainable energy generation, particularly in environments characterized by low wind speeds, high turbulence, and urban airflow conditions. However, their performance in these contexts is still an active area of research. This project aims to design and evaluate a VAWT concept with a focus on these challenging conditions.

2.3 Scope

Our team is Phase 1 of a multiphase project on the design and optimization of a vertical axis wind turbine for low wind speed rooftop applications, proposed by HRI/99P Labs. As the Phase 1 team, we have focused on the exploration of an emergent technology through initial design and modeling, physical prototyping and testing, and performance evaluation. This initial phase is an exploratory phase, aimed at initializing the process of technical work for a multi-phase project. Through this technical work, we have gained expertise allowing us to make recommendations to HRI on future directions for this project as well as more specific next steps related to the various pieces of technical work we completed. Our main deliverables consist of the results from our initial technical work and a series of recommendations that HRI and a future phase team can use to build on our work.

3. Background

We began our project by conducting background research to build the technical foundation necessary for ideation. This section provides an overview of the information most relevant to the rest of our project. It begins with a comparison between horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs), followed by a discussion of urban airflow characteristics, which together explain why VAWTs are best suited for our problem space. Next, it introduces key technical parameters related to power output and concludes with an overview of general categories of VAWTs that will be referenced throughout this report.

3.1 HAWTs vs VAWTs

There are two broad categories of wind turbine: VAWTs and HAWTs (Fig. 1). VAWTs have an axis of rotation perpendicular to the direction of the wind. These differ from HAWTs, which have an axis of rotation parallel to the wind.

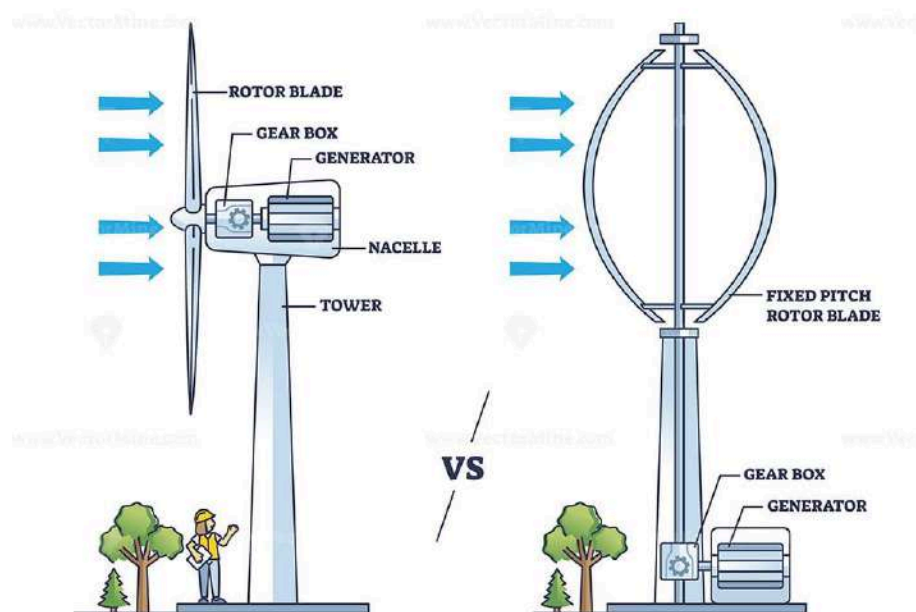


Fig. 1. Horizontal axis wind turbine (HAWT) (left) and vertical axis wind turbine (VAWT) (right) [5].

VAWTs and HAWTs have unique strengths and weaknesses which make them better suited for different applications. HAWTs are designed to operate well in open areas with consistent wind conditions and are typically used in large wind farm applications in remote and offshore locations with access to clean and undisturbed air [6]. Their ideal aerodynamic efficiency is reported within the range of 40-55% under steady wind, however, their performance diminishes

sharply in low or unsteady wind conditions [6]. To function well, their rotors need to be facing the wind flow, so they are usually equipped with a self-starter and a yaw system [6][7].

In contrast, VAWTs are omnidirectional, allowing them to take advantage of winds with changing flow directions without a direction control mechanism [7]. In addition, they have a lower “cut-in speed,” which is defined as the minimum wind speed at which the blades begin to rotate, allowing them to take advantage of slower winds [6]. However, VAWTs are a much less developed technology and struggle with low efficiencies and market penetration. Because of this, nearly all of the electricity generation in the U.S. from wind turbines comes from HAWTs. [8].

Our project focuses on an urban rooftop application, which poses unique challenges for both VAWTs and HAWTs due to the characteristics of urban airflow. Urban areas include structures that increase the surface roughness when compared with flat terrain, impacting the velocity field as shown in Fig. 2 [7][9]. The increased surface roughness causes the average wind speeds to be lower in urban areas [7]. The power that can be extracted from the wind increases with the cube of wind velocity as shown in equation (1), where ρ is the density of the air, S is the swept area, and U is the x-component of the air velocity:

$$P_{wind} = \frac{1}{2} \rho S U^3 \quad (1)$$

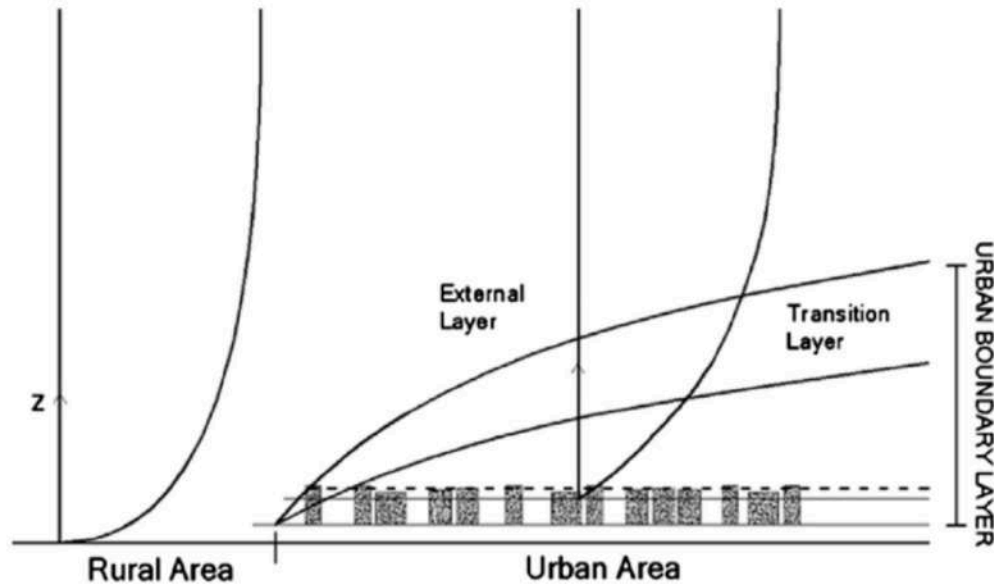


Fig. 2. Urban boundary layer and velocity profile in urban environments (right) and flat terrain (left) [9].

However, as air is forced around buildings, trains, and structures, regions with higher local average velocities and increased density are created. This obstruction of the flow path also

causes rapid changes in flow direction and higher levels of turbulence intensity [7][9]. Turbulence intensity measures turbulence strength and high turbulence intensity signifies large fluctuations in wind speed, which puts extra loads on wind turbines [9]. The slower average wind speeds combined with turbulent flow characterized by rapid changes in wind direction and speed pose challenges for the design of efficient and effective wind turbines [7].

While these conditions pose challenges for both VAWTs and HAWTs, VAWTs are better equipped to handle them due to their omnidirectional nature and lower cut-in speeds. HAWTs struggle in these conditions as their performance decreases significantly in low or unsteady wind conditions and the constant change in wind direction exceeds their yawing ability. For these reasons, our project is focused on the design of a VAWT rather than a HAWT. Table 1 provides a summary of the benefits, drawbacks, and applications of VAWTs and HAWTs. A discussion about the differences between VAWTs and HAWTs with regard to cost, noise, and impact on wildlife can be found in Appendix A.

Table 1
Benefits, drawbacks, and applications of VAWTs and HAWTs

	VAWT	HAWT
Benefits	• Smaller [10] • Lower noise [11] • Lower vibration [11] • Better performance with changing wind directions and turbulence [7][9] • Cheaper/easier maintenance [12]	• 40-55% efficiency under steady wind [13] • Better all around performance [13] • Proven technology widely used in wind farms [7] • Wide range of commercial product options [7] • Cost effective [12]
Drawbacks	• Less efficient [13] • Not well proven [7] • Lower market penetration	• Performs poorly with changing wind directions [7] • Higher noise and vibration [11] • Larger [10]
Applications	• Urban environments [3] • Distributed energy [13] • Smaller scale [13]	• Medium to large scale • Centralized/grid level energy • Flat terrain wind conditions [9]

3.2 Relevant Parameters

There are many parameters related to the performance of VAWTs that we will be using throughout the rest of this report. In this section, we will define some of these key terms.

A power curve, which plots power output with respect to wind speed, can be used to evaluate the performance of a wind turbine (Fig. 3). There are three key regions of a power curve, bounded by the cut-in speed, the rated-speed, and the cut-out speed. The cut-in speed is defined as the wind speed at which the turbine begins spinning. At wind speeds below the cut-in speed, the turbine will not generate power.

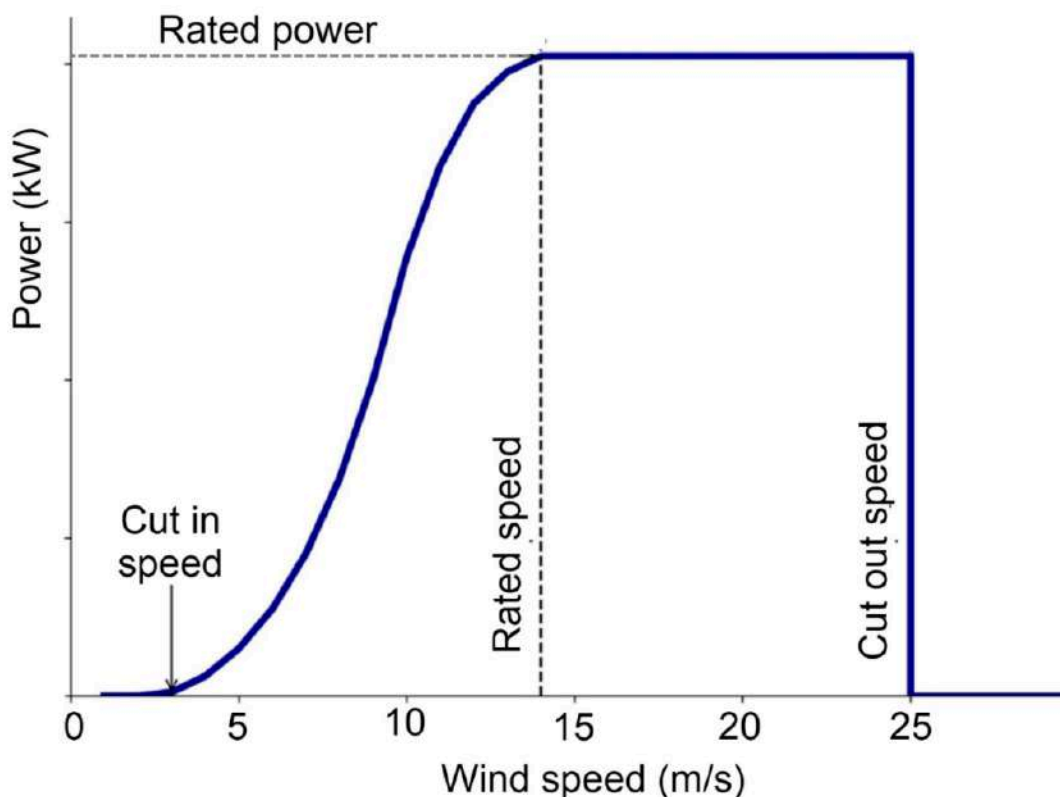


Fig 3. Generalized wind turbine power curve showing cut-in speed, rated speed, and rated power [14].

After the cut-in speed has been reached, as the wind speed increases, the turbine's power output increases exponentially until the rated wind speed is reached. At this point, the power output levels out to the rated power. As the wind speed increases from the rated speed, the power output remains constant until the cut-out speed is reached, when the turbine will usually be shut down to prevent damage. The turbine produces the most power when the wind speed is between the rated and cut-out speed; however, in urban areas, the wind speeds are often much lower than the rated speed. Another key parameter related to the cut-in of a turbine, is the starting torque, which is

defined as the torque generated by the turbine before it begins rotating. A turbine will be able to cut-in or self-start, if its starting torque exceeds the static friction in the bearings and power electronics [15]. If a turbine has low starting torque, that indicates that it will need an external power source to help start it. These terms along with additional metrics related to wind turbine performance are summarized in Table 2.

Table 2
Key parameters related to wind turbine performance

Parameter	Description	Equation
Cut-in Speed	The wind speed at which the turbine begins spinning.	N/A
Starting Torque	The torque generated by the turbine before it begins rotating.	N/A
Rated Power	The maximum power output of a turbine.	N/A
Rated Speed	The wind speed at which the maximum power output is reached.	N/A
Cut-out Speed	The wind speed at which the turbine is shut down to prevent damage.	N/A
Swept Area (S)	The product of the height and diameter of the turbine.	N/A
Tip Speed Ratio (TSR)	The ratio between the tip speed to the turbine and the free stream velocity.	$TSR = \frac{\omega \cdot R}{V}$
Moment Coefficient (C_M) Torque Coefficient (C_T)	A nondimensional measure of the torque produced by a turbine.	$C_M = C_T = \frac{T}{\frac{1}{2}\rho S R U^2}$
Coefficient of Power (C_P)	A common measure of wind turbine efficiency defined as the ratio between the power delivered by the turbine (P_T) and the total power available in the wind (P_W).	$C_P = \frac{P_T}{P_W} = \frac{T\Omega}{\frac{1}{2}\rho S U^3}$ $C_P = C_M \cdot TSR$
Capacity Factor (CF)	A ratio that estimates how often within a timeframe the turbine is operating at its rated power conditions.	$CF = \frac{CN}{P_{rated} \cdot \text{hours}}$

3.3 Types of VAWTs

There are three main types of VAWTs: Darrieus turbines, Savonius turbines, and hybrid turbines. This section introduces each type of turbine, its advantages and disadvantages, and work that has been done to improve its performance.

3.3.1 Darrieus Turbines

Darrieus turbines are lift-based turbines meaning they generate electricity using aerodynamic lift to turn the rotor. As air flows around the airfoil shaped blades, a high pressure zone is created on one side of the blade while a low pressure zone is created on the other, as seen in Fig. 4. The resulting pressure imbalance generates a lift force acting perpendicular to the wind direction relative to the blades, as shown in Fig. 5 [16].

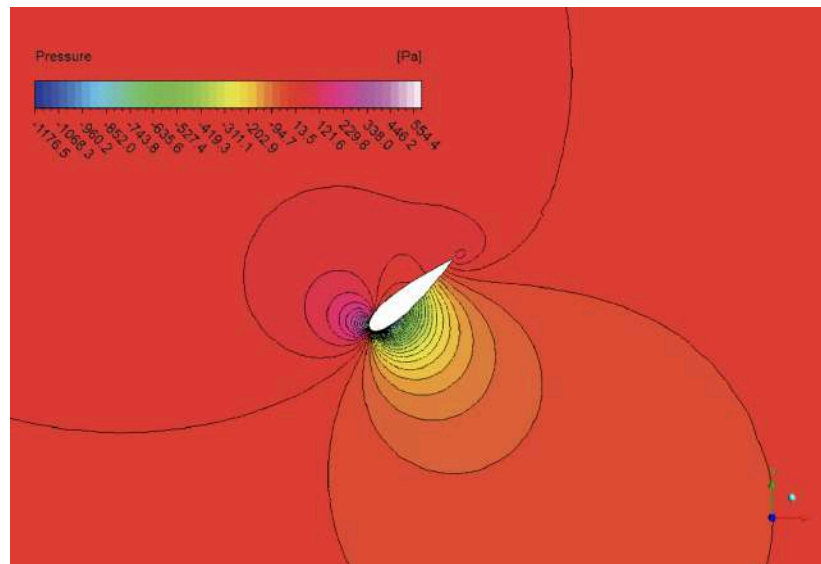


Fig. 4. Pressure contour from Darrieus turbine CFD showing high pressure above the airfoil blade and low pressure below it causing rotating in the counterclockwise direction [17].

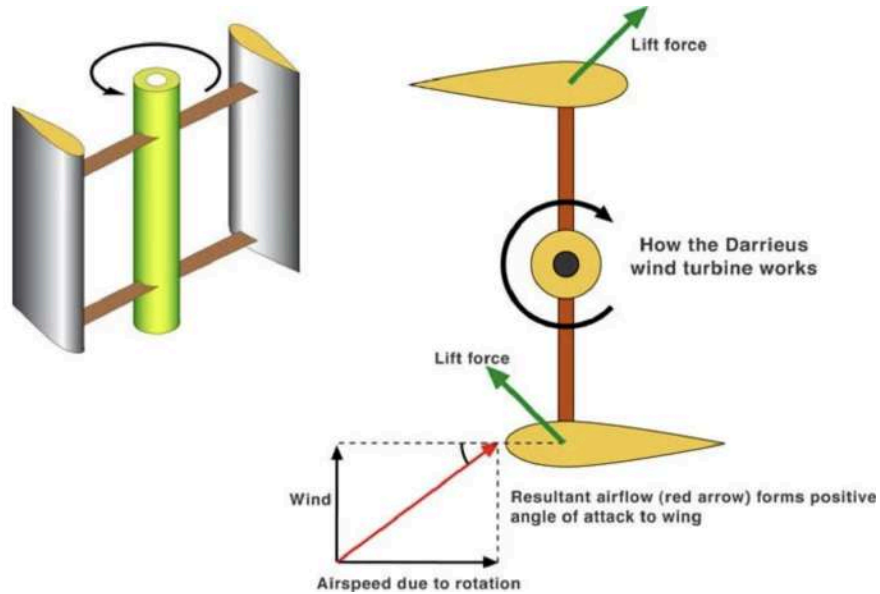


Fig 5. Darrieus turbine working principal [18].

There are three main types of Darrieus turbines, which are shown below in Fig. 6. These include the D-rotor, also referred to as the Eggbeater Darrieus, the H-rotor Darrieus, and the helical Darrieus. The three types of Darrieus rotors are all lift-based turbines, but their different shapes can lead to variation in self-starting abilities, torque consistency, and manufacturability. The standard H-rotor Darrieus has a uniform angle of attack, while the eggbeater and helical Darrieus rotors have varying angle of attacks due to the curvature of the blades.

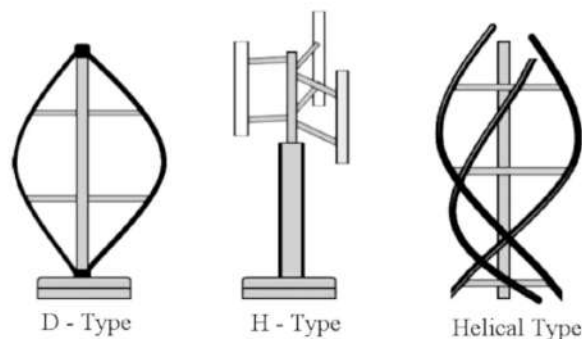


Fig. 6. Different Types of Darrieus VAWTs [19].

Once a Darrieus turbine has begun to rotate, it is able to rotate at speeds much higher than the free-stream wind velocity, resulting in a tip speed ratio (TSR) greater than 1. This makes it particularly effective at generating electricity at higher wind speeds, where the lift-based mechanism can be fully utilized [20]. Darrieus turbines are more efficient than drag-based Savonius turbines and typically achieve efficiencies of 30% to 40%. Due to their consistent and

smooth energy output, Darrieus turbines are useful in situations that require consistent energy output, like larger scale applications [21].

However, Darrieus turbines typically are not able to start on their own and depend on an external starting mechanism to initiate their rotation, which is a major drawback [20]. Much of the research into Darrieus turbines has focused on improving their self starting ability to address this shortcoming. A more detailed discussion of this work can be found in Appendix B.

3.3.2 Savonius Turbines

Savonius turbines are drag based turbines, meaning the force responsible for their rotation is the drag force [22]. Drag is a force which acts in the opposite direction of the motion of any object moving with respect to the surrounding fluid. A classical two-bladed Savonius turbine consists of two semicircular surfaces on opposite sides of a vertical shaft, one convex and the other concave as shown in Fig. 7 [22][23]. As the wind comes into contact with the two opposite facing surfaces, lift and drag forces are exerted on them [24]. A greater drag force is exerted on the concave surface than the convex one, causing the rotation of the turbine [23]. Since Savonius turbines operate on drag, they cannot rotate faster than the wind speed. This means that the tip speed ratio (TSR) is always between 0 and 1 for Savonius turbines [22]. Fig. 8 shows two examples of Savonius turbines: one classical, and the other helical.

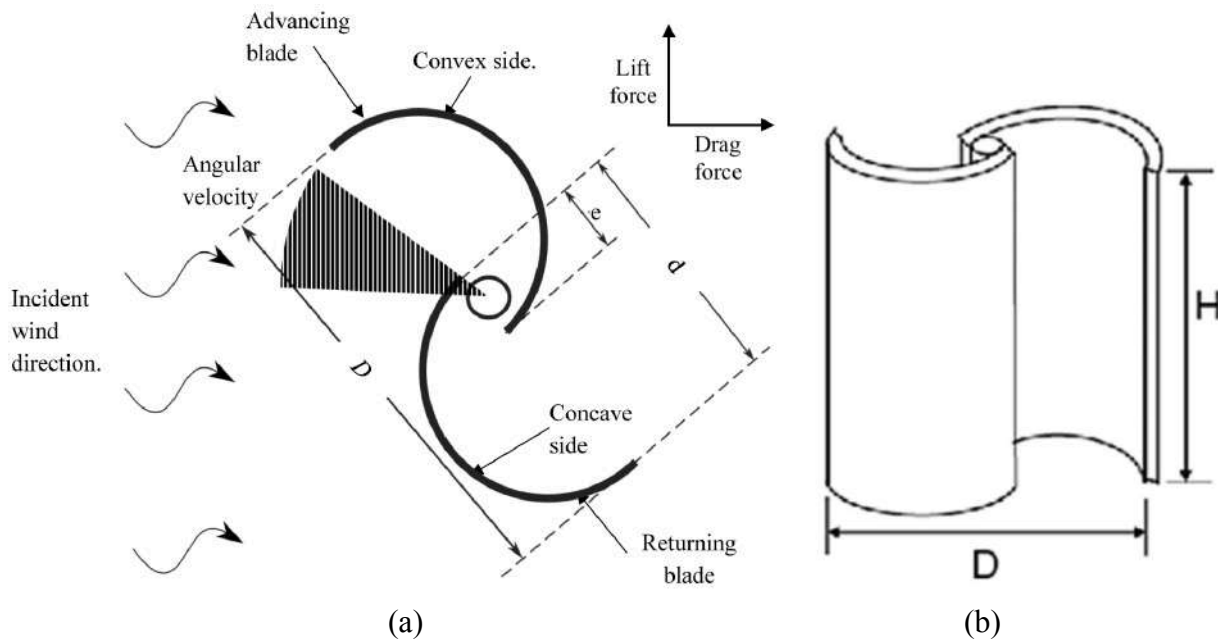


Fig. 7. Savonius turbine diagrams, (a) adapted from [23], (b) adapted from [25].

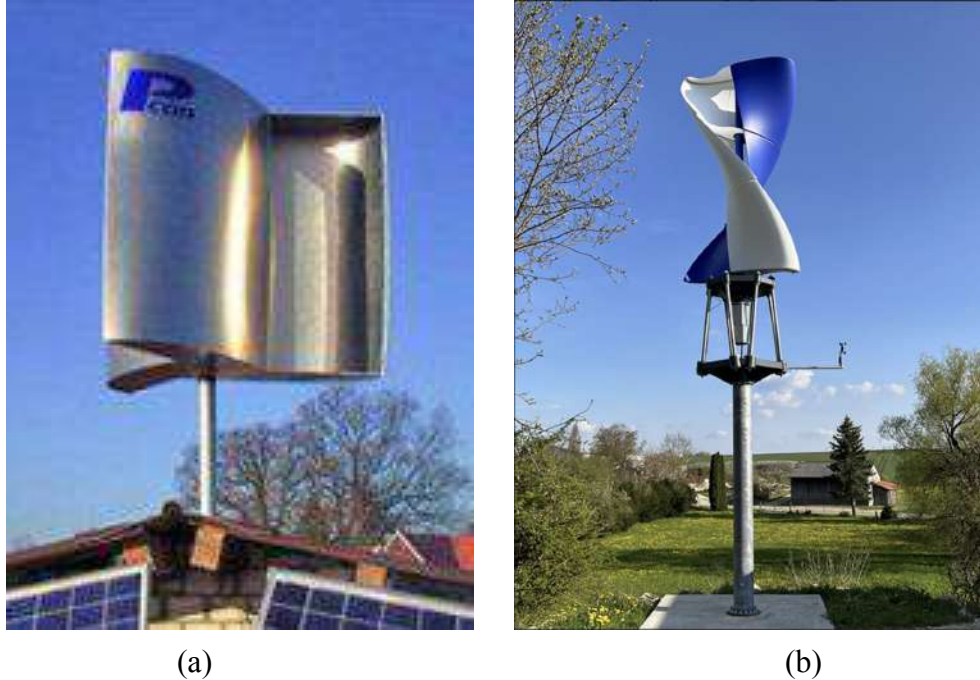


Fig. 8. Classical Savonius (a), adapted from [26], helical Savonius (b), adapted from [27].

Savonius turbines have many advantages including their simple construction and installation, low cost, ability to operate at slow wind speeds, and their self-starting capacity [22][23][25]. The low operating speed of Savonius turbines also make them lower noise compared to other VAWTs. These qualities make them attractive for regions with high turbulence intensity and low wind speeds [23]. However, they also suffer from major drawbacks, the most significant being high negative torque generated during operation and the associated loss of efficiency. Negative torque is the resistive force that opposes the turbine's rotation, caused by the drag force on the returning blade as the wind pushes on it. This negative torque forces the turbine to overcome an additional force to start or continue rotating [23].

To decrease negative torque and improve the C_p of Savonius turbines, researchers have worked to optimize various parameters of the turbine including the number of stages, the number of blades (n), the overlap ratio (OR), the aspect ratio (AR), and the blade shape [25]. Another method researchers have focused on to decrease negative torque is through augmentation devices that direct windflow toward the convex blade and away from the concave blade. While these strategies have been effective at increasing the coefficient of power, they often increase the size and complexity of the turbine and reduce their effectiveness at receiving wind from all directions [28]. Additional details on Savonius turbine optimization and augmentation can be found in Appendix C.

3.3.3 Hybrid Turbines

Hybrid turbines combine Darrieus and Savonius rotors into one VAWT to address the shortcomings of both turbines including the low starting torque of the Darrieus rotor and the low coefficient of power of the Savonius rotor. Hybrid turbines are gaining popularity within urban environments and off-grid applications as they have the potential to operate effectively in lower, more variable wind conditions. Hybrid turbines typically consist of an outer Darrieus, which has high efficiency at high wind speeds but has a high cut in speed, with an inner Savonius rotor to provide torque at low wind speeds, as shown below in Fig. 9.

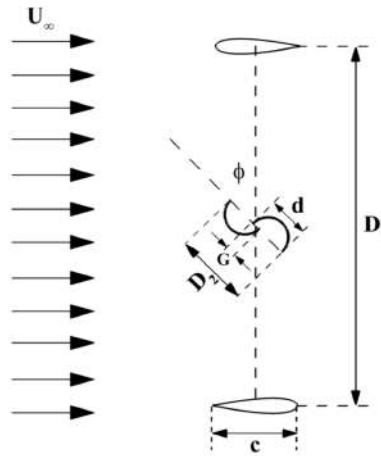
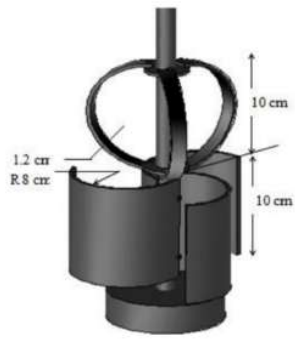
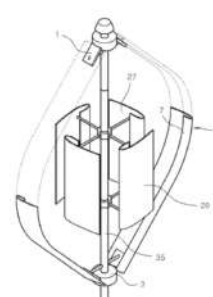
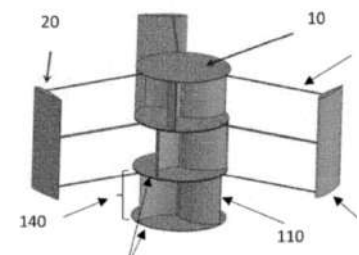


Fig. 9. Hybrid VAWT with inner classical Savonius and outer H-rotor Darrieus [29].

There are many different types of hybrid configurations that vary the type of Savonius and Darrieus rotors and their placement relative to each other. Some hybrid configurations are shown in Table 3.

Table 3
Different hybrid VAWT configurations

Eggbeater Darrieus above Savonius	Double Darrieus with inner H-rotor and outer eggbeater	Multi-Stage Savonius within H-rotor Darrieus
 [30]	 [31]	 [32]

4 Design Considerations

To guide the development of our VAWT design, we identified key stakeholders and considered their needs within the context of installation on Smith College campus. The primary stakeholders include Honda Research Institute (HRI) as the project sponsor, Smith College students and faculty who will live and work in close proximity to the VAWT, maintenance personnel responsible for system upkeep, and future capstone teams who will build upon this work.

Based on these stakeholder needs, we developed a set of design considerations that capture the key factors influencing the success of the overall project. These considerations reflect performance, safety, economic, and integration priorities that would need to be addressed for a fully realized future VAWT prototype.

Considering the full scope of this project, we identified several high-level design considerations as shown in Table 4. These represent the major factors that would influence the feasibility and success of a completely designed, manufactured, and installed VAWT.

Table 4
Full project design considerations

DC ID	Design Consideration	Description
DC-01	Noise and Vibration	Minimization of noise and mechanical vibrations generated during operation to ensure minimal disturbance to nearby occupants and reduce long-term structural wear.
DC-02	Durability and Structural Stability	Ability of the system to withstand environmental loads and maintain structural integrity and reliable performance over time.
DC-03	Manufacturability	Feasibility of fabricating, assembling, and installing the design at full scale, considering material selection, geometric complexity, and available manufacturing methods.
DC-04	Maintenance Costs	Expected cost and effort required for inspection, repair, and upkeep over the system's lifetime, including accessibility and component longevity.
DC-05	Compatibility with College Campus Architecture	Ability of the VAWT to integrate with existing campus structures, including spatial constraints, installation feasibility, and visual impact on the built environment.
DC-06	Power Generation	Capacity of the system to generate sufficient electrical power under low-speed and turbulent urban wind conditions.

Within the scope of this phase, we focused on a subset of design considerations that were most relevant to early-stage design and prototyping: manufacturability, compatibility with college campus architecture, and power generation. These considerations reflect the aspects of the VAWT that we were able to evaluate and iterate on given project constraints, with power generation being our highest priority.

5 Design Development

This section describes the process used to generate, evaluate, and optimize potential VAWT designs. We began by exploring a wide range of commercial and theoretical concepts and narrowed these ideas through a structured concept selection process. The most promising concepts were then modeled in Fusion, 3D printed, and tested in the wind tunnel to evaluate performance. Results from these experiments informed subsequent refinement and design selection.

5.1 Concept Generation and Organization

We began the design process by exploring the existing design space of VAWTs. During this stage, our goal was to identify a wide range of possible concepts rather than narrowing the design space prematurely. We did this by gathering information from literature, looking at commercially available VAWTs, and brainstorming our own concepts.

Once we had gained sufficient technical foundation on Darrieus, Savonius, and Hybrid VAWTs, we compiled a list of 33 VAWTs that are on the market to determine which types of design have been successful as well as gain information on size, power electronics, and expected power output. From this list of 33 VAWTs, we chose five diverse designs to study in depth for variety and based on the availability of information. A specific discussion of our methodology and the five chosen turbines can be found in Appendix D.

Overall, we compiled VAWT concepts from several sources, including commercial technologies, academic research papers, patents, and original ideas generated by team members. This broad exploration allowed us to capture a diverse set of aerodynamic approaches to VAWT design. In total, we documented over 200 VAWT concepts as can be seen in Fig. 10 and detailed in Appendix E.

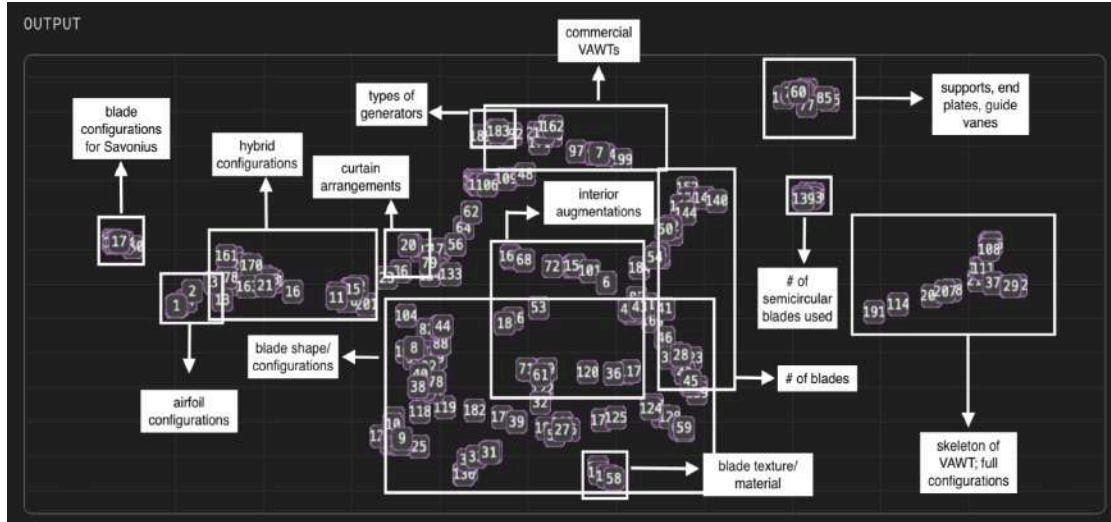


Fig. 10. Design space concept organization [33].

After compiling the full set of concepts, we organized them into design categories to simplify comparison and evaluation. These categories included:

- Skeleton of a VAWT (overall turbine configuration)
- Blade Shape
- Interior Augmentation
- Exterior Augmentation
- Other Optimization

The Skeleton of a VAWT category describes the fundamental turbine configuration, such as Darrieus rotors, Savonius rotors, or hybrid rotor configurations. The remaining categories represent modifications to specific VAWT components. More in-depth descriptions of each category can be found in Appendix F.

During our organization stage, we removed duplicate concepts, combined closely related ideas, and eliminated entries that were not standalone concepts (such as material selections). This process reduced redundancy and clarified relationships between different design approaches. A more detailed description of our concept generation methodology can be found in Appendix E.

5.2 Initial Concept Screening

After organizing the design space, we began a winnowing process to identify concepts suitable for further analysis. We evaluated each concept for feasibility within the scope of this phase, with particular emphasis on manufacturability (DC-03), compatibility with campus architecture (DC-05), and power generation (DC-06). We removed concepts if they were too complex to realistically manufacture or model at this stage, required external starting mechanisms that would

complicate implementation, or were unlikely to generate meaningful power under low and turbulent wind conditions. Additionally, we eliminated designs that compromised the VAWT's ability to operate omnidirectionally, as this would limit performance in variable urban wind environments.

Following this feasibility screening, we further reduced the remaining concepts by focusing on the Skeleton of a VAWT category. We determined that variations in VAWT skeleton would have a larger impact on performance than smaller design changes such as blade shape or minor augmentations. Limiting the design space to skeleton configurations helped us reduce our list to approximately 30 concepts.

5.3 Concept Selection

To further narrow the design space, we evaluated the remaining concepts using an evaluation matrix. Each team member independently evaluated a subset of the concepts using criteria derived from stakeholder needs and design considerations.

The evaluation criteria included:

- Expected power generation in low wind speeds
- Modeling and prototyping feasibility
- Rotor height compatibility with rooftop applications
- Team interest in pursuing the concept

We evaluated some of the concepts using reported cut-in speed values if that information was available. However, because many published concepts did not provide this parameter, we ultimately incorporated it into the broader criterion of expected power generation in low wind conditions. We scored each concept on a five-point scale ranging from passable to ideal. After completing individual evaluations, the team compared results and discussed discrepancies to reduce bias and develop a shared understanding of the strengths and limitations of each design.

Through the iterative winnowing and evaluation process described in Appendix F, we reduced the design space from over 200 initial concepts to a final set of four concepts. Selecting four concepts allowed each team member to take primary responsibility for developing and analyzing one design while maintaining collaboration across the team. These concepts represent a range of VAWT configurations that balance feasibility, expected performance in low wind conditions, and potential for further development. These prototypes, shown in Fig. 11 served as the foundation for the experimental evaluation described in the following sections.

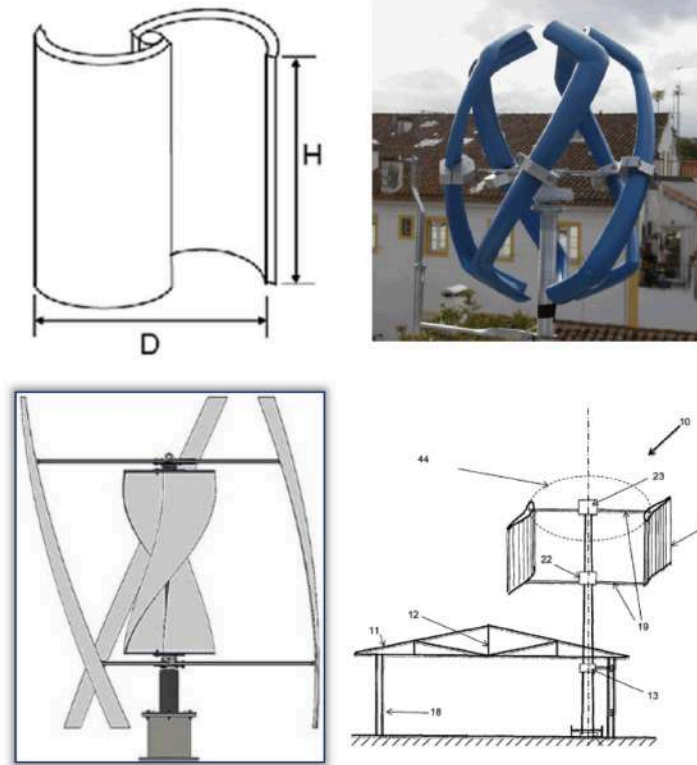


Fig. 11. Classical Savonius (top left) [34], EN0005 (top right) [35], Helical Savonius within a Helical Darrieus (bottom left) [36], and H-rotor Darrieus with Savonius Compartments (bottom right) [37].

We selected these four concepts for initial small scale prototyping and experimental evaluation. Each configuration represented a distinct approach to VAWT design, allowing us to compare different aerodynamic methods for initiating rotation in low wind speeds.

5.4 Prototype Development

We translated each of the four selected turbine concepts into CAD models using Fusion and fabricated them as small-scale 3D printed prototypes as shown in Fig. 12. We chose prototype dimensions of 5 inches tall x 4.5 inches wide to maintain consistent swept areas across all designs, allowing fair performance comparisons.

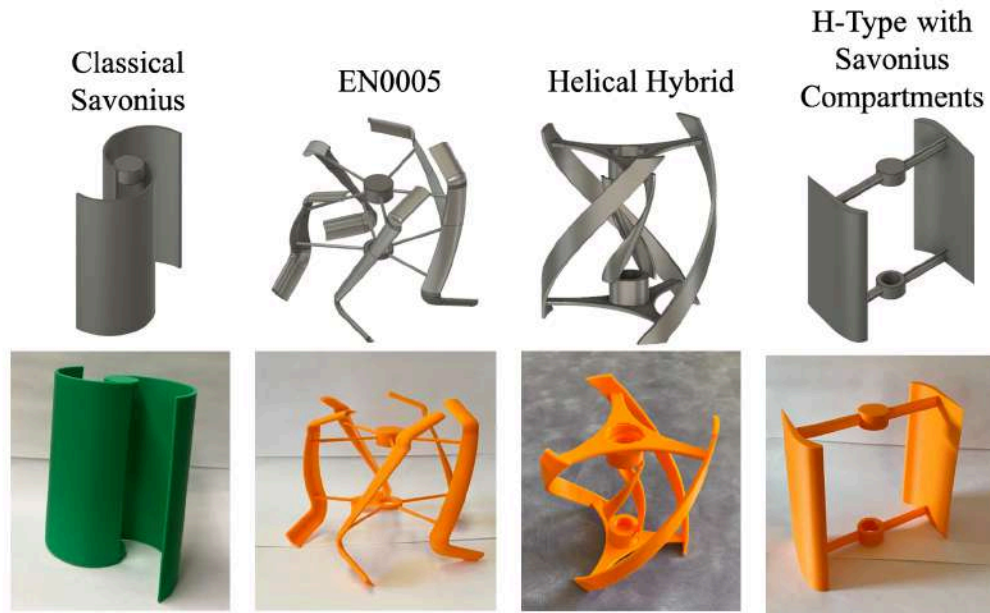


Fig. 12. CAD and 3D printed models of four selected concepts.

5.5 Wind Tunnel Testing

We conducted wind tunnel testing to evaluate each prototype's ability to initiate rotation under low wind speeds using the small-scale 3D printed prototypes. We designed a common central attachment to connect with two ball bearings at the top and bottom of the prototype to minimize friction. The central attachment allows the prototypes to sit on a metal rod within the wind tunnel and ensures they can freely rotate during testing, as can be seen in Fig. 13. We increased the wind tunnel speed incrementally in steps of 0.1 Hz starting at 0.4 Hz, converting into m/s after testing.

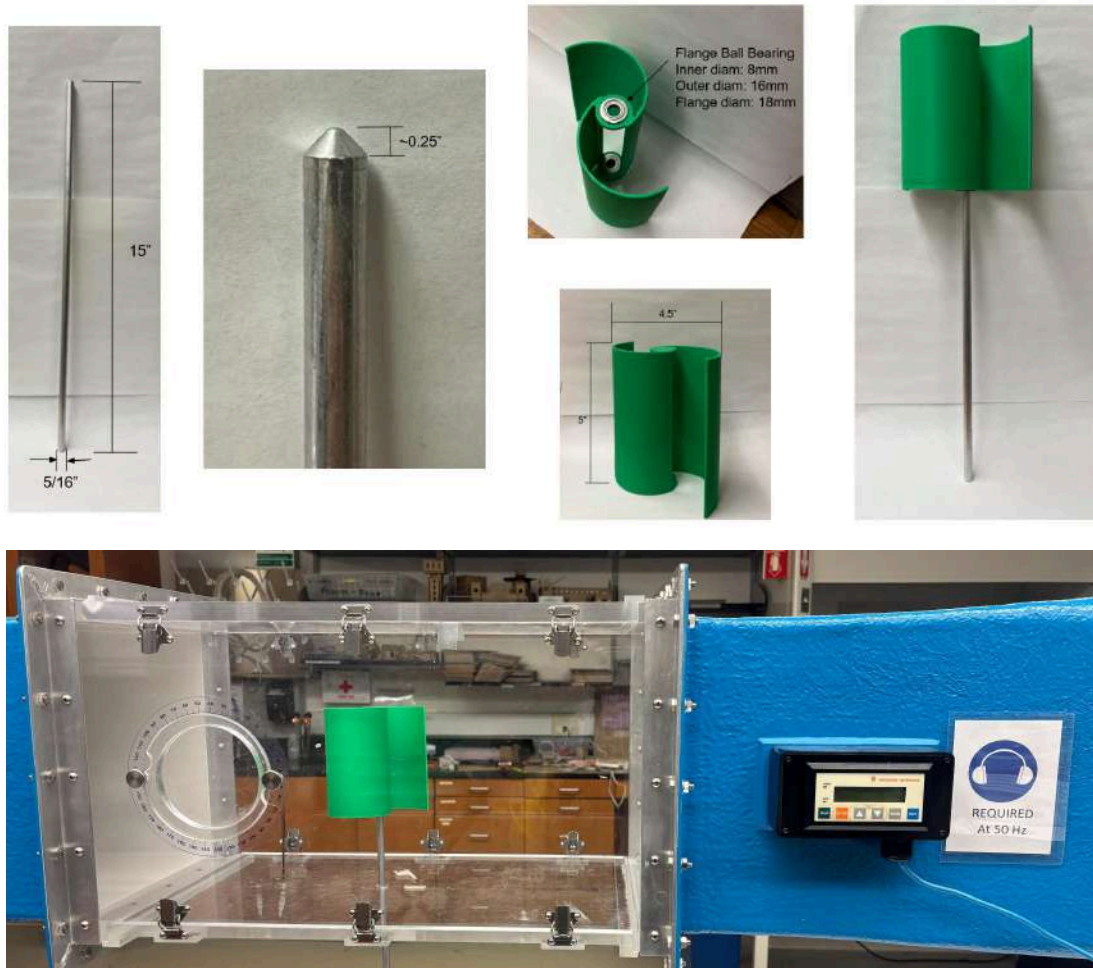


Fig. 13. Wind tunnel testing setup.

At each wind speed increment, we observed the turbine behavior and recorded one of three states:

- No Spin: the turbine remained stationary
- Some Spin: intermittent or inconsistent rotation occurred
- Constant Spin: the turbine rotated continuously

We recorded the wind speed at which continuous rotation first occurred as the cut-in speed for that prototype, and we tested each prototype twice to ensure consistent results.

During this testing phase, the Darrieus with Savonius Compartments design was unable to cut-in and lacked sufficient support in existing literature to justify further optimization within the project timeline. As a result, we removed this concept from further development. Further testing focused on the three remaining turbine configurations: the Classical Savonius, EN0005, and the Helical Hybrid. Across multiple rounds of testing, we evaluated several prototype variations of these three concepts that incorporated aerodynamic augmentations identified through literature

review. These augmentations included modifications to blade geometry and structural features intended to improve startup behavior and rotational stability. Fig. 14 shows optimization and testing results for the initial rounds of optimization focused on all three remaining concepts. Fig. 15 shows optimization and testing results for the additional optimization we completed on the Helical Hybrid. All of the 3D-printed prototypes are also shown in Appendix G.

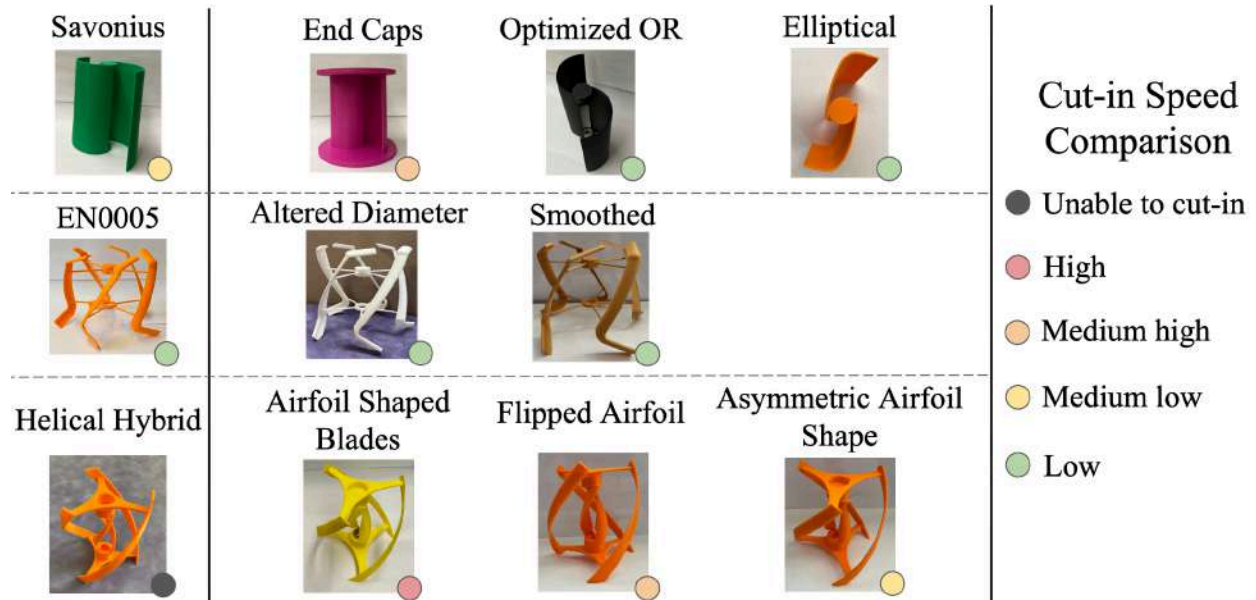


Fig. 14. Initial 3D models and cut-in speed comparison results for three remaining concepts.

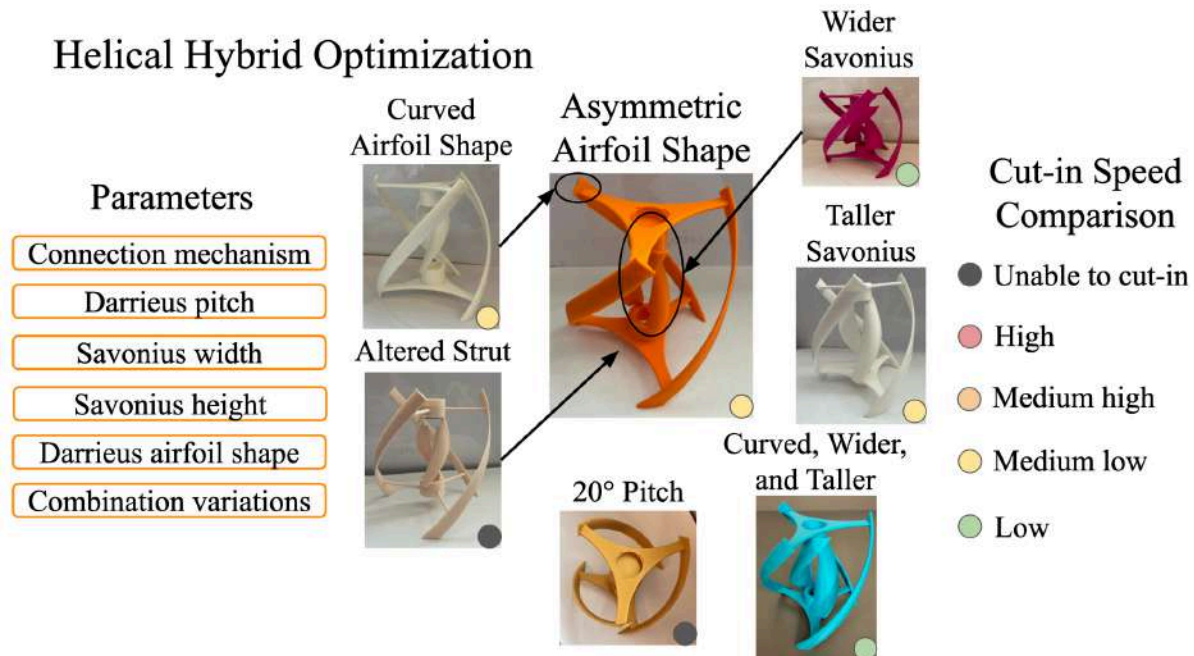


Fig. 15. Helical Hybrid optimization parameters and cut-in speed comparison.

After each testing round, we selected the best-performing prototypes for additional refinement, updating the CAD and reprinting them for further testing. Because of project time constraints, we limited the number of optimization iterations, and as a result, the selected prototype represents the most promising configuration tested rather than a fully optimized VAWT design. We believe our selected concept still has room for future optimization.

Cut-in speed measurements for all prototypes are summarized in Appendix H, and angular velocity measurements collected using a tachometer are provided in Appendix I.

5.6 Concept Evaluation

After completing the final round of prototype testing, we compared the remaining VAWT configurations using an evaluation matrix that incorporated both experimental results and practical design considerations. The evaluation criteria included angular velocity, cut-in speed, moment of inertia, sentiment from researchers, cost of manufacturing, team contributions, and potential for future improvement. Based on this evaluation, the Helical Hybrid concept achieved the highest overall score and we chose it as the selected VAWT configuration for the project.

A full sensitivity analysis and detailed scoring breakdown are provided in Appendix J.

5.7 Selected Design Geometry

The selected VAWT geometry, shown in Fig. 16, is based on the Helical Hybrid concept and incorporates some of the most effective features identified during testing. The design consists of asymmetrical helical Darrieus blades surrounding a widened internal helical Savonius rotor with an optimized blade overlap ratio.



Fig. 16. Final CAD model of the Helical Hybrid VAWT.

5.8 Building Selection and VAWT Scale

The purpose of selecting a specific Smith College building was to have a potential testing site for a full scale VAWT built by a future phase team. We identified buildings on campus that would be suitable for VAWT implementation based on these criteria:

- Building accessibility
- Structural integrity
- Obstructions
- Height

After reaching out to Smith College Facilities Management and relevant building managers, we determined which rooftops were accessible, and carried out a series of site visits. Ultimately, we selected McConnell Hall due to its height, structural integrity and electrical accessibility, as there were already solar panels installed on the roof. The main limiting dimension of available space on the roof of McConnell Hall was about 10 ft across, so we set our full scale diameter to be about 7.0 ft and scaled the height to about 7.8 ft based on the diameter to height ratio we had used in our wind tunnel testing.

6 Performance Evaluation

Once we had selected a design to move forward with, we needed to evaluate its performance. Through our wind tunnel testing, we were able to compare cut-in speeds between concepts and use angular velocity measurements and moment of inertia together to estimate how the power generation of different iterations compared. However, through wind tunnel testing alone, we were not able to determine a coefficient of power or estimate power generation, nor make conclusions about whether our selected concept would cut-in on a rooftop at full scale. Without these pieces of information, we were not able to reliably evaluate the performance of our selected design.

To fill in these gaps, we conducted additional technical work including analysis of wind speeds on McConnell roof and Computational Fluid Dynamics (CFD). Through the wind tunnel testing described in Section 5.5, wind speed data, and CFD, we had information on three key areas of our project. To connect these areas and validate them against each other, we did a wake comparison between CFD and our wind tunnel testing, as well as tested the impact of scaling our turbine up or down in the wind tunnel. This process is summarized in Fig. 17.

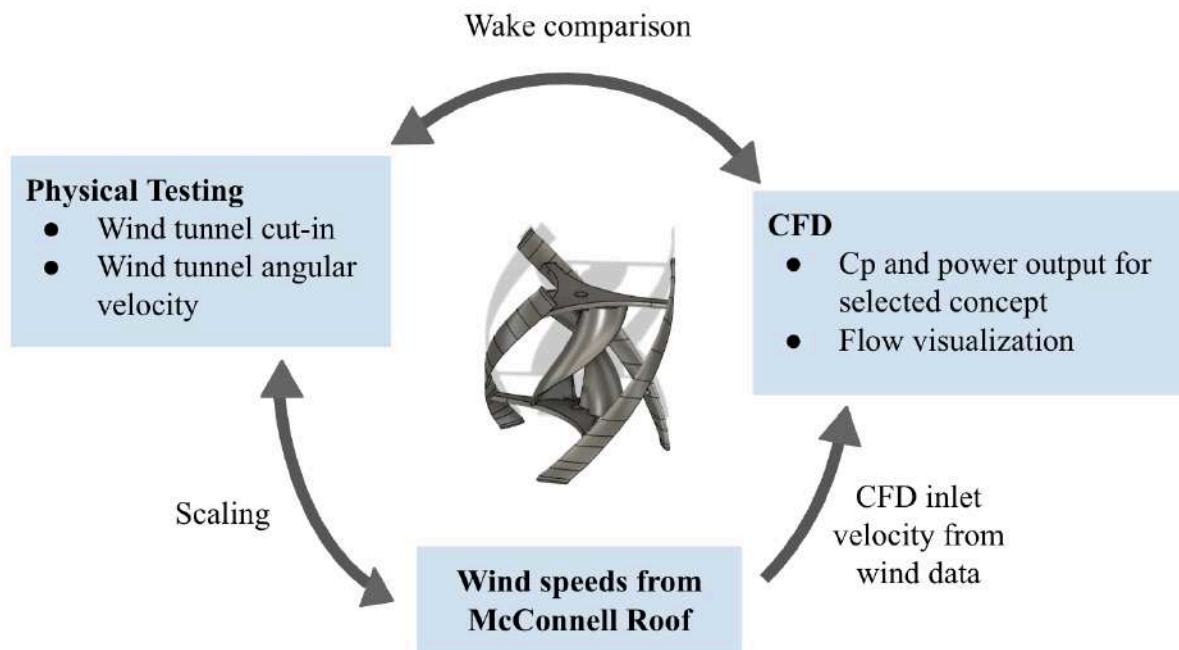


Fig. 17. Connections between different aspects of technical work.

This section introduces each of the four additional technical aspects of our project and explains what we were able to learn from each as well as their limitations. It then describes how the different pieces come together to allow us to evaluate the performance of our selected design. Finally, using conclusions from the other technical sections, we completed an initial economic analysis to evaluate the economic feasibility of our selected concept. The results described here provide a brief summary; detailed descriptions about our set-ups, thought processes, and procedures can be found in Appendices L through P.

6.1 Wind Data

From our background research, we knew that urban airflow is typically characterized by low wind speeds with high multidirectionality and turbulence. However, to evaluate the performance of our selected design for a Smith College application, we needed more specific data about wind conditions on the rooftop of our selected building, McConnell Hall. This data was also necessary to determine the inlet velocity for our CFD and the operational wind speed range for our VAWT. Fortunately, we did not need to take our own data because Nathanael Fortune, a professor from the Smith College physics department, already had an omni-directional anemometer set-up on the roof, and we were able to access the complete data set with year-round wind data from the last 10 years. We chose to analyze the most recent year of data, which spans from January to December of 2025. The anemometer reports daily highs, lows, and the daily average, while excluding wind gusts. Fig. 18 shows the daily high wind speed, low wind speed, and average wind speed for each day in 2025.

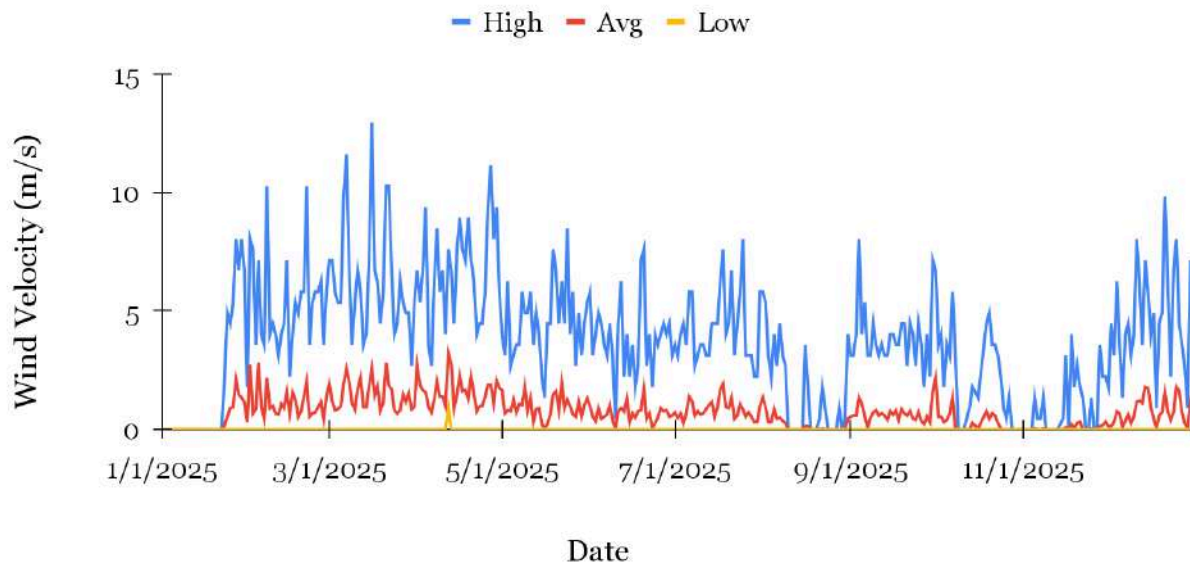


Fig. 18. Wind data from McConnell rooftop.

From this data, we averaged the daily high wind speeds and daily average wind speeds over the course of the year and found that the average high wind speed is 4.02 m/s and the daily average wind speed is 0.67 m/s. Using this information, we chose to use an inlet velocity of 2 m/s for our CFD because it is a threshold that will be reached with some frequency. Purely based on this data, it would make more sense to use an inlet velocity of 0.67 m/s. However, we thought we could only reasonably design for a wind speed of 2 m/s based on the lowest cut-in speeds from commercial technologies and published studies. Table 5 summarizes our key takeaways from the wind data collection.

Table 5
Key takeaways from wind data exploration

What were we able to learn from analyzing wind data from McConnell Hall?	What else could be learned from collecting wind velocity measurements on McConnell Hall?	What cannot be learned from wind velocity measurements and data analysis?
Year-round daily high, low, and mean wind speeds from	How wind speed varies with height Wind speeds at the specific location we could put the turbine	From analyzing data from existing anemometers, we cannot learn how wind speeds vary at different locations of the roof. In addition, we cannot determine how wind speed varies with height above the roof or the direction from which wind is coming from. If we were to take our own data, we could learn about how wind speed varies with height and with location on the roof. However, due to time constraints, wind data collection would likely need to be done on specific days and times, making the results dependent on the wind conditions on the chosen days. This would provide limited ability to capture the variation over the course of the year.

6.2 Computational Fluid Dynamics (CFD)

As mentioned above, we were not able to draw solid conclusions about the power output of our selected design from our wind tunnel testing because we did not have a way to easily measure the torque. To address this gap, we used Computational Fluid Dynamics (CFD), which is a branch of fluid dynamics that numerically solves conservation of mass, momentum, and energy to analyze systems involving fluid flow. CFD divides a continuous fluid domain into smaller,

discrete cells, in a process known as “meshing,” where the governing equations are solved at specific locations. Using CFD, we were able to visualize the flow and predict the coefficient of power for our VAWT, helping us evaluate its performance without relying on physical testing. While CFD can be an incredibly powerful tool, it relies on careful set-up and calibration, as the results are only useful if they are an accurate representation of the physical situation.

For our CFD, we used SimScale with the goal of predicting the C_p of our selected design and determining the ideal operating conditions to maximize the C_p . We spent much of our time setting up the model, troubleshooting, and validating against literature to build confidence in our results and build a strong foundation for more extensive CFD in future phases of the project. This section starts by introducing CFD set-up for vertical axis wind turbines and the key boundary conditions and initial conditions used in our models. It then explains the work we did, primarily on a classical Savonius turbine to validate our results against literature. Next, it explains our TSR analyses and the initial results for our selected concept, and ends with the main conclusions we have been able to draw from our results. Appendices K through M contain supporting details about our CFD work.

6.2.1 Set-Up

The first step in setting up a CFD model for VAWTs is to import the turbine geometry from a CAD software and define a computational domain, which is the region of fluid flow to be simulated. This computational domain includes the turbine as well as a large portion of the surrounding environment and must be large enough to minimize the impact of artificial boundaries on the flow around the turbine. The computational domain is then divided into two zones: an inner rotating domain that includes the turbine and an outer, stationary domain that includes the rest of the surrounding fluid as shown in Fig. 19 [38].

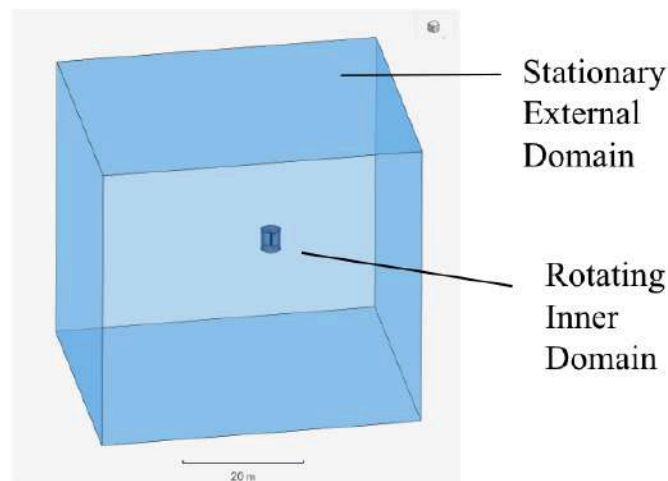


Fig. 19. CFD flow volume with stationary and rotating domains.

The rotation of the turbine can be handled in one of two ways: through physically rotating the inner domain at each time step in a transient study using an Arbitrary Mesh Interface (AMI), or through using a rotating reference frame to approximate the rotation in a steady state study using a technique known as Multiple Reference Frames (MRF) [39]. In either case, the inner domain is rotated at a prescribed angular velocity and will rotate at that angular velocity regardless of the wind speed or the aerodynamic forces on the blades.

Another key aspect of CFD set-up is appropriately choosing a turbulence model. Turbulence is characterized by chaotic, irregular flow occurring across diverse spatial and temporal scales. The free-stream air velocity is often turbulent, particularly in urban environments. In addition, as the fluid interacts with the rotating blades, it develops turbulent characteristics as boundary layers form, potentially separate, and undergo a transition from laminar to turbulent flow [38]. These factors make it necessary to treat the flow as turbulent. While directly resolving turbulence is possible, it requires numerically solving turbulent flows at a large range of temporal and spatial scales, making it nearly impossible for engineering applications. Instead, engineers use simplified turbulence models that are less computationally expensive, but still predict the main impact of turbulence on the flow [40]. Choosing an appropriate turbulence model is an important decision to balance accuracy and computational cost. We used the k-omega SST turbulence model for all our simulations because it can accurately predict power coefficients and torque while minimizing computational cost [38].

The last two steps before running the simulation are specifying boundary conditions and initial conditions, which define the physical environment and ensure the simulation reflects real atmospheric conditions, and meshing the computational domain. The quality and resolution of a mesh directly impact the stability and accuracy of the solution, so it is critical to diagnose mesh quality and ensure proper meshing, particularly in the boundary layer near the turbine blades. To minimize computational cost while ensuring high enough fidelity, we completed a mesh sensitivity analysis in which we ran a steady state model with increasing mesh fineness until the moment coefficient converged to a single value. The results from these studies can be seen in Appendix M.

6.2.2 CFD Validation

In addition to having a correct and consistent set up for each CFD model, it is also important to validate preliminary CFD results with recorded results from past studies. This initial validation is completed prior to recording real data because it is a way to gain confidence that the model is working correctly. We validated our CFD in two different ways. First, we performed a study on an airfoil and compared the coefficients of lift and drag to published results. Second, we performed a study on a classical Savonius and compared the flow field and coefficient of power to studies published in literature.

To complete our initial airfoil validation, we imported the NACA 0012 airfoil into SimScale, chose an angle of attack and Reynolds number to match data given by Airfoil Tools, and used CFD to calculate the lift and drag forces acting on the airfoil [41]. We were successfully able to match the coefficients of lift and drag to those given by Airfoil Tools at the specific Reynolds number and angle of attack. More detail on this analysis can be found in Appendix L.

After validating the airfoil, we performed a steady state study on a classical Savonius turbine with the goal of learning how to set up CFD for a VAWT and validating our results against previously published studies. This process was incredibly time consuming and required numerous iterations. One of the key challenges we encountered when setting up our study was in the meshing of the boundary layer. With our chosen turbulence model, we needed to directly resolve the boundary layer instead of using standard wall functions. We attempted to do this, but faced issues related to mesh quality and were unable to verify whether our meshing was able to accurately capture the boundary layer. Due to time constraints, we decided to stick with SimScale's default physics-based meshing, which may have implications for the validity of our results as we are not sure if it appropriately models the boundary layer for our application. Appendix K contains more detail regarding methods of boundary layer meshing and ideal CFD set-up and Appendix L details our process including the different meshes we attempted.

Using SimScale's default mesh, we were eventually able to validate our results. Fig. 20 compares the velocity field from our study with results published in a paper by Cabrera Et al. in 2026 [42]. Both of the flow visualizations show high velocity regions around the tips of the blades, low velocity in the wake of the rotors, and recirculation vortices occurring in the concave side of the blade. Our C_p from this study was 0.24, which is very similar to the C_p of 0.25 reported by Milas Et al. in 2022 at the same tip speed ratio of 0.8 [43].

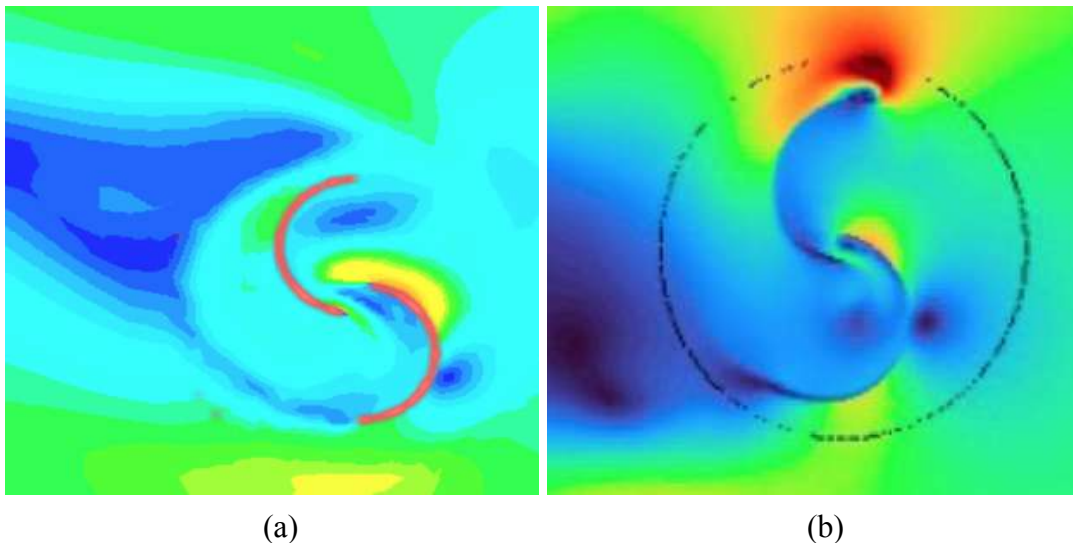


Fig. 20. (a) Velocity profile from our study (b) velocity profile from [42].

Once we had validated our classical Savonius study, we performed a steady state study on our selected helical hybrid concept, following a similar procedure with the goal of comparing our results to those found in literature. At a TSR of 1, our reported C_p of 0.19 closely matches the C_p of 0.20 found in a similar study on a helical hybrid performed by Asadi and Hassanzadeh in 2021 [44]. Further, we can use our velocity field shown in Fig. 21, as it matches what we would expect physically, and we can use it for future evaluation of VAWT performance.

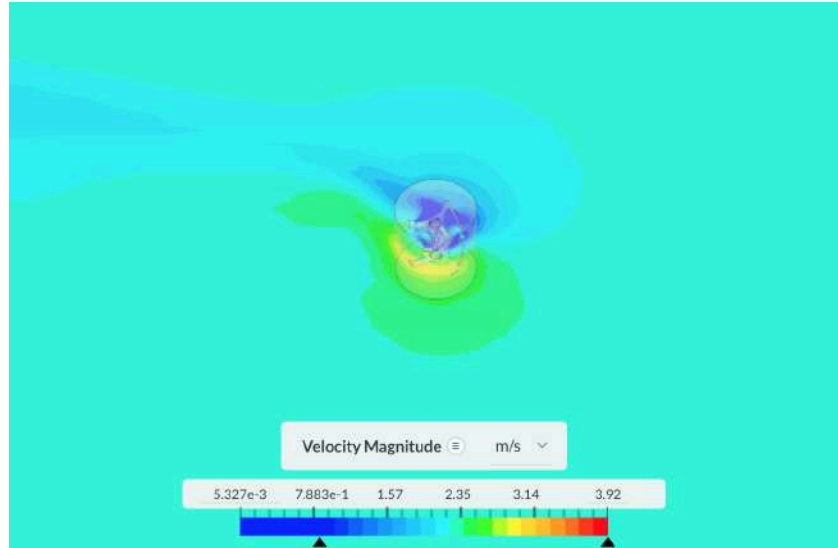


Fig. 21. Helical Hybrid Velocity Field

6.2.3 Tip Speed Ratio (TSR) Analyses

After completing our initial analyses, we performed TSR analysis on the helical hybrid to determine the TSR at which our VAWT performs best. VAWTs typically have an optimal TSR range where their performance peaks at a certain value and then declines when the TSR is out of that optimal range. Past studies have shown that the performance of a classical Savonius turbine peaks at a TSR of approximately 0.8 (refer to Appendix M for further detail). Similarly, helical hybrids have been shown to peak in performance at TSR ranging from 0.5 to 2.5 with optimal performance at higher TSR values. However as helical hybrids are a very emergent technology, optimal TSRs have not yet been determined for our specific helical hybrid, which is why our work in performing TSR analyses was important in determining the optimal range for our selected design.

To complete our initial TSR analysis on the helical hybrid, we increased the TSR from 0.5 to 2.5 in increments of 0.5 by altering the angular velocity while keeping the wind speed constant. We then plotted the C_p with respect to TSR which is shown in Appendix M. This plot shows that the C_p continuously rises with the TSR. This trend continued when we increased the TSR to 10,

which is well beyond an angular velocity that would actually occur at a given wind speed. This indicates that our CFD is not accurately predicting the parasitic forces, which account for skin friction and pressure drag, that are responsible for the decrease in C_p at high TSRs. To determine whether this phenomenon was unique to the helical hybrid, we performed a similar TSR analysis on the classical Savonius with TSRs ranging from 0 to 1.4 in increments of 0.2 and observed the same trend. At the recommendation of Zhenyu Wang at Honda, we tried the same analyses using a transient model and an Arbitrary Mesh Interface (AMI) to simulate the rotation, as we thought it might better capture the parasitic forces. Unfortunately we observed the same results and given time constraints, were not able to troubleshoot further. Further discussion on our results can be found in Appendix M.

Despite these inconclusive results, after consulting with Zhenyu again, we determined that we could report our C_p of 0.19 at a TSR of 1 because it fell within the expected range. This TSR is similar to what we would expect to observe in low wind conditions because the performance of the turbine would likely be dominated by the internal Savonius, which typically operates at low TSRs. Due to the external Darrieus, the C_p would likely be higher at a higher TSR, but we cannot make a definite conclusion due to the unexpected trend in our TSR analysis.

6.2.4 CFD Conclusions

From our preliminary work on CFD, we were able to learn best practices for CFD set-up for VAWTs, validate the velocity field and C_p of the classical Savonius turbine against studies published in literature, visualize the flow around our selected concept, and estimate its C_p at a wind speed of 2 m/s. However, to build confidence in the validity of our results, more work should be done to ensure the boundary layer is meshed appropriately, as outlined in Appendix K and determine why the C_p is continuously increasing with the TSR. It is also worth noting that our initial C_p of 0.19 of the helical hybrid is low, demonstrating that our selected concept is not extracting a large amount of power from the wind. This indicates that more optimization focused on improving the C_p in addition to decreasing the cut-in speed would need to be done to make this concept viable. Table 6 summarizes our main takeaways from this work.

Table 6
Key takeaways from CFD

What were we able to learn from CFD?	What else could be learned from CFD?	What cannot be learned from CFD
Understanding of set-up Initial C_p Flow visualization	More exact C_p At what TSR is the turbine performing best? Flow visualization could be used to aid in optimization and evaluate what is and is not working with the turbine.	From CFD, it is not possible to easily determine whether the turbine will cut-in at a given wind speed. It is also not possible to determine how it will perform on a roof because it is not possible to accurately replicate urban wind conditions in CFD nor quantify the impact of power electronics.

6.3 Wake Comparison

One of the main challenges with CFD is determining whether the results accurately reflect reality. As mentioned in the CFD section, we compared our velocity fields and C_p to studies published in literature and validated the lift and drag on a simple airfoil with known coefficients of lift and drag at a given angle of attack. These forms of validation are valuable in assessing whether our results are consistent with other studies, but do not allow us to determine whether they accurately reflect the results from our wind tunnel testing. To address this gap and validate our CFD against wind tunnel testing, we conducted a wake comparison by measuring the velocity at set points in the wind tunnel and comparing these values to CFD.

To do this, we placed a pitot probe at specified locations to measure total pressure and then calculated the velocity using the Bernoulli equation. The full lab set-up can be found in Appendix N. We then completed a CFD study on an equally scaled turbine and compared the experimental velocity to the theoretical velocity at each location. As seen in Fig. 22, the rough shape of the wake is similar between the wind tunnel test and CFD, but the velocity at each point is higher in the CFD study.

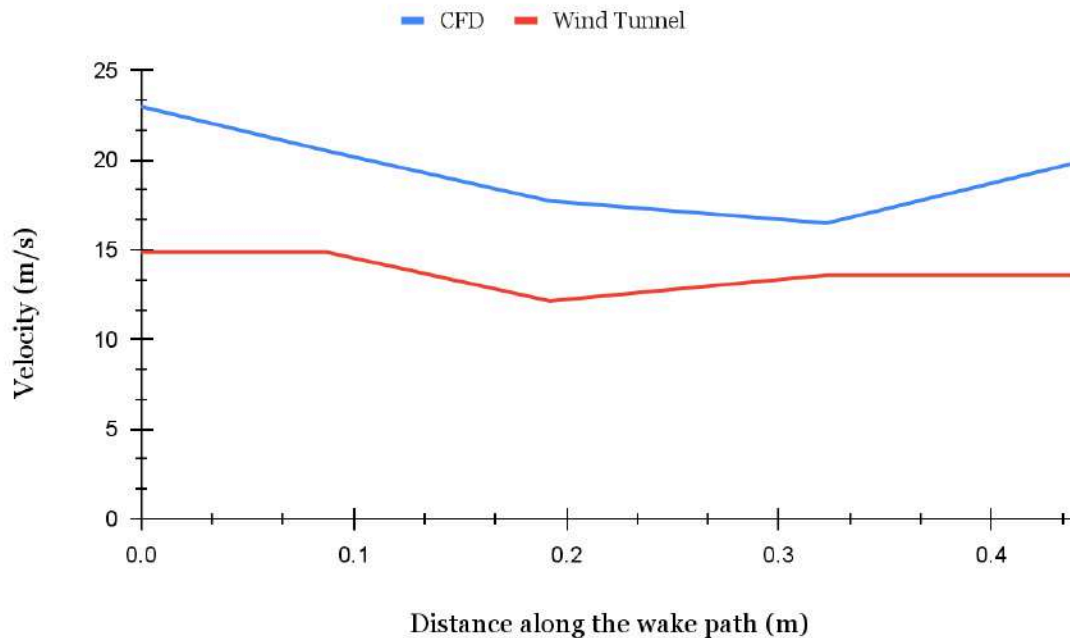


Fig. 22. Wake Profile Analysis of small scale helical hybrid.

We have two hypotheses for the source of this error. First, given time constraints, we were only able to run one test and could not capture experimental variation. It is possible the CFD results fall within this experimental range. Second, the flow volume in CFD was much larger than the physical wind tunnel. Because of this, the walls of the wind tunnel may have had more of a slowing effect on the flow than the boundaries of the computational domain in CFD. Table 7 summarizes our conclusions, areas of future study, and the limitations of a wake analysis.

Table 7
Key takeaways from wake comparison

What were we able to learn from wake comparison?	What else could be learned from wake comparison?	What cannot be learned from wake comparison?
We were able to compare the shape and magnitude of the wake between CFD and our wind tunnel testing and determined that there are some discrepancies between the two.	Do the CFD results fall within the natural variation of the experimental results? To answer this question, we would need to repeat the measurements in the wind tunnel and adjust the dimensions of our flow volume in CFD to match the dimensions of the wind tunnel.	To determine the direction of the flow in the wind tunnel, we estimated the angle using a piece of string as explained in Appendix N. Without a more sophisticated set-up, we cannot precisely quantify the flow direction in the wake.

6.4 Scaling

As mentioned previously, from our wind tunnel testing alone, we were not able to determine whether our selected concept would cut-in on a rooftop at full scale due to the influence of power electronics, unsteady and multidirectional wind conditions, and differences in scaling. One aspect we could effectively study was the impact of scaling. In many fluid dynamics problems, the Reynolds number and Mach number can be used to create dynamic similarity between small models and full size configurations, allowing for experimental data from scaled models to be used to accurately predict full-scale aerodynamic forces such as lift and drag. However, for a wind turbine, we did not believe the results would scale properly using Reynolds number matching alone without accounting for the impact of the tip-speed ratio.

To study the impact of scaling, we printed our selected design in three sizes, however there was a printing error with the smallest so we did not use it to make conclusions from testing. We did cut-in speed and angular velocity testing on the medium and large turbines in the wind tunnel. We performed cut-in speed to understand the impact of scaling on cut-in speed. We performed angular velocity testing to understand the impact of scaling using Reynolds number on tip speed ratio (TSR). A description of how we determined the sizing of each turbine, the tests performed, and associated calculations can be found in Appendix O.

6.4.1 Cut-in Speed Testing

For cut-in speed testing, we calculated the Reynolds number from the medium sized model by experimentally finding its cut-in speed. We then changed the velocity to match this Reynolds number for the large model. This is the theoretical cut-in speed for the large model. From there, we experimentally found the cut-in of the large model and compared the theoretical and experimental results (Table 8).

Table 8
Cut-in speed for large (7 in x 6.3 in) VAWT model using Reynolds number calculated from experimental results for medium (5 in x 4.5 in) turbine

Size (height x diameter)	Experimental Cut-in Speed	Predicted Cut-in Speed by $Re = 2.5 \times 10^4$
7 in x 6.3 in	2.5 m/s	2.3 m/s

The results from our cut-in speed testing indicate a similar value for the experimental and predicted cut-in speed. This indicates that the cut-in speed of the full-scale VAWT may be able to be estimated using Reynolds number matching. In a wind tunnel without power electronics, we calculated the theoretical cut-in speed of the full-scale 7 ft diameter VAWT using a Reynolds number of 2.5×10^4 to be 0.17 m/s (see calculations in Appendix O). This is much lower than we'd expect for outdoor conditions, however it could be possible in a wind tunnel. More work should be done to verify these results at varying scales and to account for power electronics and the turbulent wind conditions on a rooftop.

6.4.2 Tip Speed Ratio Testing

In tip speed ratio testing, we calculated the Reynolds number of the medium turbine using its experimental wind speed and then calculated the necessary wind speed for the large turbine to match this Reynolds number. We then did angular velocity testing and calculated the tip speed ratio (TSR) using those experimental values. The TSR values were found using Equation (2), where ω is the angular velocity of the turbine, R is radius, and V is the velocity of the wind.

$$TSR = \frac{\omega \cdot R}{V} \quad (2)$$

TSR remaining constant between the two scales would indicate aerodynamic similarity, meaning the wake profiles and coefficient of torque would be similar between the different models [45]. If the coefficient of torque is the same, the coefficient of power and therefore power generation itself will be the same for both designs. Therefore, if the TSR remained constant, Reynolds number alone could be used to estimate power production capabilities of a full-scale turbine based on a small-scale model. The results from TSR testing are shown in Table 9 below.

Table 9
Results for TSR at consistent spin with wind speed scaled by Reynolds number

Size (height x diameter)	Wind Speed	TSR
5 in x 4.5 in	6.8 m/s	0.11
7 in x 6.3 in	4.7 m/s	0.29

The results from TSR testing indicate that TSR does not remain the same at varying scales, even when keeping Reynolds number constant. This indicates that C_p and power generation cannot be estimated using Reynolds number matching alone. More work should be done to verify these tests and understand how differing TSR at varying scales will affect conclusions about the aerodynamic behavior of the turbine. Table 10 summarizes our conclusions from our work on scaling and the limitations to this work.

Table 10
Wind tunnel scaling key takeaways

What were we able to learn from wind tunnel scaling?	What else could be learned from wind tunnel scaling?	What cannot be learned from wind tunnel scaling?
Initial results indicate cut-in can be scaled by Reynolds number alone. We would expect the cut-in speed to decrease as the size of the turbine increases, all else constant. The TSR changes when wind speed is changed with scale to match Reynolds number.	By printing and testing more sizes of turbine, a future team could validate how cut-in speed scales under uniform wind conditions. By attaching a hobby motor, a future team could better understand how power electronics affect scaling.	We cannot determine how the wind turbine would perform on the roof since unsteady, turbulent, and multidirectional wind conditions cannot be replicated in a wind tunnel.

6.6 Economic Analysis

To understand whether our VAWT design could be commercially feasible, we performed an economic analysis. In our economic analysis, we produced a cost estimate for the full-scale seven foot diameter prototype and calculated the amount of power the selected VAWT could produce. From there, we calculated the breakeven time at the given economics and the equivalent amount of greenhouse gas emissions saved from the energy produced.

We estimate the cost of the full-scale prototype to be \$12,000. This price is highly dependent on the cost to 3D print the VAWT, which we estimate at roughly \$10,000. To calculate power production, we used a C_p of 0.19 based on the results from our CFD analysis and average wind speeds over 2025 from the wind data collected on McConnell. We used a TSR of 0.8 to make conservative power generation estimates, since the Savonius is the main portion of the hybrid causing the turbine to spin. Using these values, we determined an estimated total power production of 10 kWh/yr. More details on the cost and power production estimates can be found in Appendix P.

From this 10 kWh/yr predicted power output and \$12,000 initial cost estimate, we calculated a break even duration of over 5,000 years. This is well over the predicted lifetime of a VAWT, which is within 20-30 years, therefore making the design economically unfeasible at the \$12,000 pricepoint and low level of power production.

A potential buyer could purchase a VAWT for non-monetary reasons, including off-grid independent energy production and to reduce greenhouse gas and carbon emissions. According to the United States Environmental Protection Agency, the amount of energy our selected VAWT would produce over an estimated 20 year lifetime is equivalent to offsetting 336 miles driven by car per year [46]. This environmental incentive is not currently enough to justify the purchase of our selected VAWT.

We performed some additional analyses with higher wind speed and C_p (see Appendix P), but ultimately concluded that the VAWT is not economically or environmentally feasible at this point in its development. We note, however, that as technology moves into mass production, prices decrease significantly. For example, solar panels were once considered economically unattractive, but have since dropped in cost and improved in efficiency dramatically [47].

7 Recommendations and Next Steps

There are many different directions this project could go in the future. Based on the conclusions we have come to from our technical work, we have collaborated with our liaisons at HRI to recommend three possible future directions to which a next phase team could contribute. This section describes each possible direction and why we would recommend taking the project in that direction. It then concludes with general recommendations that could be applied to any of the pathways.

7.1 Continue to Target Low, Multidirectional Wind Conditions

One possible direction for this project is to continue focusing on designing a VAWT for urban rooftop applications with the associated low wind speeds and high levels of turbulence and multidirectionality. Based on our technical work and the initial economic analysis, we have concluded that our selected design is not yet viable in these conditions and that there is more work to be done to improve its performance and better understand how it would perform on a rooftop. There is currently not a turbine that works effectively in urban areas. We believe there is value in spending more time developing technologies that aim to take advantage of the untapped wind resources in these areas, despite the challenges associated with them. If a next phase team were to choose this project direction, we would recommend they focus their efforts on continued optimization and physical testing and follow the follow broad steps:

1. Redesign wind tunnel testing set-up to be able to measure torque in addition to angular velocity.
2. Continue optimizing the helical hybrid using new wind tunnel set-up to evaluate iterations based on cut-in speed and C_p calculated from torque, angular velocity, and freestream wind velocity.
3. Test scaled up and scaled down versions in the wind tunnel to make more concrete conclusions about the impact of scaling, taking into account C_p . A key piece of information is how the angular velocity and TSR change with scale.
4. Select an improved design to proceed with for rooftop testing.
5. Test selected design on a rooftop, potentially with power electronics and compare the results to wind tunnel tests. This would not be a full-sized turbine.
6. Based on the results, continue with optimization as needed.
7. It may also be beneficial to test scaled up and scaled down versions on a roof to see if conclusions related to scaling from wind tunnel testing hold in rooftop conditions.

To effectively follow this recommended procedure, the next phase team would need to take wind measurements at different heights on McConnell Hall to choose a height for the VAWT that maximizes wind speeds without compromising the aesthetics of a college campus. They would

also need to think about how to temporarily attach the turbine to the roof and whether to include power electronics in their testing. The main focus of this project would be improving the C_p and understanding how the turbine would perform on a roof, taking into account scaling, urban airflow conditions, and possibly the impact of power electronics. Due to this focus, we do not foresee continued work on CFD as beneficial because it cannot be effectively used to model urban airflow or make conclusions about cut-in speed. A next phase team should choose this project if they want to prioritize designing a VAWT for urban rooftop environments.

7.2 Change Application to Areas with Higher Wind Speeds

A second possible direction for this project is changing the application to an area with higher wind speeds. From our technical work and economic analysis, we learned that the most important factors in power generation are the wind speeds, the swept area of the turbine, and the C_p . When designing a wind turbine for residential areas, the wind speeds are typically low and there are significant size constraints on the turbine. For these reasons, it is very challenging for currently available technologies to perform well. To address these challenges, a next phase team could choose to change to an application with higher wind speeds and less constraints on turbine diameter. This could be a skyscraper in a large city, as the turbine would be high enough to access higher wind speeds and there would be fewer concerns about the aesthetic integration with the surrounding buildings.

If a next phase team chose this project, they would need to redesign a turbine with a higher wind speed application in mind, as a Darrieus turbine would likely be more effective than a hybrid, depending on the wind speeds at the chosen location. We envision that the focus of this project would be on the selection, construction, and testing of a turbine because Darrieus turbines already have relatively high C_p and there would be fewer concerns about cut-in speed.

7.3 Focus on Computational Modeling for a Digital Twin

Finally, the third possible direction for this project would be to switch the focus to computational modeling for a future digital twin. We laid the groundwork for CFD, but were not able to entirely follow the best practices outlined in Appendix K due to time constraints and limits in computational resources. For a digital twin to be effective, we would need higher fidelity CFD studies such that we are confident that the set-up appropriately models the situation. If a next phase team decided on this direction, they would need to switch to a different CFD platform with more flexibility and control, such as ANSYS. We would recommend they focus their efforts on boundary layer meshing with $y^+ \leq 1$ and switching to a hybrid mesh, as explained in Appendix K.

If a next phase team decided to choose this pathway, we would recommend they start by comparing their computational model to wind tunnel tests because a wind tunnel allows for a controlled, constant inlet velocity that parallels typical CFD setup. Once they have validated with

wind tunnel tests, they could choose to compare to rooftop tests, however, we would expect there to be inconsistencies due to the variable and multidirectional rooftop wind conditions. We do not think it is worth spending time attempting to model urban wind conditions in CFD, at least in the next phase, due to the computational expense and complexity. We would recommend this direction if the next phase team wanted to focus on creating a high-fidelity model of a complex system and contribute to an eventual digital twin of a physical VAWT. This project would not be directly focused on improving the performance or viability of VAWTs and would instead focus on high fidelity computational modeling and the process of creating a digital twin.

7.4 General Recommendations

In addition to directions for the next phase of this project, we developed a few general recommendations that apply to multiple directions. These include recommendations on power electronics, construction, and structural analysis. Details about these recommendations can be found in Appendices Q through S.

We provide the next team with a recommendation for an off-the shelf generator to be used with the selected VAWT. We selected the Greef 0.5 kW Permanent Magnet Generator based on its low starting torque, low rated rotations per minute, and its ability to work under variable wind conditions [48]. This recommendation, as well as our research on power electronics, will be useful to the team for any direction they decide to move in. See Appendix Q for additional details on the generator and the importance of power electronics.

To construct our selected VAWT at full scale, we would recommend large scale Fused Deposition Modeling (FDM) 3D printing for the majority of the body of the turbine (Fig. 23). The only elements that should not be 3D printed are in the connections to the central metal pole and generator, which would be metal flange mounts. We would recommend 3D printing the majority of the VAWT so that most of the connections are between two components of the same material, increasing the strength. To 3D print such a large and complex design, it will be necessary for a future team to split the VAWT into multiple pieces and have them glued together rather than ask for the design to be printed as a whole. See Appendix R for additional details on construction.



Fig. 23. CAD for 3D printed segment of full-scale VAWT.

To understand whether the construction of the next team's VAWT will be structurally sound at full scale, the team will need to perform some structural analyses on their selected design. We recommend evaluating the blades, the shaft and rotor, the blade-strut attachment, vibration and resonance analysis, and the critical speed of the central shaft. We provide more detailed recommendations for the structural evaluation in Appendix S.

8 Conclusion

VAWT Ventures completed Phase 1 of a multiphase project for HRI/99P Labs investigating the innovative technology of vertical axis wind turbines. HRI was motivated by this project because of their focus on emerging sustainable technologies and computational design. Within this phase of the project, we compiled and generated over 200 concepts, then down-selected to four designs to optimize for cut-in speed, and ultimately selected the widened Savonius helical hybrid. We evaluated the performance of this design by integrating wind tunnel testing, rooftop wind data analysis, computational fluid dynamics (CFD), wake comparison, and scaling. From this work, we gained insight into the performance of our turbine and established a technical foundation for a future phase team to build on. Key limitations of our technical work include our inability to conclude whether our design will cut-in on McConnell roof at full scale as well as limited confidence in the C_p predicted by our CFD results due to potential issues with meshing and the TSR analysis. In addition, we performed an initial economic analysis, from which we concluded that our current design is not viable for low-wind speed rooftop applications due to its low predicted power output. From our conclusions and limitations, we provided recommendations and directions for future phases of the project, including continued design for low wind conditions, relocation to higher wind conditions, or a refocus on the digital twin to mirror a wind tunnel rather than a rooftop situation. We have laid the technical groundwork for the future phases of this project and look forward to seeing where HRI chooses to take it next.

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Appendices

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Appendix A: HAWTs vs VAWTs in Urban Airflow Conditions

This appendix compares HAWTs and VAWTs in urban airflow conditions, focusing on key factors such as noise, cost, and environmental impact.

Appendix A: HAWTs vs VAWTs in Urban Airflow Conditions

This appendix compares HAWTs and VAWTs in urban airflow conditions, focusing on key factors such as noise, cost, and environmental impact.

Noise

VAWTs minimize both noise and vibration as compared to HAWTs on a similar scale. Noise emitted from wind turbines can be divided into mechanical and aerodynamic noise, with the mechanical noise coming from the gearbox and the mechanics of the system, while the aerodynamic noise is due to the wind force on the blades and the movement of the blades through the fluid. For HAWTs, most of the aerodynamic noise is generated by the wing tip as the blade travels around the shaft [A1]. Because VAWT blades are moving slower compared to HAWT blades, aerodynamic noise is typically lower for VAWTs.

In a study performed by Möllerström et. al. [A2], numerical methods were used to simulate aerodynamic noise for a 200 kW VAWT and compare these results to similarly scaled HAWTs. They found that the noise emission at 10 m above the ground while operating at optimum tip speeds, at wind speeds of 6 m/s and 8 m/s, to be 94.1dBA and 96.2dBA respectively. These emissions fall at the absolute lower range of similar size HAWTs of 95.1–100.2 dBA and 97.3–102.4 dBA for 6 m/s and 8 m/s respectively [A2].

In another study, by Larsson et al [A3], initial noise measurements were performed on a 200kW vertical axis wind turbine (VAWT) and results were compared to a similar size horizontal axis wind turbine (HAWT). The results from the propagation measurements indicated that noise declines more rapidly with distance for the VAWT than for the HAWT, as illustrated in Fig. A1, where the VAWT (red) exhibits a steeper decline in sound intensity than the HAWT (blue). In addition, at the initial measurement distance of 20m, the VAWT produces lower noise levels, at 47 dBA, compared to approximately 56 dBA for the HAWT.

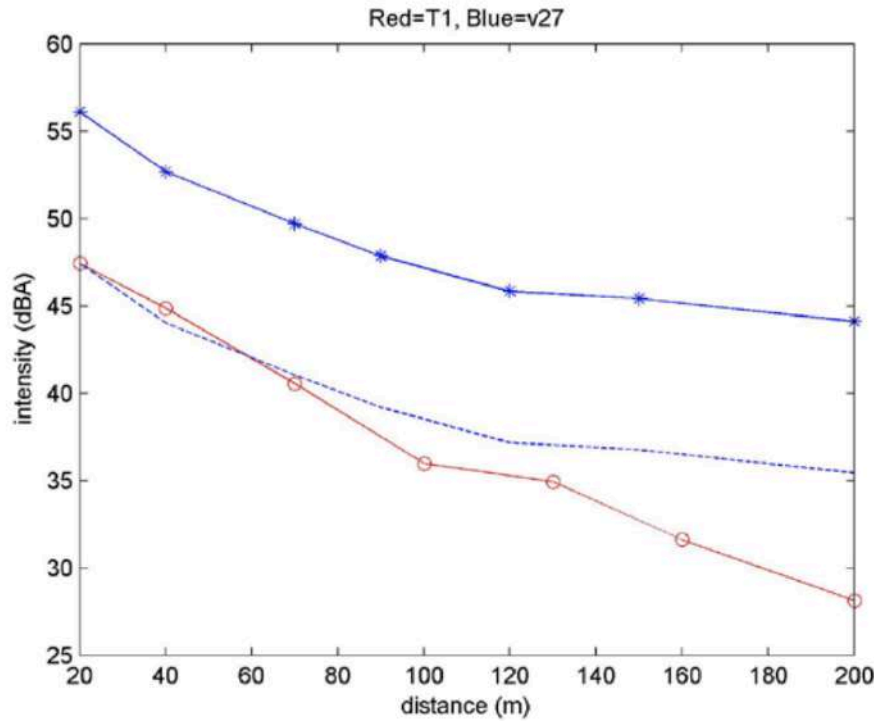


Fig. A1. Noise propagation comparing a VAWT (red) to a similarly scaled HAWT (blue) [A3].

Cost

VAWTs are generally not cheaper to manufacture and install than HAWTs when compared on a similar scale for commercial power generation. Additionally, the energy conversion efficiency for VAWTs is generally lower [A4]. This means that, over time, the cost per unit of electricity generated is typically higher for VAWTs. Estimates place VAWT power generation costs at around 20-30% higher than HAWTs on comparable scales [A4].

In a recent study performed by Ahmad Shah Irshad, the Multi Objective Genetic Algorithm (MOGA) in MATLAB was used for the sizing of hybrid sustainable energy systems with wind turbines (HAWTs and VAWTs) [A5]. Table A1 compares the cost of energy, net present cost, and total cost of a HAWT and a similarly scaled VAWT. For each metric, the VAWT was significantly more expensive than the HAWT.

Table A1
Economic comparative analysis results from Ahmad Shah Irshad study on a VAWT and HAWT
[A5]

	Cost of energy (\$/kWh)	Net present cost (\$/kWh)	Total cost (\$/kWh)
HAWT	0.02	85,905	332,240
Similarly scaled VAWT	0.06	129,932	502,511

However, when comparing the manufacturing costs of VAWTs and HAWTs, it is necessary to consider that HAWTs have been produced for much longer than VAWTs and are produced in large numbers. This decreases their price since parts can be mass produced. In recent years, the trend in wind power has been to increase the size of the turbines. For off-shore applications, this is especially important because foundation and installation costs are so high that larger, higher power output turbines are more economical [A6]. This increase in scale, both for on-shore and off-shore HAWTs, lowers the cost per installed kW further [A7]. Due to these factors, HAWTs have become so economical that VAWTs are currently incapable of surpassing them in large scale applications. However, small VAWTs can play a role in areas where HAWTs are not effective, such as within urban environments [A6].

Wildlife

Currently, there is no empirical evidence to support the claim that VAWTs pose less risk to wildlife than HAWTs. A review of small urban wind turbines, which includes both VAWTs and HAWTs, found that while urban wildlife may be affected, only two studies in the article even mention wildlife impacts, and neither provide field data [A8]. Most existing work focuses on public perception or theoretical risks rather than measured outcomes. In another study focused on the correlation between energy production and wildlife fatalities, it was found that avian and bat mortality rate was constant per unit of energy produced across all sizes and types of turbines [A9].

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Appendix B: Darrieus VAWTs

This appendix reviews key design parameters of Darrieus VAWTs, such as blade pitch and airfoil selection, and their influence on turbine efficiency and self-starting performance.

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Blade Pitch

Darrieus wind turbines have a very low starting torque, so they are very difficult to start and usually require an external energy source. Researchers have used mechanical systems to optimize the blade pitch and have studied the specific blade profiles that are capable of making the Darrieus self-starting [B1] [B2]. M. Douak and Z. Aouachria [B3], tested variable pitch machines to see if this would optimize the low initial torque of a Darrieus turbine with NACA-0015 airfoil blades. Variable pitch machines have blades that can be rotated about their axis, which changes the blades' pitch angle. This, in turn, alters the angle of attack and increases torque.

For any airfoil to generate lift, the attack angle, shown in Fig. B1, must remain less than the airfoil stalling angle [B3]. The stalling angle of the airfoil is determined from the lift coefficient curve of the airfoil. Researchers M. Douak and Z. Aouachria found that the optimal angle of attack ranges from (4° - 10°), where the attack angle remains smaller than the stalling angle and so lift is produced for this range.

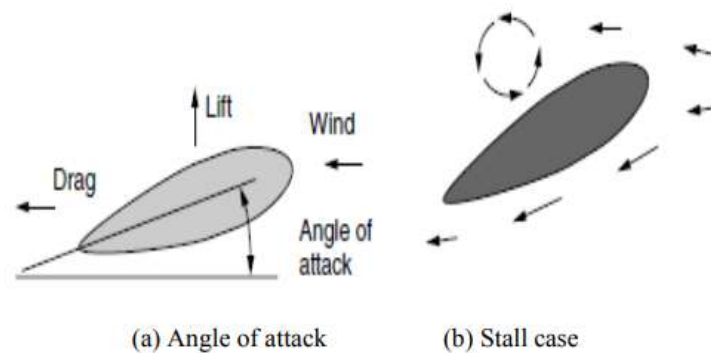


Fig. B1. Diagram of angle of attack and dynamic stall [B3].

Airfoil Type

Most modern configurations employ symmetrical NACA airfoil profiles, with thickness ratios ranging from 12% to 21%, which is a percentage of the maximum thickness to chord length and used to optimize for stable aerodynamic performance and reduced drag [B4]. These airfoils, such as the NACA 0012 profile, below in Fig. B2, are commonly used due to their well-documented aerodynamic characteristics and predictable behavior under varying flow conditions [B5].

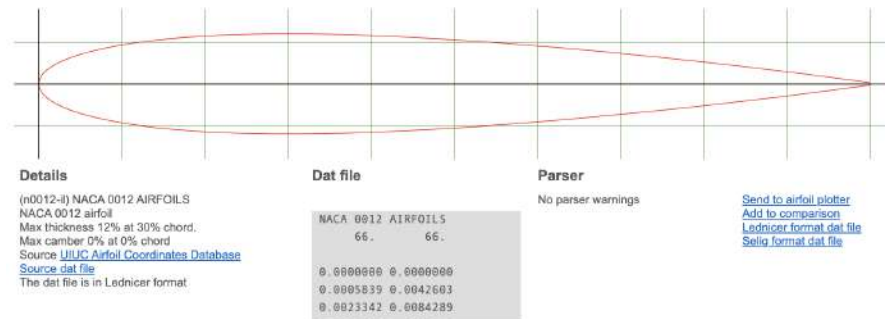


Fig. B2. NACA 0012 Airfoil [B6].

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Appendix C: Savonius VAWTs

This appendix summarizes key parameters and augmentation strategies related to Savonius VAWTs and how they have been optimized to improve the performance of Savonius turbines.

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Parameters

There are many parameters of a Savonius turbine that impact its performance including the number of stages, the number of blades (n), the overlap ratio (OR), the aspect ratio (AR), and the blade shape [C1]. This section defines each parameter and summarizes relevant research.

The number of stages in a Savonius rotor refers to the number of individual rotors that are stacked on top of each other, with the number of stages typically not exceeding three (Fig. C1). According to several researchers, three-stage rotors improve self-starting ability by reducing fluctuations in the static torque coefficient, but decrease the coefficient of power when compared with a single-stage rotor with the same aspect ratio [C2].

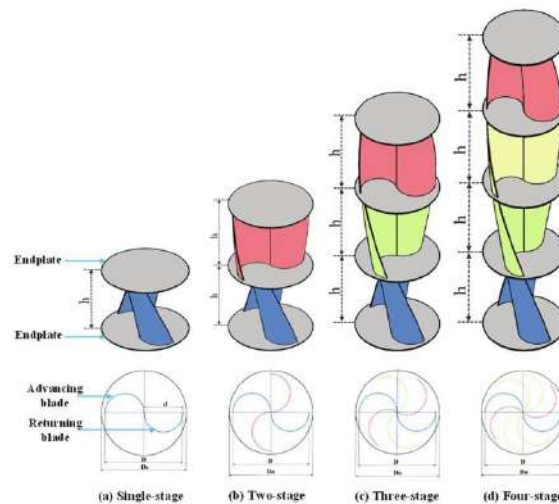


Fig. C1. Single-stage (a) , two-stage (b) three-stage (c), and four-stage (d) Savonius wind turbines [C2].

The efficiency of a Savonius rotor is affected by the number of blades. Within literature, rotors with two, three, and four blades have been studied. Saha et al. conducted experiments using single, double, and triple stages of Savonius turbine rotors and found that the optimal number of blades was independent of the number of stages [C3]. Ali concluded that a two-blade Savonius rotor produced more power than a three-bladed rotor under the same testing conditions [C4] [C1]. Based on the numerical and experimental studies from literature compiled by Altan et. al, it appears that two-bladed Savonius turbines generally have higher power coefficients than the three bladed turbines, which agrees with the findings from Ali's study [C5].

The aspect ratio (AR) is the ratio between the height of the turbine, H , and its diameter, D , as defined above in Fig. C1 is shown in Equation (C1).

$$AR = \frac{H}{D} \quad (C1)$$

Mahmoud et al reviewed configuration at aspect ratios of 0.5, 1.0, 2.0, 4.0, and 5.0 and observed that increasing the aspect ratio caused the power coefficient to increase, keeping other parameters constant [C6]. Another study done by Kamoji shows that an aspect ratio of 0.7 produced the maximum power coefficient of 0.21 [C7]. A good performance is recorded by keeping the aspect ratio between the range 1.5 – 2. However, most existing rotors keep the aspect ratios closer to 1.0 for structural reasons [C1].

The overlap ratio (OR) is the ratio between of the distance of overlap between the two blades, e , and the chord length of the blades, d , as defined above in Fig. C1 and shown in Equation (C2).

$$OR = \frac{e}{d} \quad (C2)$$

The amount of wind passing through the gap between the blades increases with an increase in the overlap of the blades. This leads to wind flowing through the concave side to the returning blade, producing more thrust. Tania et al. studied compared overlap ratios of 0.15, 0.2, 0.25, and 0.30 for a classical Savonius turbine and found that for wind speeds smaller than 4.0m/s, 0.15 is a suitable OR, whereas for wind speeds greater than 4.0m/s, an OR of 0.30 was more appropriate [C8]. The variation in performance was accounted for by the turbulent character of the wind at higher speeds. Alom et al performed a 2-D unsteady simulation around the rotor for elliptical blades, testing OR between 0.0 and 0.30 [C9]. They found that the coefficient of power was maximized for $OR = 0.15$ [C1]. According to Blackwell, the value of the optimal OR is within the range 0.1 - 0.15 [C10]. J. Menet found that the OR must be between 0.15 and 0.3 [C11] [C12]. While there is no widespread agreement on the optimal OR, based on these studies, it appears that the optimal OR lies between 0.1 and 0.3, with 0.15 being a frequently cited number.

Fig. C2 shows four different blade shapes (semicircular, benesh, elliptical, modified bach) tested by Alom et al. both numerically and experimentally [C9] [C1]. As summarized in Table C1, the Benesh, Modified Bach, and Elliptical blade profiles had higher coefficients of power than the standard semicircular blade profile in both numerical and wind tunnel tests, with the elliptical blade performing best in both cases.

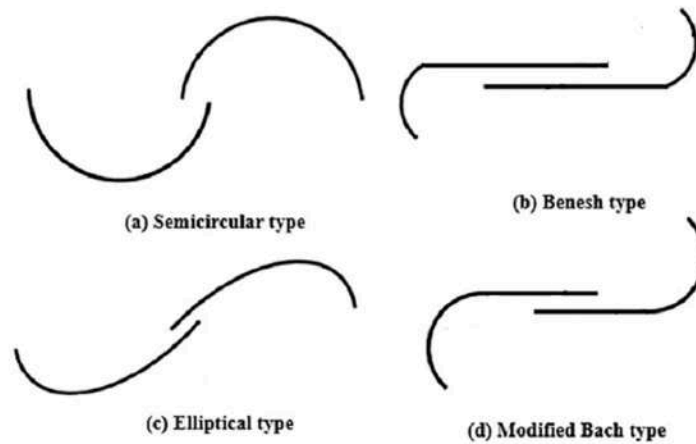


Fig. C2. Savonius blade shapes [C1].

Table C1

Results from Alom et al study on the impact of blade shape on coefficient of power [C9]

Blade type	C_P max numerical	C_P max wind tunnel
Semi circular	0.272	0.158
Benesh	0.294	0.159
Modified bach	0.304	0.162
Elliptical	0.34	0.19

Lee et al. examined the performance of helical-shaped Savonius wind turbines by varying the helical angle of the blades from 0° to 135° [C3]. A maximum power coefficient value was obtained at a blade twist angle of 45° (Fig. C3a). There was a decrease in the power coefficient by 25.5% at a twist angle of 90° [C1].

Laws et al. investigated two modified blade designs, Models A and B, with respect to a conventional one and compared the power and torque generated using numerical methods (Fig. C3(b)) [C4]. Model-A showed a higher coefficient of power due to its reduced surface area at the blade tip and less pressure difference on both sides of the blade. Model-A and Model-B predicted an improvement in coefficient of power over conventional blades of 28.12% and 10.53% respectively.

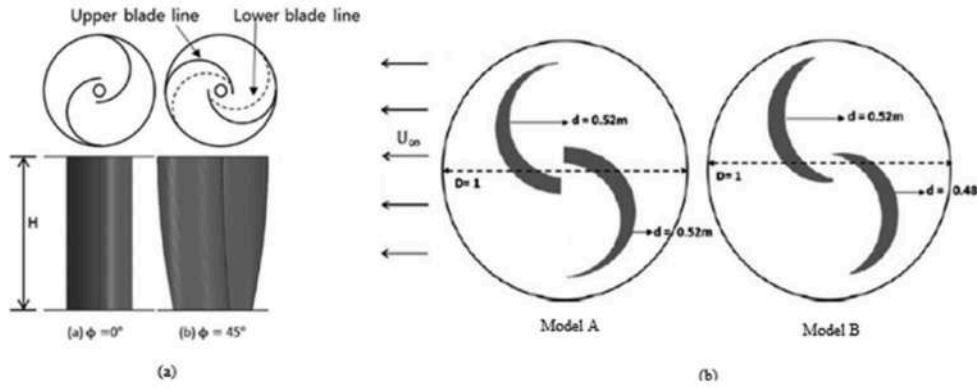


Fig. C3: (a) Top and side views of blades with twist angle $\phi = 0^\circ$ and $\phi = 135^\circ$ [C3] and (b) model A and model B [C1] [C4].

Many blade profile models other than the classical blade shape have been analyzed in terms of their performance. Altan et. al compiled numerical and experimental studies from literature relating to blade shape [C5]. Within this study, the highest reported coefficient of power was 0.40 from a deformable blade designed by Sobczak et al. [C13].

Augmentation Devices

To increase the efficiency and decrease the negative torque present in Savonius wind turbines, many augmentation devices, both internal and external, have been developed. These devices intend to direct wind to parts of the turbine and/or block it from sections. The following section explains a subset of these devices.

Adding endplates to the top and bottom of the turbine prevents air from escaping from the tips of the concave side of the advancing and returning blades (Fig. C4(a)). The ratio of the diameter of the endplate, D_o to the diameter of the blades, D can be varied to maximize the coefficient of power [C1].

A curtaining arrangement is made from wind deflecting plates that are placed in front of the rotor to direct the airflow, as depicted in Fig. C4(b) [C12].

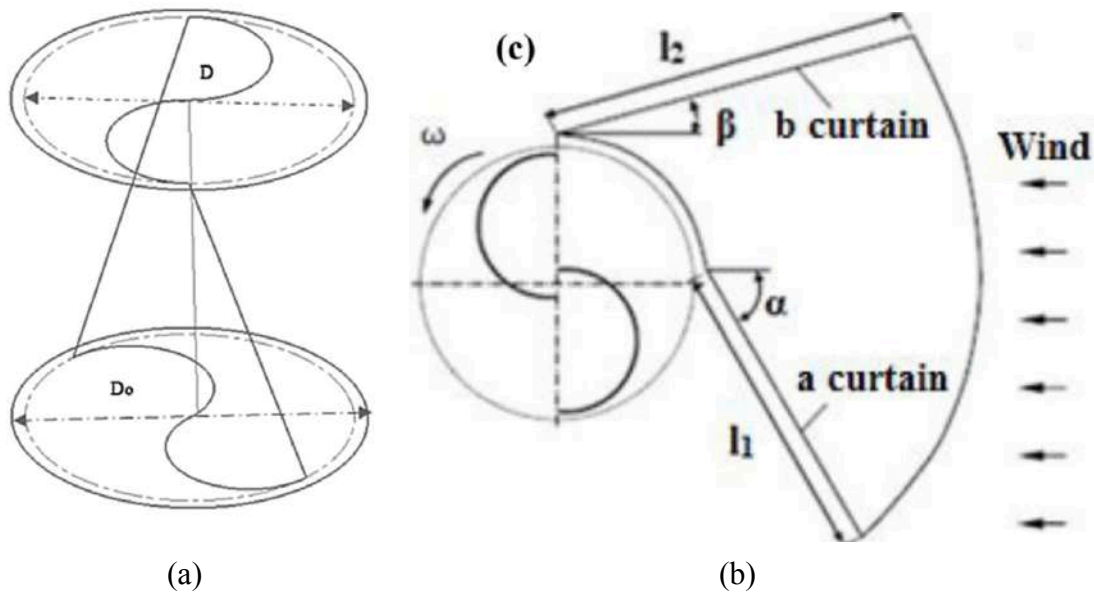


Fig. C4. (a) Circular end plate [C1], (b) curtaining arrangement [C12].

Shielding obstacles are plates placed to shield the returning blades from this wind. Their purpose is to decrease negative torque and improve self-starting capabilities for the Savonius rotor (Fig. C5(a)) [C1] [C12]. Guiding vanes direct incoming wind toward the advancing blade and reduce air flow to the returning blade. They also provide a funneling effect, accelerating the wind in the upstream of the rotor (C5(b)) [C1].

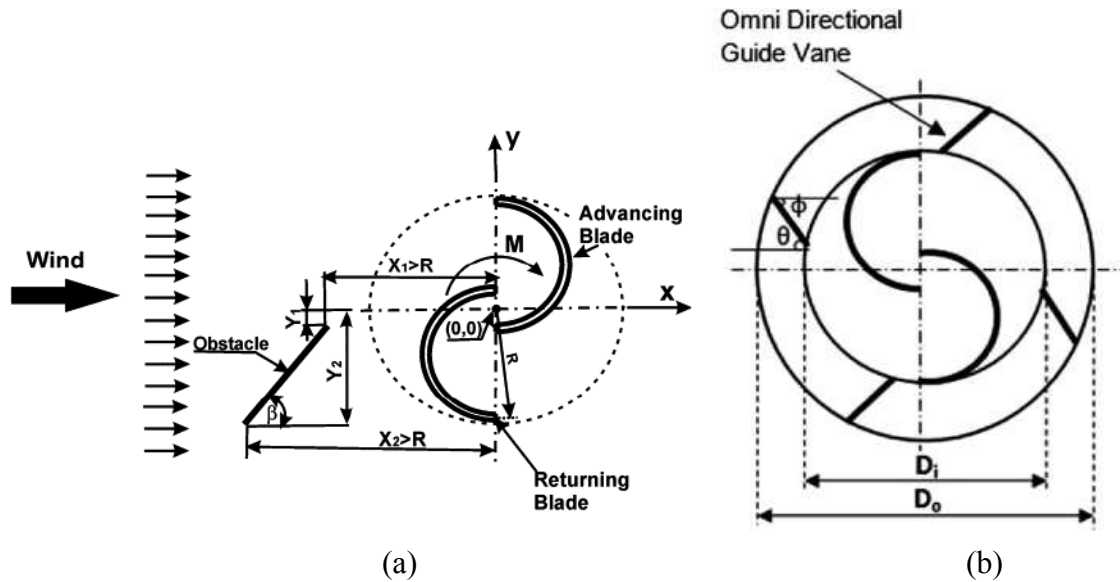


Fig. C5. (a) Shielding obstacle [C5], (b) guiding vanes [C14].

Miniature blades and quarter blades when placed concentrically within the rotor blades increase the efficiency of a Savonius wind turbine. The increased surface area leads to better utilization of the kinetic energy of the incoming wind [C1]. A top view of miniature and quarter blades is shown in Fig. C6.

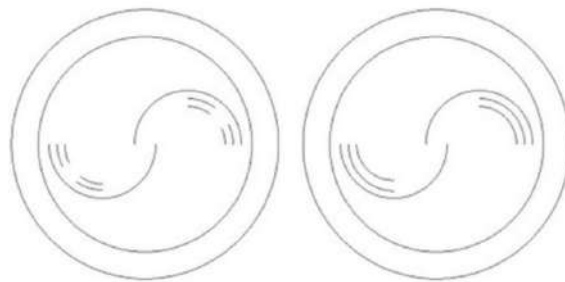


Fig. C6. Top view of multiple miniature (left) and quarter blades (right) [C1].

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Appendix D: Commercial VAWT Technologies

This appendix describes the breadth of commercial VAWTs available, investigates five commercial VAWTs in more depth, and provides a table of opportunities for improvement.

Appendix D: Commercial VAWT Technologies

Introduction

In this appendix, we describe the breadth of commercial VAWTs available, investigate five commercial VAWTs in more depth, and provide a table of opportunities for improvement. Each of the five are described in separate sections, in which we provide necessary technological information and our considerations of where these designs have succeeded and where they are limited.

Study Methodology

To investigate the breadth of current commercial vertical axis wind turbine technology, we compiled a list of 33 VAWTs using “Commercial Small-Scale Horizontal and Vertical Wind Turbines: A Comprehensive Review of Geometry, Materials, Costs and Performance” [D1], as well as a list of the most commercially successful VAWTs from Perplexity, an Artificial Intelligence software. We did a broad investigation into the basic designs and parameters of each of these turbines. From these designs, we evaluated one design of each common type of vertical axis wind turbine (Darrieus: Helical or Eggbeater or H-type, Savonius: Helical or Classical). We decided which of the designs to evaluate based on how much documentation is given, how commercially successful the design appears to be, and how common the design is in the broader sphere of commercially available VAWTs. We studied 5 designs more in depth: The Quiet Revolution Qr6 (Fig. D1), The Wind Harvester 4.0 (Fig. D2), The Tulip (Fig. D4), The DS3000 (Fig. D5), and The UGE 4k (Fig. D8).

1. Quiet Revolution Qr6 Vertical Axis Wind Turbine

The Quiet Revolution 7.5kW Qr6 Vertical Axis Wind Turbine (Fig. D1) is a helical 3-bladed Darrieus-type turbine designed for urban environments. Manufactured by VWT Power Limited in the UK, the Qr6 has a cut-in speed of 3m/s, a high wind cut-out speed around 20m/s, and a low wind cut-out speed of 2.0m/s [D2].



Fig. D1. Quiet Revolution Qr6 Vertical Axis Wind Turbine static (left) and in motion (right). adapted from [D2].

The turbine measures 5.5m in height and 3.1m in diameter, giving it a swept area of about 16m², and weighs roughly 1,650kg including its mast and base [D3]. It can be roof-mounted on a 6m tilt-down mast or ground-mounted on 15m or 18m masts, making it adaptable for urban or rural settings [D4]. The mast itself is modular, making installation and maintenance simpler and less expensive by allowing the turbine to be tilted down or partially disassembled [D4]. The Qr6 uses aero-elastic carbon-fiber composite blades which serve to absorb vibration [D3]. The Qr6 has an operating temperature range of -30°C to 55°C, sells for around \$44,684 USD, and has an expected design life of 30+ years [D4].

Key features of the Qr6 provide useful insights for a future VAWT design. The helical blades could be explored to optimize torque smoothness and improve energy capture, the aero-elastic composite blades merit further study to assess how certain materials can reduce vibration and mitigate structural stress, and the modular mast warrants consideration for simplifying installation and maintenance while lowering costs. Additionally, the inclusion of a programmable controller highlights the potential benefits of active control and automated protection for safe and efficient operation across variable wind conditions.

2. Wind Harvester 4.0

Another type of VAWT commonly seen in commercial technology is the H-type or straight bladed VAWT. An emerging company that produces H-type VAWTs is “Wind Harvest,” based in Sacramento, California [D5]. The company caters to wind farms, rather than urban designs. However, the design is a good demonstration of what is currently available and who these

designs target. One of their designs, the “Wind Harvester 4.0” (Fig. D2) is available for order now, to be delivered in 2026.



Fig. D2. Wind Harvester 4.0. [D5].

The Wind Harvester 4.0 is made of galvanized steel and aluminum for the base and blade extruded aircraft aluminum for the blades. The turbine has a 13m rotor diameter, three 13m blades, and a total minimum height of 17.5m (Fig. D2). It requires maintenance and part replacement every 15-20 years. The ideal power generated from the smallest size of Wind Harvester is 70kW. The rated speed is 11m/s, the cut-in speed is 5m/s, the cut-out speed is 25m/s, and the survival wind speed is 60m/s. At 6m/s, around the average wind speed in urban environments, provides a capacity factor of 29.5%, this would provide 181 MWh/year/turbine [D5].

A model of the rated (maximum) power based on wind speed for the current model, the former model, and the current model when coupled with other wind turbines (Fig. D3) provides further insight into the Electric Power the Wind Harvester 4.0 is capable of producing. A feature of many VAWTs often highlighted in commercial applications is the Coupled Vortex Effect, where lining multiple VAWTs in close proximity creates a synergistic effect by increasing the wind speed through all the VAWTs rotors due to how their vortices (air patterns that form around the rotating blades) interact with each other [D6].

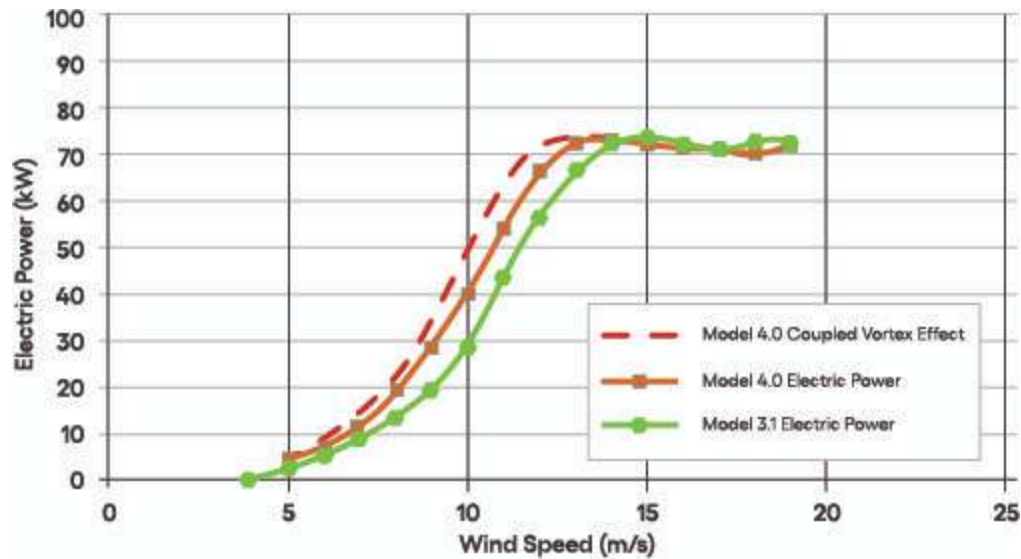


Fig. D3. Wind speed and electric power relationship for Wind Harvester [D5].

The most important insights provided by The Wind Harvester are in its patented support features, which could be explored for other VAWT designs more applicable to rooftops [D7]. First, the hinge blade connections, located between the mast and the arms, ensure this connection is flexible and not rigid. This decreases the likelihood of fractures at the mast-arm connection. The hexagonal center axis allows for easier attachment of wind turbine components to the mast. A cylindrical central mast does not allow for connections to be made as easily by an operator or maintenance personnel on the turbine. Another insight, noted above, is the Coupled Vortex Effect which can be leveraged by using multiple turbines in tandem. The major drawback of this particular commercial VAWT is that it is not directly applicable to rooftops. Decreasing the size and diameter of the rotor could be worth exploring to improve its effectiveness and feasibility in this project.

3. Tulip Vertical Axis Wind Turbine

The Flower Turbines 500W Medium Tulip Vertical Axis Wind Turbine (Fig. D4) is a compact, Savonius-type turbine designed for residential and small-scale commercial applications [D8].



Fig. D4. Tulip Vertical Axis Wind Turbine side view (left) and top view (right) adapted from [D8].

The Tulip has a cut-in speed of 0.7m/s, a max survival speed of 54m/s, and the cut-out speed is regulated by an electrical brake system [9]. It is approximately 3m tall with two 2m x 1.18m thermoplastic blades. The turbine converts mechanical energy to electricity through a permanent magnet generator connected to a battery and inverter system, supporting both off-grid and on-grid configurations. Its lightweight design of 227.25kg and modular pole system, which can tilt down for maintenance, make it adaptable to a variety of installation sites, including rooftops that can safely support its weight and ground-based concrete foundations. The Tulip has an operating temperature range of -15°C to 50°C, sells for around \$9,349.26 USD, and has an expected design life of 40 years with yearly maintenance [D9].

Several features of the Flower Turbine provide insights for a future VAWT design. Related to the compact “tulip” shape of the VAWT, its “Bouquet Effect” enhances the performance of neighboring turbines, with closely positioned units producing more total energy than the same turbines separated, suggesting that turbine interactions could be leveraged to improve array efficiency [D8]. This also highlights the factor of how a turbine’s design can influence airflow patterns, which may be important when considering placement on rooftops and constrained environments. The modular pole system merits consideration for simplifying installation and maintenance, similar to the Qr6’s mast design. The use of thermoplastic blades warrants further study, as the material is uncommon for VAWTs and may offer advantages in performance, flexibility, or durability.

4. DS3000W

The DS3000W (Fig. D5) is a hybrid wind turbine with a rated power at 3kW, it consists of an outer “Egg-Beater” or H-type Darrieus and an inner 2-layered Classical Savonius.



Fig. D5. DS3000W model adapted from [D10].

The Darrieus has 3 blades and each Savonius has 2 blades. The DS3000W is made by Etneo Italia srl, located in Novara, Italy. The applications this model is marketed towards are single-family homes, wind farms, parking lots, and radio towers. The start-up speed for this model is 2.0m/s, the cut-in speed is 2.2m/s, the cut-out speed is 14.0m/s, and the survival wind speed is 60m/s. The DS3000W is made of anodized aluminum, has a rotor diameter of 4m, Darrieus blade length of 4.16m, and a tower height of 4m, not including the turbine itself. It has operating temperatures between 20 and 40°C. This turbine costs 17,500 Euros, which is around \$20,500 [D11, D10].

The company additionally provides expected annual power production. They indicate a yearly energy output ranging from 2,851 kWh at 5m/s to 8,945 kWh at 8m/s. The rated power of 3kW occurs at 12m/s, though while mounted on a rooftop in an urban area, it would generally be

operating at lower wind speeds around the 5m/s range. Fig. D6 shows an efficiency curve, demonstrating the efficiency of the wind turbine at different wind speeds (Fig. D6) [D11, D10].

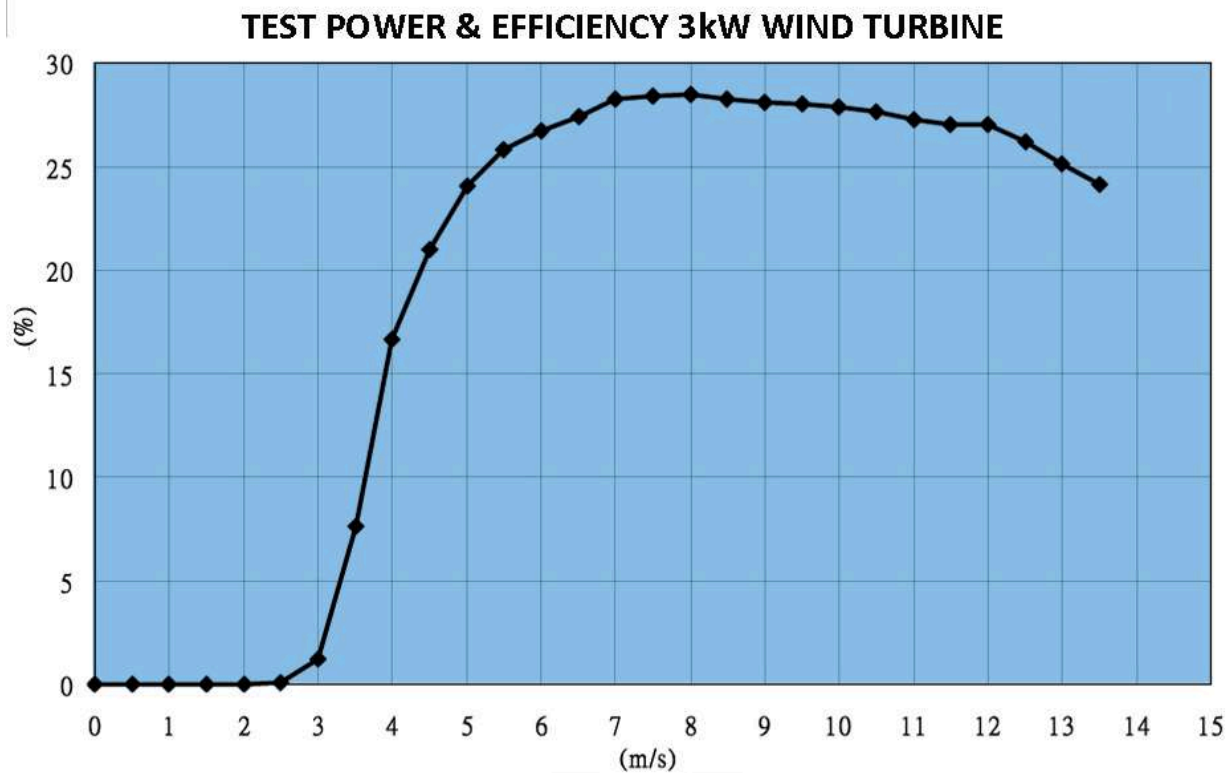


Fig. D6. Efficiency curve for DS3000W [D10].

The hybrid design of the DS3000 provides it with the capability to capture low wind speeds via the Savonius element, and higher wind speeds via the Darrieus element [D10]. The Savonius segment has blades facing in all four cardinal directions to capture wind from all those directions (Fig. D7). The design additionally boasts strong connections for the Darrieus blades via connecting brackets.

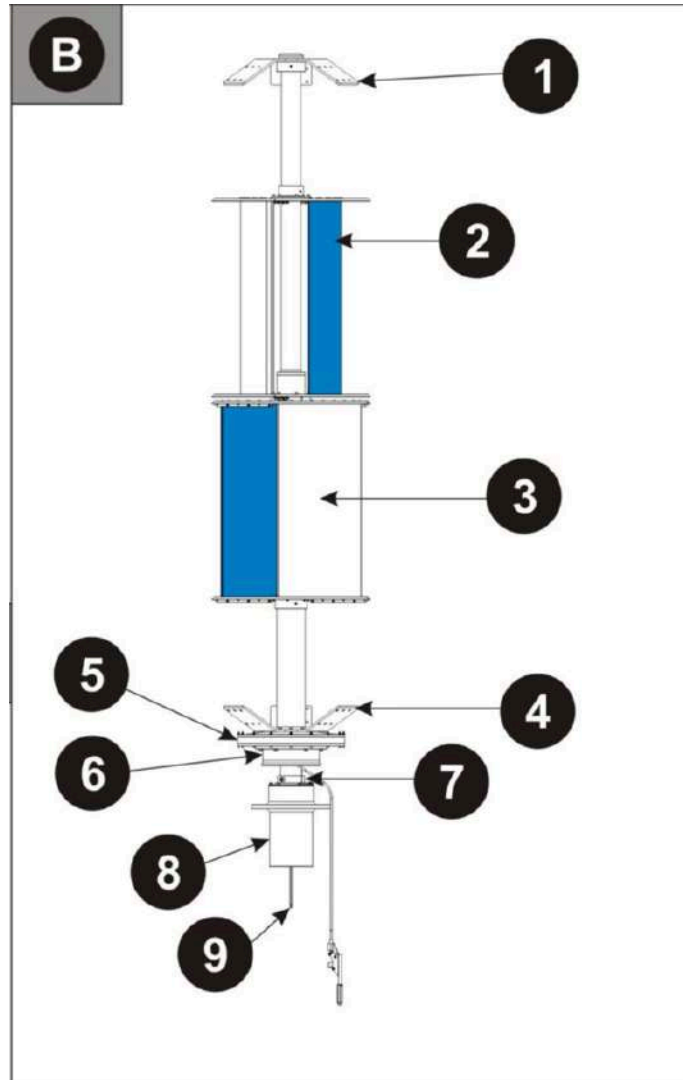


Fig. D7. Notes 1 and 4 indicate where the Darrieus blades connect into the center pole. Notes 2 and 3 illustrate the directions the Savonius blades face [D10].

We chose the DS3000 for in depth investigation because it is ICC (International Code Council) certified and boasts of being commercially available, with installations all over the world [D12]. It was the first vertical axis wind turbine to be ICC certified in the US in 2019. An additional reason we investigated this design is that hybrids, which combine Savonius and Darrieus in one turbine, are one of the more promising options in small wind power [D13]. There are many different hybrid models using different sizes and types of each design, this is one successful example representing a wide range of hybrids.

The major insights gained from the investigation of the DS3000 is in its hybrid nature. The Savonius aspect allows it to capture wind at low speeds, while the Darrieus aspect increases the power generation capabilities of the turbine at higher wind speeds [D10]. The use of a

multi-stage (or multi-layered) Savonius is innovative in a hybrid and could be something worth exploring as we move further into the project. One potential drawback of hybrids that is worth exploring is whether the outer Darrieus damages the ability of the inner Savonius to capture wind and maximize energy generation at low wind speeds, since this is the range at which our turbine will be operating.

5. Urban Green Energy 4K

The UGE-4K Vertical Axis Wind Turbine (Fig. D8) is a helical-bladed Darrieus-type model developed by Urban Green Energy (UGE) for distributed and urban wind generation.



Fig. D8. Urban Green Energy 4K Vertical Axis Wind Turbine adapted from [D14].

The turbine is no longer in production following the sale and rebranding of UGE's wind division as V-Air Wind [D15]. It stands approximately 4.6m tall with a 3.1m rotor diameter, giving a swept area of about 14.1m², and weighs roughly 461kg [D16]. The UGE-4K's cut-in wind speed is 3.5m/s, rated wind speed is 12m/s, cut-out is 25m/s, and survival speed is 60m/s, with an operating temperature range of -20°C to 50°C [D16]. The turbine features a permanent magnet direct-drive generator and a patented Dual-Axis Technology (DAT) system, which distributes loads more evenly across the rotor and tower, suggesting that exploring similar load management approaches could improve structural stability and longevity in a future VAWT design [D14].

Opportunities for Optimization

There are several areas where current VAWT technology presents opportunities for further improvement. These opportunities focus on enhancing performance, reliability, cost-effectiveness, and suitability for operation in urban environments. Table D1 identifies key areas for optimization based on known limitations of existing VAWT designs and our stakeholder needs, and provides a brief rationale for each. These optimization opportunities will help inform design decisions and highlight areas where targeted improvements could significantly increase the overall value and feasibility of the proposed VAWT.

Table D1
Rationale of opportunities for optimization

Opportunity for Optimization	Rationale
Reduce cut in speed	Darrieus VAWTs currently face a big challenge when it comes to low starting torque due to high cut in speeds therefore an opportunity for optimization can be to reduce that cut in speed [D17].
Increase efficiency (in turbulent conditions)	Savonius VAWTs currently have low efficiency in turbulent conditions so an area for optimization is to increase the power output in an urban (turbulent) environment [D18]. The efficiency of Darrieus turbines could also be improved.
Reduce noise/vibration	While VAWTs produce lower noise/vibration than HAWTs [D19], our VAWT may still face challenges when being integrated into the Smith campus as the noise requirements of students may differ from other areas that VAWTs have been integrated into, therefore we want to minimize this parameter as much as possible.
Reduce upfront cost	VAWTs are currently very expensive [D20] and therefore inaccessible. An area for optimization is reducing their upfront cost so that they can reach a broader market.
Durability (fatigue failure)	Current VAWT technology also has some drawbacks in the quality of products produced. The majority of commercial VAWTs are found on un reputable sites like AliExpress, so the quality of product produced has room to grow [D21]. Our designed VAWT should be able to structurally withstand different weather conditions including severe and turbulent weather throughout its life. In other words, it is necessary to minimize the risk of fatigue failure.
Stalling in high wind speeds	Savonius VAWTs tend to stall in high wind speeds due to dynamic stall [D22], so an opportunity for optimization could be to minimize the frequency of stalling in high winds.
Reduce maintenance frequency	Maintenance frequency can be reduced by optimizing the structural integrity and safety of the turbine, with a focus on preventing failures resulting from initial design and manufacturing choices.

Additional Considerations

When installing VAWTs in urban environments, several site-specific factors must be considered to ensure efficient performance and structural feasibility. Prior studies suggest that an average wind speed of approximately 5.5 m/s is desirable for efficient turbine operation, however, this value should be treated as a guideline rather than a strict requirement [D23]. Urban wind conditions vary significantly and may still support viable energy generation below this threshold depending on our turbine design and placement.

To reduce turbulence and improve energy capture, the turbine hub is often recommended to be positioned above surrounding structures, with some studies suggesting heights on the order of 30% above the rooftop and above the turbulent boundary layer [D23]. In practice, these recommendations must be balanced against campus-specific constraints, including architectural integration and maximum allowable structure height, as outlined in the design requirements. High-rise buildings are generally more suitable sites, as they experience stronger and steadier wind flows, while positioning VAWTs near roof edges can take advantage of upward-inclined wind patterns where the turbulent layer is thinner [D23]. Smaller-scale turbines also tend to perform better on towers than on low-rise rooftops, where wind speed amplification is typically lower [D23]. In addition to aerodynamic considerations, practical factors such as building load capacity, vibration transmission, maintenance accessibility, and potential noise or visual impacts must also be evaluated prior to installation.

Conclusion

Through this review of existing commercial VAWT designs, we identified several trends and opportunities for improvement. The next steps include further investigation of patents related to promising design features such as aero-elastic composite blades for vibration reduction, hybrid configurations for broader wind-speed performance, and load-distribution systems like UGE's Dual-Axis Technology (DAT) for enhanced structural stability. Modular mast or pole systems that simplify installation and maintenance are also worth exploring.

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Appendix E: Concept Generation Memo

This appendix is a memo that compiles and organizes a wide range of VAWT concepts into comparative tables categorized by the three primary VAWT configurations: Darrieus, Savonius, and hybrid designs. These tables serve as a reference for understanding the breadth of existing and potential design approaches and provide the foundation for subsequent evaluation and concept selection.

Appendix E: Concept Generation Memo

To: Susannah Howe and HRI Liaisons

From: VAWT Ventures

Date: November 5, 2025

Subject: Concepts from commercial technologies, research studies, patents, and emergent ideas from VAWT Ventures

Introduction

This memo supports our team's design effort to address the following problem statement: How might we design a vertical axis wind turbine to increase energy independence in urban areas, reduce strain on the electrical grid, and decrease dependency on fossil fuels? In response to this challenge, the purpose of this memo is to define the design space by presenting a structured overview of vertical-axis wind turbine (VAWT) concepts from which a final concept will be selected and further developed.

The memo compiles and organizes a wide range of VAWT concepts into comparative tables categorized by the three primary VAWT configurations: Darrieus, Savonius, and hybrid designs. These tables serve as a reference for understanding the breadth of existing and potential design approaches and provide the foundation for subsequent evaluation and concept selection.

Concept Generation Methodology

To address the design problem, we prioritized broad exploration of existing VAWT technologies. The concept generation phase focused on the collection of as many relevant VAWT concepts as possible from a wide range of sources in order to capture diverse design approaches and configurations. Sources included commercial products, academic research studies, patents, informal design concepts, and original ideas generated by team members through independent and collaborative ideation.

Rather than filtering concepts early, the team intentionally emphasized quantity and variety to avoid prematurely limiting our options. All identified concepts were documented and organized based on their configuration, allowing for structured comparison across different aerodynamic and mechanical approaches. Once organized, the concepts were then assessed based on their maturity and readiness for further analysis, enabling the team to identify which concepts could be evaluated immediately and which would require additional development. This assessment process is described in the following section.

Level of Development Methodology

As we sorted the concepts into their respective tables, we assigned each one a numerical value representing its level of development. Concepts that were marked with a 1 or 2 require more research and testing, which may include CAD modeling and simulation, before the team can evaluate, while concepts given a 3 are ones that we can immediately proceed with in evaluation. The scale is further provided below:

- 3 - ready to evaluate now
- 2 - minimal development
- 1 - needs significant development

Darrieus

Darrieus VAWTs are lift-based turbines that use airfoil-shaped blades to generate torque as wind flows across their surfaces. They can be subcategorized as D-type (eggbeater) as shown in Fig. E1, H-type, or Helical. While Darrieus VAWTs tend to be more efficient than drag-based VAWTs, they are unable to self-start and experience high fluctuating torque during rotation. Table E1 contains VAWT concepts sourced from research papers, patents, and commercial technologies meant to address issues specifically related to Darrieus VAWTs.

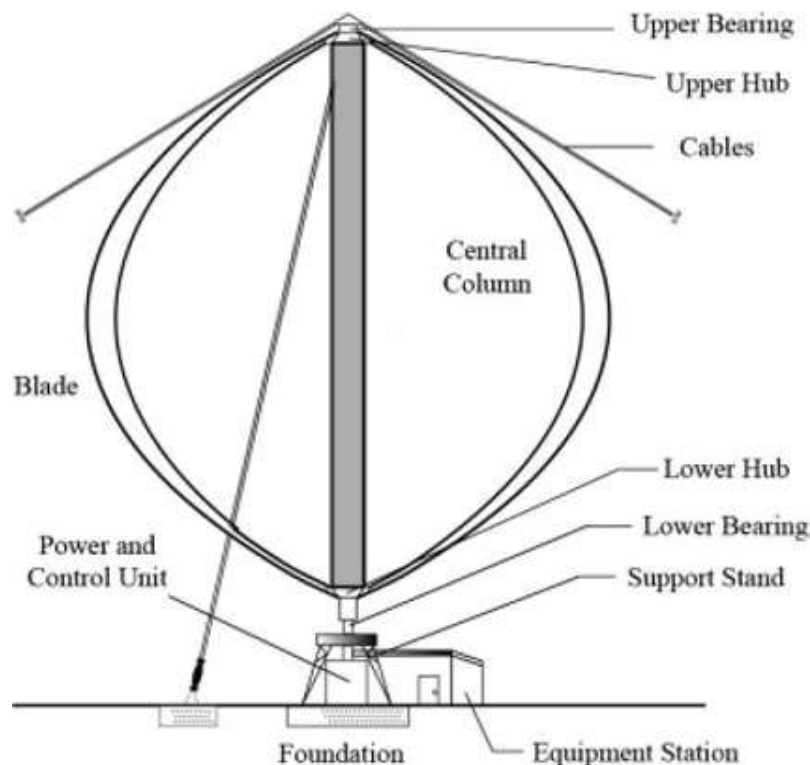
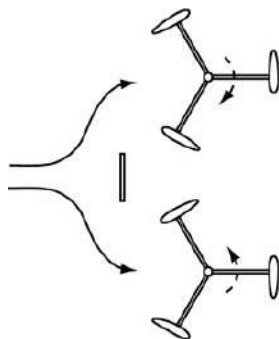
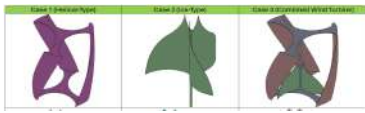
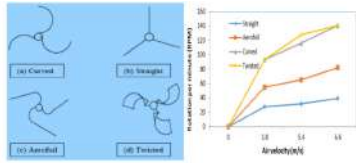
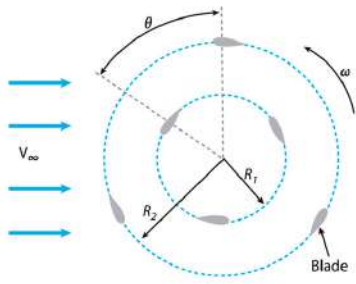


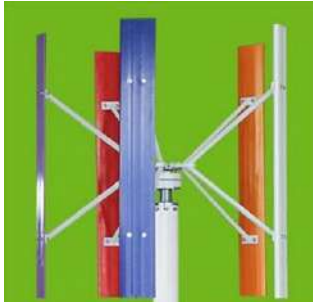
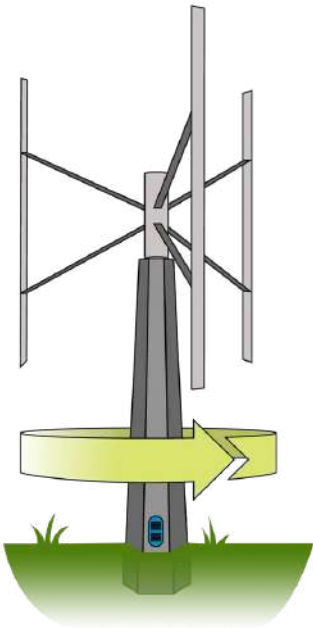
Fig. E1. Diagram of a D-type Darrieus [E1].

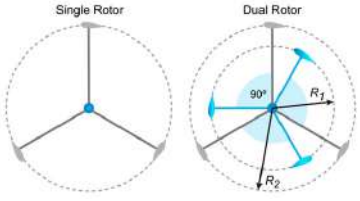
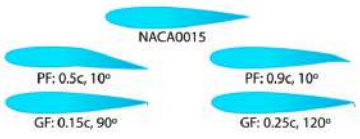
Table E1
Darrieus VAWT concepts

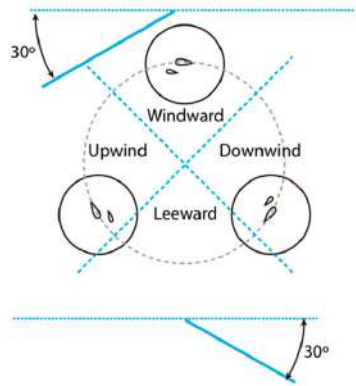
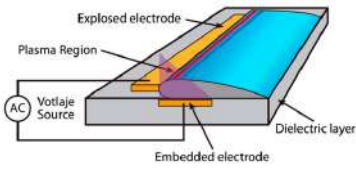
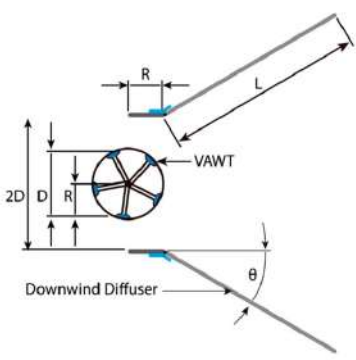
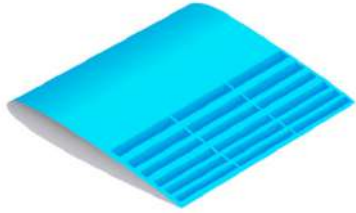
Concept	Description	Level of Development (1-3)	Image	Reference number
D1	Adding a dimple to the airfoil profile of a Darrieus turbine	1		[E2]
D2	Intelligent blade pitch control for Darrieus - improved power output by 25% compared to a fixed pitch angle	1		[E2]
D3	Darrieus with auxiliary internal blades with fixed chord ratio, better for low wind speed	1		[E2]
D4	NACA0018 airfoil shape for Darrieus	1		[E2]
D5	S-1046 non-symmetric airfoil for Darrieus	1		[E2]
D6	Wind-gathering device (WGD)	1		[E2]
D7	Adding a deflector to redirect airflow (effectiveness depends on deflector position)	2		[E2][E3]
D8	Addition of small Savonius rotor(s) for startup assistance	2		[E1][E4]
D9	Curved airfoil blades arranged vertically on a rotary framework	1		[E1]
D10	Channel beam reinforcement	1		[E5]
D11	Lateral restraint supports	1		[E5]
D12	Variable-pitch blade configuration for straight-bladed	1		[E6]

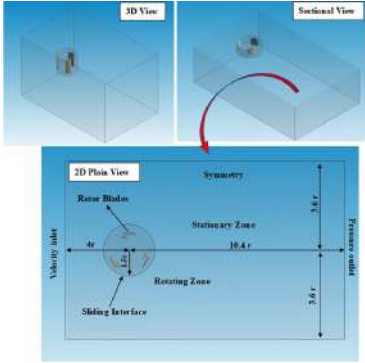
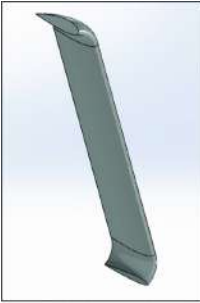
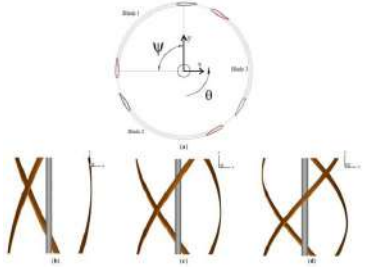
Concept	Description	Level of Development (1-3)	Image	Reference number
	VAWTs			
D13	Winglet addition at blade tip	1		[E6]
D14	Helical Darrieus	3		[E7]
D15	4 types of helical darrieus blades (comparison)	2	 Fig. 6. A schematic view of curved blade designs and variation of TSR in blade design with wind speed [10].	[E8]
D16	3-blade helical darrieus	3		[E9]
D17	Doubling the number of blades used (3 blades to 6 blades)	2		[E10][E11]

Concept	Description	Level of Development (1-3)	Image	Reference number
D18	Using a horizontal Savonius profile combined with a vertical Darrieus one	2		[E10]
D19	Anodizing the blades	2		[E12]
D20	Zinc plating the blades	2		[E12]
D21	Using C%+M paint coating for the blades	2		[E12]
D22	Electro-magnetic brakes	2		[E12]
D23	Eliminating friction from disk generator	3		[E13]

Concept	Description	Level of Development (1-3)	Image	Reference number
D24	Quiet Revolution Qr 6	3		[E14]
D25	Wind Harvester Model 4.0	3		[E15]
D26	Eastern Wind Power's Sky Farm™ 50 kW Vertical Axis Wind Turbine	3		[E16]
D27	Using cambered airfoils instead	1		[E11]

Concept	Description	Level of Development (1-3)	Image	Reference number
	of symmetric ones			
D28	J-type airfoil profiles	2		[E11]
D29	Hybrid blade sections	2		[E11]
D30	Adjusting solidity	2		[E11]
D31	Optimizing number of blades	2		[E11]
D32	Variable or dual-radius blades	2		[E11]
D33	Dual-row or hybrid rotor configurations			[E11]
D34	Variable geometry rotors			[E11]
D35	Passive devices (Gurney flaps, edge modifications, vortex generators)	2		[E11]
D36	Surface texturing of blades	2		[E11]

Concept	Description	Level of Development (1-3)	Image	Reference number
D37	Guide vanes or deflectors	2	 The diagram illustrates the use of guide vanes or deflectors in a flow field. It shows two sets of vanes, one at the top and one at the bottom, both angled at 30 degrees relative to the horizontal flow direction. The flow is depicted as a series of dashed lines curving around the vanes. Labels include 'Windward', 'Upwind', 'Downwind', and 'Leeward' to indicate the flow direction and regions.	[E11]
D38	Active pitch control or adaptive blade geometry	2		[E11]
D39	Active boundary-layer control (synthetic jets, plasma actuators)	2	 The diagram shows a cross-section of a surface with a plasma actuator. An 'Exposed electrode' is on the surface, connected to an 'AC Voltage Source'. Below it is an 'Embedded electrode'. The region between them is labeled 'Plasma Region'. A 'Dielectric layer' is shown on the bottom surface.	[E11]
D40	Dynamic rotor geometry adjustment	2		[E11]
D41	Diffusers, shrouds, or concentrators around rotor	2	 The diagram shows a vertical axis wind turbine (VAWT) with a circular rotor. It is surrounded by a 'Downwind Diffuser' and a 'Shroud'. The diffuser is angled at θ. Dimensions are labeled: R for the rotor radius, L for the shroud length, D for the diffuser diameter, and $2D$ for the total height. The rotor is labeled 'VAWT'.	[E11]
D42	Flow-guiding structures	2	 A 3D rendering of a flow-guiding structure, showing a series of parallel, slightly curved blades or vanes arranged in a row.	[E11]

Concept	Description	Level of Development (1-3)	Image	Reference number
D43	Incorporation of auxiliary airfoils with varying aspect ratios onto the H-type Darrieus rotor	3		[E17]
D44	Variation of rotor aspect ratio (AR) for different auxiliary configurations	3		[E17]
D45	Integration of deflectors on airfoil blades	2		[E18]
D46	Airfoil geometry modification (thickness increase)	2		[E18]
D47	60 degree angle/angle optimization for helical turbine blades	2		[E19]

Concept	Description	Level of Development (1-3)	Image	Reference number
D48	Carbon fiber blades for a helical darrieus	3		[E20]

Savonius

Savonius VAWTs are drag-based turbines that typically consist of two curved blades, one convex and one concave as shown in Fig. E2. The working concept for Savonius VAWTs is a difference in drag between the convex and concave blades which causes the turbine to rotate. Savonius VAWTs face challenges related to low power generation and efficiency because certain portions of the rotation produce negative torque. A wide range of these concepts aim to address this challenge, found in research papers and commercial technology, are listed in Table E2. These primarily include changes to blade design and external augmentation to direct windflow, with the goal of improving turbine efficiency, increasing net power output, and reducing the negative torque experienced during rotation.

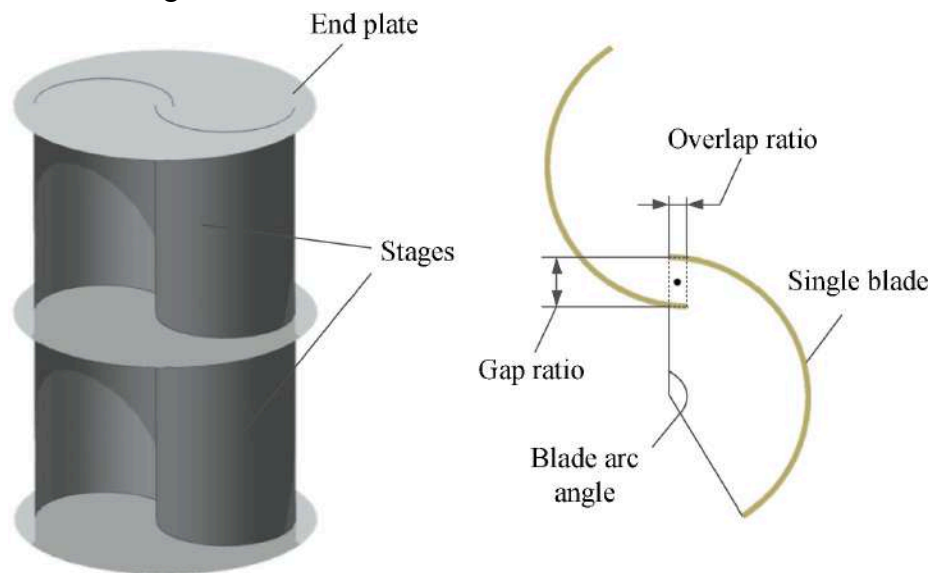
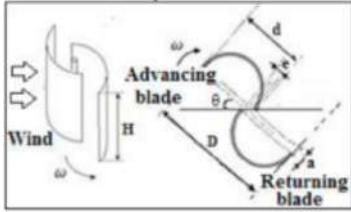
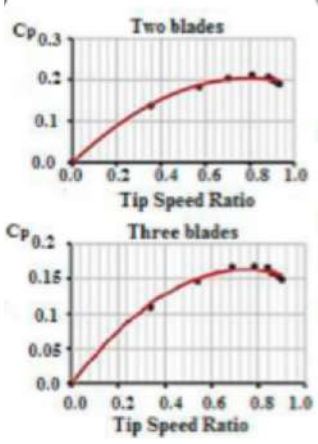
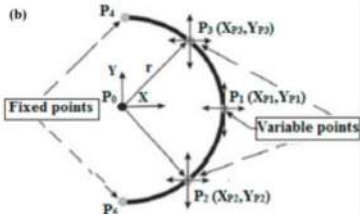
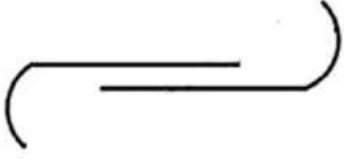
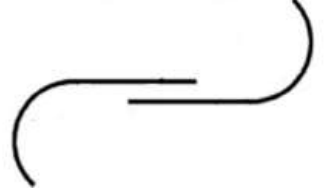
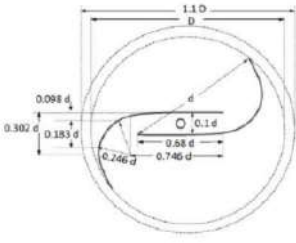


Fig. E2. Parameters optimized in classical Savonius for various studies [E28].

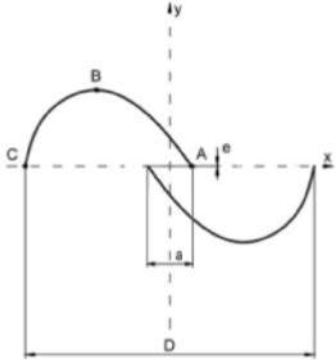
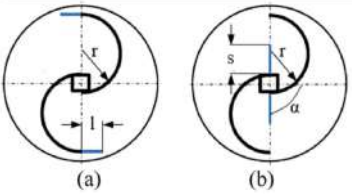
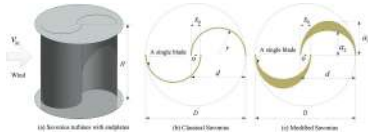
Table E2
Savonius VAWT concepts

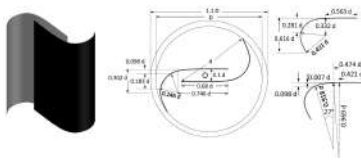
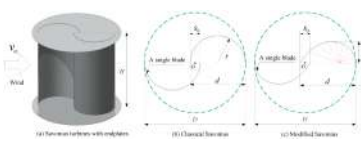
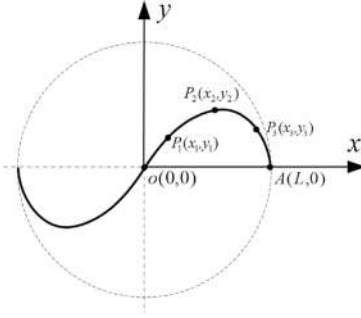
Concept	Description	Level of Development (1-3)	Image	Reference number
S1	Optimization of diameter, thickness, and attachment angle of semi-circle blade.	3		[E2]
S2	Optimization of Aspect Ratio, getting larger increases the power coefficient, but decreases the structural stability.	2		[E8]
S3	2-bladed classical Savonius shows higher power coefficient compared to 3-bladed of the same blade design.	2		[E8]
S4	Overlap ratio optimization within 0.1 and 0.3.	3		[E8]

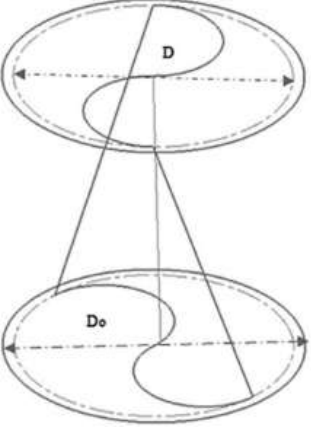
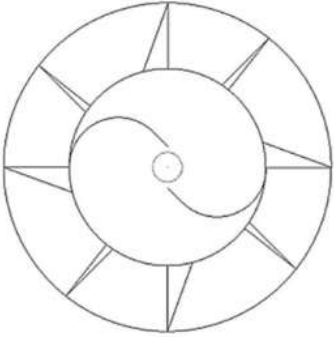
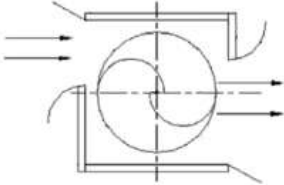
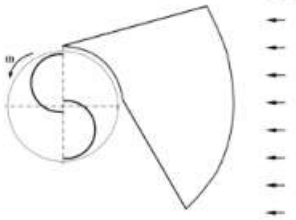
Concept	Description	Level of Development (1-3)	Image	Reference number
S5	Obstacle shielding with diagonal plate	3	(a)	[E8]
S6	Curtain shielding	3	(c)	[E8]
S7	Quarter blade shielding	3	(e)	[E8]
S8	Hinged Deflector	3	(f)	[E8]
S9	Elliptical blade shape	3	(g)	[E8]

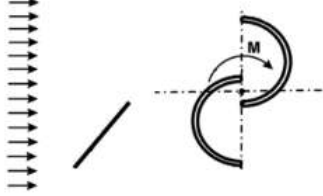
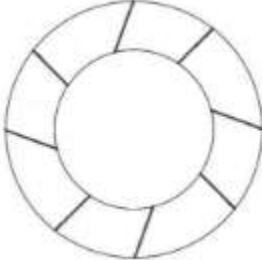
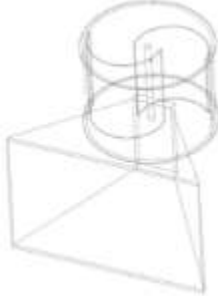
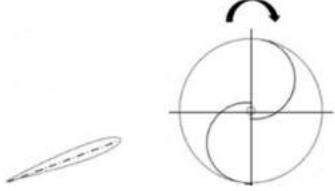
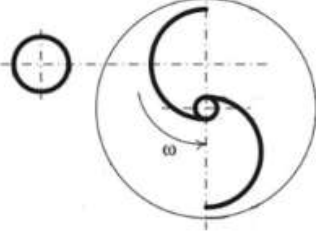
Concept	Description	Level of Development (1-3)	Image	Reference number
S10	Optimized positioning for obstacle shielding	3		[E8]
S11	Semicircular Savonius blade shape	2		[E21]
S12	Benesh Savonius Blade Shape	2		[E21]
S13	Elliptical Savonius Blade Shape	2		[E21]
S14	Modified Bach Savonius Blade Shape	2		[E21]
S15	Newly developed blade, flat internal segment with length between bach and benesh and more elliptical blade shape for blade edges	2		[E22]

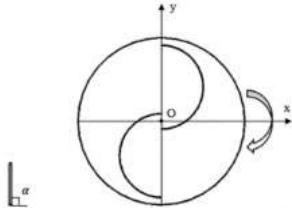
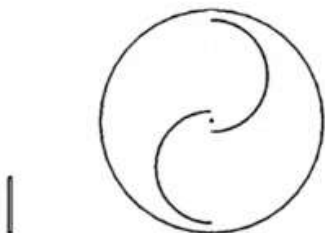
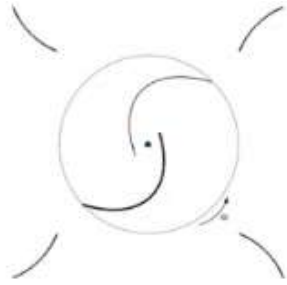
Concept	Description	Level of Development (1-3)	Image	Reference number
S16	Optimization of Twist Angle of Blade (45 degrees)	3	Upper blade line Lower blade line H (a) $\phi = 0^\circ$ (b) $\phi = 45^\circ$	[E21]
S17	Conveyor deflector curtain system	3		[E21][E23]
S18	Optimized Bach-type	2	Advancing blade Returning blade Bach turbine	[E24]
S19	Another Optimized Bach-type	3		[E25]

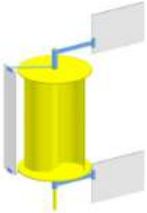
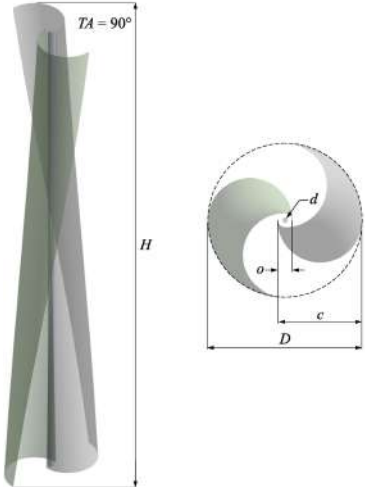
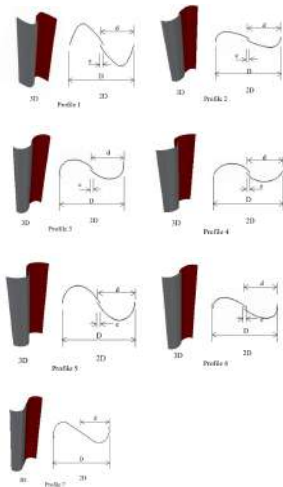
Concept	Description	Level of Development (1-3)	Image	Reference number
S20	Elliptical Blade Design	3		[E25]
S21	Optimized Blade Arc Angle, 160 degree angle generated the most power for 2- bladed classical Savonius	2		[E26]
S22	Vented elliptical blade	2		[E23]
S23	Non-vented elliptical blade	2		[E23]
S24	S-Shaped Optimum Blade Design	2		[E23]
S25	Twisted Modified Design	2		[E23]
S26	Helical Bach Design	2		[E23]
S27	Bezier Curved Blade	2		[E23]
S28	Three-Fourth Modified Blade	2		[E23]
S29	Multiple Quarter Blades	2		[E23]
S30	Additional Design: Increased blade length and addition of internal straight blades to optimized classical Savonius	2		[E27]
S31	Multiple Miniature Blades	2		[E23]
S32	Optimal Design: Thickened blades for 2-bladed classical Savonius	2		[E28]

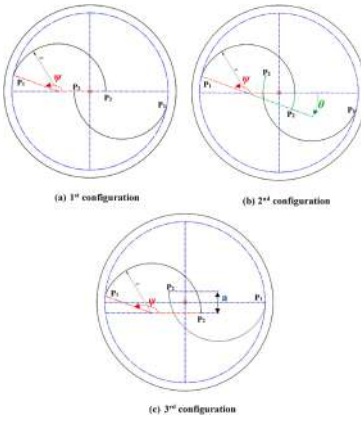
Concept	Description	Level of Development (1-3)	Image	Reference number
S33	Two-quarters conventional blade	2		[E23]
S34	Additional inner blade	2		[E23]
S35	Multi-blade geometry	2		[E23]
S36	Zigzag surface blade	2		[E23]
S37	Newly developed blade: Bach with extended internal flat blade and more obtuse blade ends.	2		[E29]
S38	Fullness of blade	2		[E23]
S39	New Blade design with moment arms	2		[E23]
S40	Optimal Design: Use of parametric curve to alter shape of classical savonius blade	2		[E30]
S41	Optimized Blade shape alteration based on genetic algorithm	2		[E31]
S42	Flexible-blade	2		[E23]
S43	Deformable blade	2		[E23]
S44	Novel delta-bladed	2		[E23]
S45	Airfoil-shaped blade	2		[E23]

Concept	Description	Level of Development (1-3)	Image	Reference number
S46	Circular End Plate	3		[E21]
S47	Guide Vanes	3		[E21]
S48	Miniature and quarter blades (co-centrally within rotor blades)	2		[E21]
S49	Guide Box Tunnel	3		[E23]
S50	Curtain Arrangement	3		[E23]

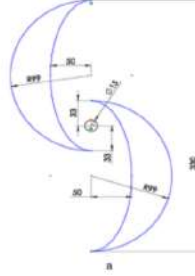
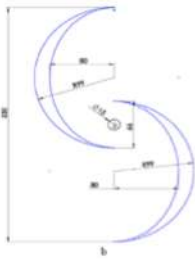
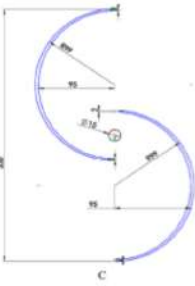
Concept	Description	Level of Development (1-3)	Image	Reference number
S51	Shielding Obstacle	3		[E23]
S52	Guide Blade Arrangement	3		[E23]
S53	Nozzle Design	3		[E23]
S54	Airfoil-shaped deflector	3		[E23]
S55	Circular cylinder	3		[E23]

Concept	Description	Level of Development (1-3)	Image	Reference number
S56	Porous deflector	3		[E23]
S57	Guide vane	3		[E23]
S58	Wind-lens	3		[E23]
S59	Wind-lens with a dual turbine	3		[E23]
S60	Nanofiber-based deflector	3		[E23]
S61	Deflector Blade	3		[E23]

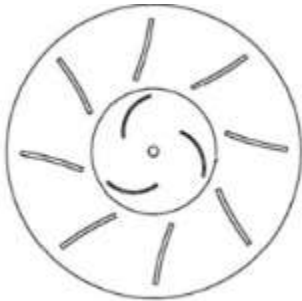
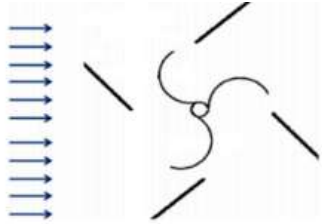
Concept	Description	Level of Development (1-3)	Image	Reference number
S62	Passive deflector	3		[E23]
S63	Ice Type	3		[E32]
S64	Inward and outward overlaps	2		[E33]
S65	A novel SWT design method	2		[E34]
S66	Aerodynamic performance Investigation: 7 different 2-bladed twin-rotor Savonius turbine blade designs suggested, tested, and compared	2		[E35]

Concept	Description	Level of Development (1-3)	Image	Reference number
S67	Twisted blade profile	2		[E33]
S68	V-shaped rotor	2		[E33]
S69	Blade arc: changing blade arc angle on classical Savonius to optimize power generation	2	 (a) 1st configuration (b) 2nd configuration (c) 3rd configuration	[E36]
S70	Tiered zig-zag shaped surface	2		[E33]
S71	Enhanced aerofoil shaped blade	2		[E33]
S72	Modified batch Savonius	2		[E33]
S73	Optimized blade plane	2		[E33]
S74	Modified blade	2		[E33]
S75	elliptical-semi circle design	2		[E33]
S76	Redesigned blade profile	2		[E33]
S77	Scooplet-based design	2		[E33]
S78	triangular plate blocked the air	2		[E33]
S79	a rotating cylinder for vortical shedding	2		[E33]
S80	wake-controlling splinters	2		[E33]
S81	a structured surface roughness approach to managing the wake on the deflector	2		[E33]
S82	Single-, two- and three-stage (max. two-stage) Semicircular and twisted blade (max. twisted blade) Two and three bladed	2		[E37]

Concept	Description	Level of Development (1-3)	Image	Reference number
	(max. two-bladed)			
S83	Elliptical-bladed multistage (one, two, three-stage) (max. two-stage)	2		[E37]
S84	Multi-stage turbines with twisted blades (a) single-stage, (b) two-stage, (c) three-stage, (d) four-stage (max. four-stage)	2		[E37]
S85	2 blade simple rotor, semicircular	2		[E22]
S86	2 blade simple rotor, twisted (12.5)	2		[E22]
S87	3 blade simple rotor, semicircular	2		[E22]
S88	3 blade simple rotor, twisted (12.5)	2		[E22]
S89	2 blade double rotor, semicircular	2		[E22]
S90	2 blade double rotor, twisted	2		[E22]
S91	3 blade double rotor, semicircular	2		[E22]
S92	3 blade double rotor, twisted	2		[E22]
S93	2 blade triple rotor, semicircular	2		[E22]
S94	2 blade triple rotor, twisted	2		[E22]
S95	3 blade triple rotor, semicircular	2		[E22]
S96	3 blade triple rotor, twisted	2		[E22]
S97	ice wind rotor (3 & 4 blades)	2		[E22]
S98	deformable blade	2		[E22]

Concept	Description	Level of Development (1-3)	Image	Reference number
S99	Savonius 2-blade classical thickness (highest)	3		[E38]
S100	Savonius 2-blade classical blade thickness (med)	3		[E38]
S101	Savonius 2-blade classical blade thickness (low)	3		[E38]
S102	Persian original VAWT	3		[E9]
S103	2 blade helical Savonius	3		[E9]
S104	2 layered classical Savonius	3		[E9]
S105	ODGV Turbine	3		[E9]
S106	diffuser system that stabilizes turbulent airflow.	3		[E39]
S107	remote wifi-monitoring system	3		[E39]
S108	waterproof enclosure for the electronics	3		[E39]

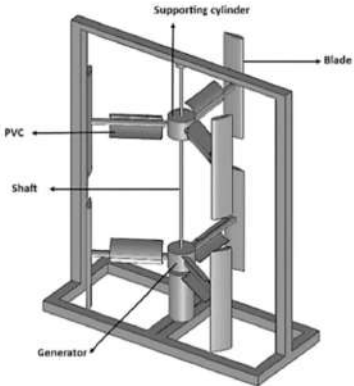
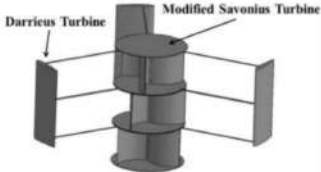
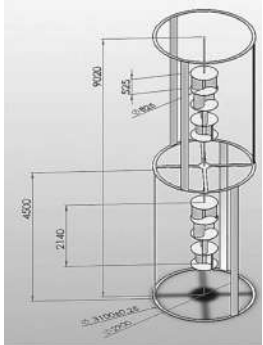
Concept	Description	Level of Development (1-3)	Image	Reference number
S109	Curved "tulip" type blade design	3		[E40]
S110	aircraft wing design	3		[E40]
S111	coreless generator	3		[E40]
S112	smaller rotor radius	3		[E40]
S113	FLTXNY 1000W Vertical Wind Turbine Permanent Magnet Generator 3 Phase 12V 24V Vertical Axis Coreless Wind Generator	3		[E41]
S114	FT 2M-Lite Turbine : 2 Bladed Vertical Axis Wind Turbine	3		[E42]
S115	Using High efficiency permanent magnetic generators	3		[E42]
S116	using fiberglass for the blades	3		[E42]
S117	using multiple VAWTs in tandem	3		[E42]

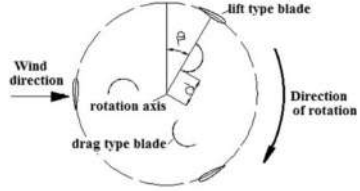
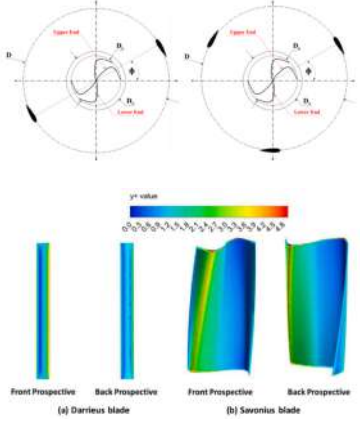
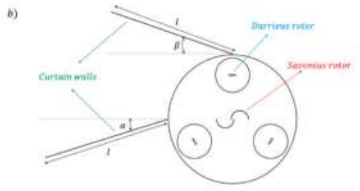
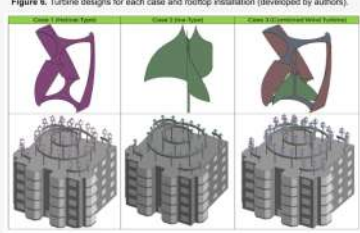
Concept	Description	Level of Development (1-3)	Image	Reference number
S118	Helix Wind Corp S594 wind turbine	3		[E43]
S119	single stage helical bach	3		[E44]
S120	add valve to rotor	3		[E22]
S121	tower cowling	3		[E23]
S122	rotor house	3		[E23]

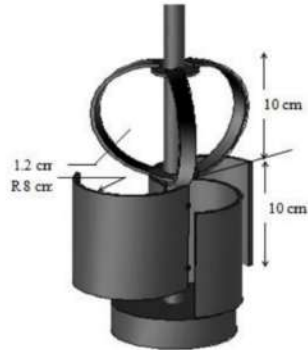
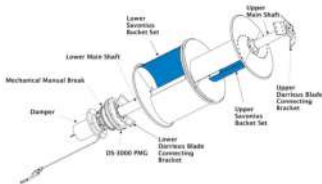
Hybrid

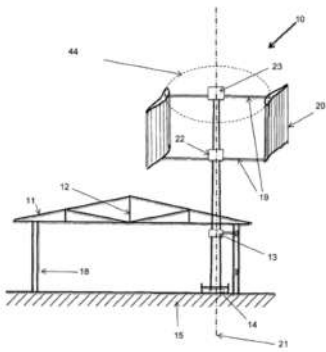
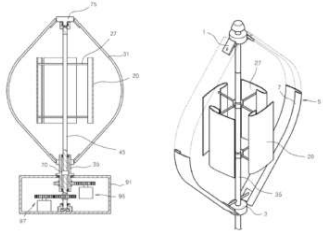
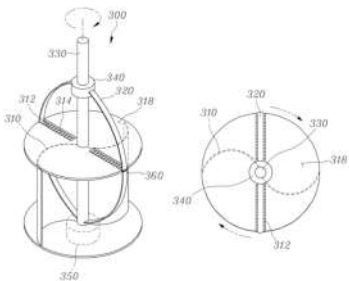
Hybrid VAWTs combine aspects of Darrieus and Savonius turbines. They often include one or more Savonius rotors within a larger Darrieus rotor. Table E3 lists hybrid VAWT concepts. It includes both single stage and multi-stage designs with varying types of Darrieus and Savonius rotors. In addition, some concepts combine multiple Savonius or Darrieus rotors into a single turbine.

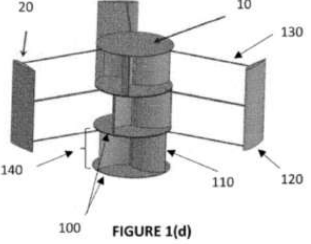
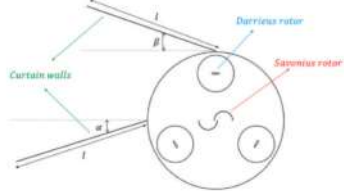
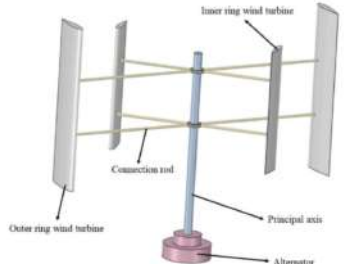
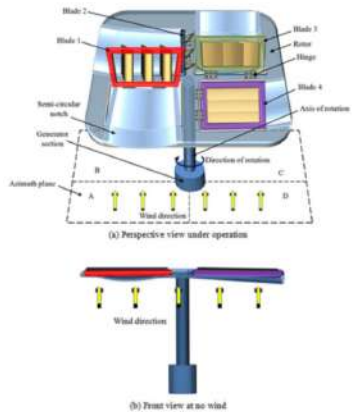
Table E3
Hybrid VAWT concepts

Concept	Description	Level of Development (1-3)	Image	Reference number
H1	Hybrid with three internal Savonius blades and three external Darrieus blades There are two stacked rotors spinning along the same axis, but in opposite directions	2		[E45]
H2	Hybrid with three modified internal Savonius blades and three external Darrieus blades	2		[E46]
H3	Two tiers - each with four two blade bach Savonius turbines and one three blade H-rotor Darrieus	2		[E47]
H4	Electro-magnetic switch mechanism for dis-/engagement mechanism to run Darrieus and Savonius together or separately	1		[E48]

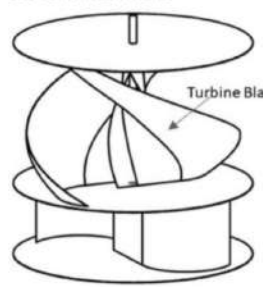
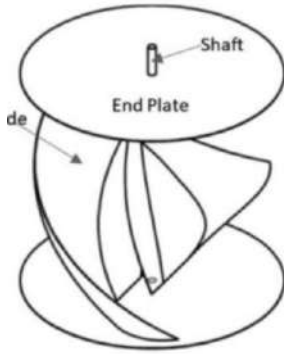
Concept	Description	Level of Development (1-3)	Image	Reference number
H5	Combined 3 blade Savonius-type Bach turbine and a 3-bladed H-Darrieus turbine	3		[E48]
H6	Hybrid wind rotor has twisted Savonius blades with a modified blade profile combined with 2 or 3 Darrieus blades	2		[E49]
H7	Two blade Savonius, three blade darrieus hybrid with curtain	2		[E4]
H8	Combined helical + IceWind	1		[E32]

Concept	Description	Level of Development (1-3)	Image	Reference number
H9	Hybrid 3 blade Eggbeater + 3 blade classical Savonius Darrieus stacked above Savonius	2		[E50]
H10	Two stacked two-blade Savonius within a 3-blade eggbeater Darrieus	3		[E51][E52]
H11	Stacked Savonius of different sizes within a Darrieus	2		[E52]
H12	Using ASTM A283 grade D steel for the VAWT axis pole	3		[E52]
H13	Adding a damper	3		[E52]

Concept	Description	Level of Development (1-3)	Image	Reference number
H14	Stacked DS-3000W VAWT, 3 blade darrieus, 2 blade Savonius	3		[E53]
H15	Darrieus with two horizontal channel beams with compartments that support each blade. The channels act similarly to Savonius type VAWT generate torque	1		[E54]
H16	Double Darrieus hybrid - H-rotor inside an eggbeater	2		[E55]
H17	Darrieus Savonius hybrid where the Darrieus can be moved closer or further from the center - starting far out and moving closer	2		[E56][E57]

Concept	Description	Level of Development (1-3)	Image	Reference number
H18	3 layer 3 blade classical Savonius + 3 blade H-rotor Darrieus	2	 FIGURE 1(d)	[E58][E59]
H19	Classical 2-blade Savonius + 3 blade H-rotor Darrieus with curtain	2		[E4]
H20	Double H-rotor Darrieus (4 blades, 2 lower radius interior and 2 larger radius exterior)	2	 Fig. 1. Schematic diagram of the DD-VAWT model.	[E60]
H21	New "eccentric" VAWT with characteristics of both Darrieus and Savonius, seems complicated	1	 (a) Perspective view under operation (b) Front view at no wind	[E61]

Concept	Description	Level of Development (1-3)	Image	Reference number
H22	2-bladed Savonius and 3 bladed H-rotor Darrieus	2		[E62]
H23	2-bladed Savonius and 2 bladed H-rotor darrieus	2		[E63]
H24	Double Savonius hybrid - stacked helical and standard	2		[E44]
H25	Double Savonius hybrid - stacked simple helical and helical bach	2		[E44]

Concept	Description	Level of Development (1-3)	Image	Reference number
H26	Double Savonius hybrid - stacked simple bach and helical bach	2		[E44]
H27	Single stage helical bach turbine	2		[E44]
H28	Crossflex turbine - building integrated	2		[E9]

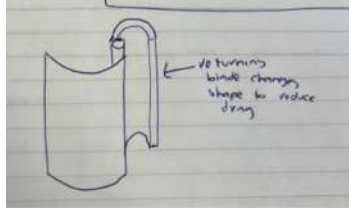
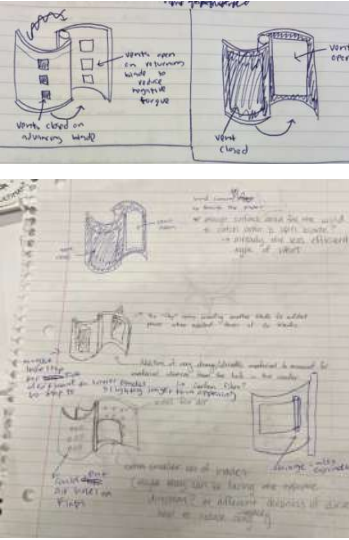
Emergent Ideation by VAWT Ventures

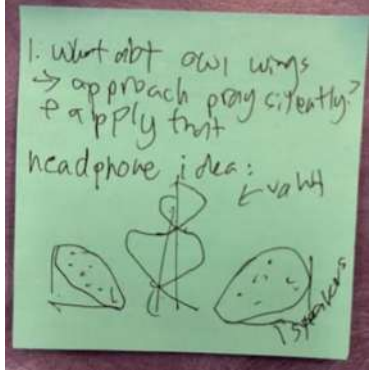
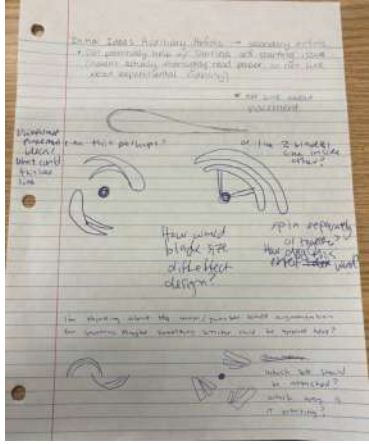
The Emergent Ideation Table compiles concept ideation done by members of the group, including full VAWTs, specific adjustments, and augmentation ideas. The processes used for this were SCAMPER, Biomimicry, Brain Writing, Brute Think, and Concept Tables. The SCAMPER method is a structured approach consisting of asking multiple questions about a specific design problem. The acronym SCAMPER stands for Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, and Reverse. SCAMPER is a useful method because it helps overcome conventional thinking patterns and also helps facilitate innovative solutions. Biomimicry is the process of researching and applying the ways in which nature has provided solutions to current problems. Brain Writing is the process of stating a design problem and working as a team to generate ideas through collaboration and idea circulation. This method was used the most during

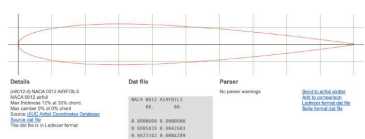
team meetings; an initial concept/design problem with emergent ideas was listed, and then the concepts/ideas would be passed around the group multiple times. Each member would add their own concepts and ideas, and the final result was a compilation of ideas generated by the team, which are provided in Table E4. Another method used in individual concept generation was Brute Think which consists of selecting a random word, thinking about things associated with that word, and then forcing connections between the word and the problem. Finally, when using Concept Tables for individual concept generation, we identified parameters in the solution, listed options for each parameter, and then experimented with different combinations.

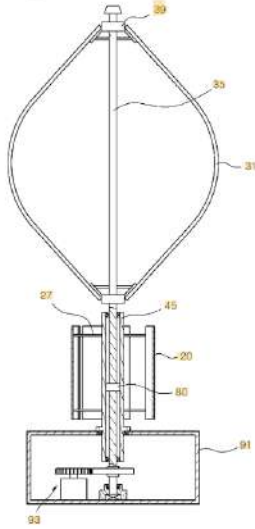
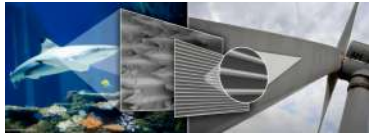
Table E4
Emergent ideation

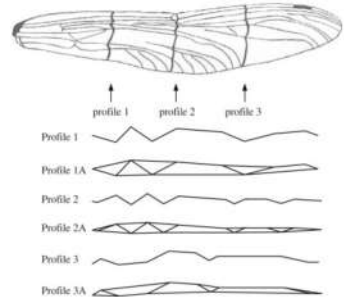
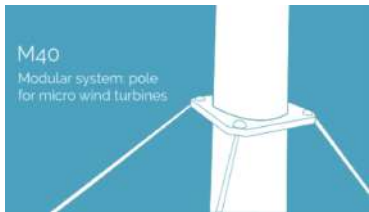
Concept	Description	Level of Development (1-3)	Image	Reference number
E1	Savonius blade design based on the fibonacci spiral	2		[E63][E64]
E2	Helical blade shape based on seed pods of two trees: Mimosa and Bauhinia Variegata	2		[E65]
E3	Serrated edge inspired by owl feathers to reduce turbulence behind the blade, allowing the rotor to spin faster	1		[E66]
E4	Improve efficiency of turbine blades by adding bumps inspired by the tubercles on the leading edge of humpback whale flippers	1		[E67]

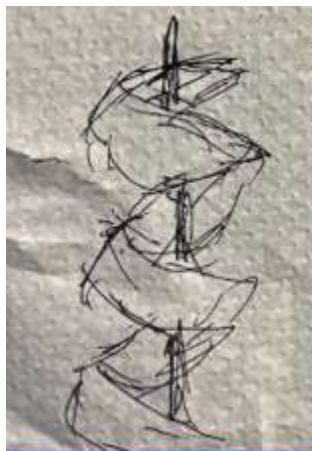
Concept	Description	Level of Development (1-3)	Image	Reference number
E5	Flexible blades that change shape as they return to decrease drag	1		
E6	Coating or texture on blades - maybe different on either side	1	For example, the textured NACA0015 	[E11]
E7	Introduce vents or holes in the returning blade to allow some air to pass through to decrease difference in pressure and negative torque (Brain Writing)	1		
E8	Soundproofing the mechanical gearbox to reduce mechanical noise	3		[E67]
E9	Altering airfoil profile to reduce noise	2		

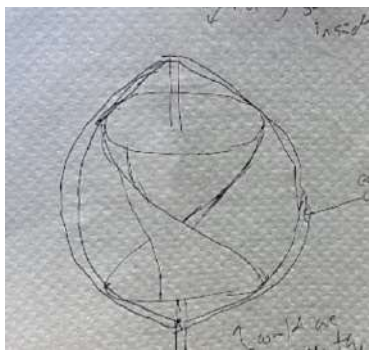
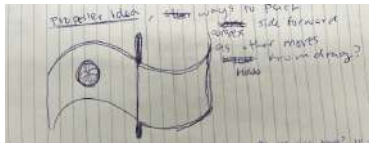
Concept	Description	Level of Development (1-3)	Image	Reference number
E10	System that produces equal opposite phase frequency waves to cancel out the hum of the VAWT (like noise cancelling headphones)	1	 A handwritten note on a piece of green paper. The text reads: "1. What abt owl wings → approach progressively? + apply that", "headphone idea: ← vawt". Below the text are three simple sketches: a cross-section of a wing, a VAWT, and a pair of headphones.	[E68]
E11	Using sound absorbing materials, such as insulation placed around the base of the VAWT	2		
E12	A setup around the VAWT to dampen noise without blocking wind	2		
E13	Pole made of sound absorbent material	2		
E14	Secondary/auxiliary airfoils (Brain Writing)	2	 A handwritten note on a piece of lined paper. The text includes: "In the table, Auxiliary Airfoils - secondary airfoils", "→ can potentially help w/ starting and stopping stroke", "→ can't actually absorb any real power, so the idea", "isn't representative (silly)", "→ not sure about", "placement", "Secondary Airfoils - this perhaps?", "don't work", "this one", "at the 2 blades", "can provide", "extra?", "How would", "blade type", "or the best", "design?", "split separately", "of blades?", "the blades", "wouldn't work", "too", "the thinking about the way / shape that airfoils are", "for starting / stopping something would be optimal idea?", "which air should", "be attached?", "which way is", "it rotating?", "it rotating?"	
E15	Add elements of Savonius without passing the hybrid threshold	2		

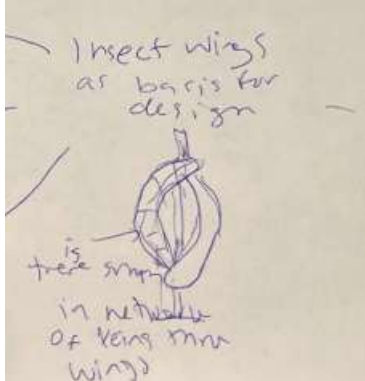
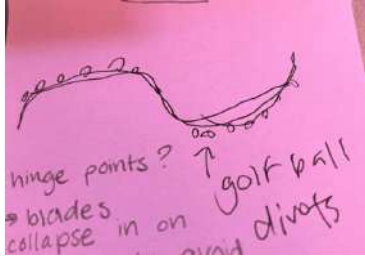
Concept	Description	Level of Development (1-3)	Image	Reference number
E16	Using more blades for maximized power output	3		[E69]
E17	Runs on lift and drag	3		
E18	Stacked Darrieus and Savonius → Savonius helps to start Darrieus	3		[E53]
E19	Switches from Savonius to Darrieus	1		
E20	Expandable blades	1		
E21	Use of more aerodynamic blades For example using NACA 0012 airfoil blades, known for their symmetry and aerodynamic properties	2		[E70]

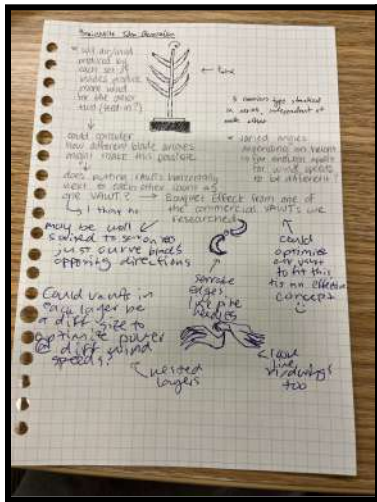
Concept	Description	Level of Development (1-3)	Image	Reference number
E22	Using lift-based blades	3	Fig. 5  Like a Vertical shaft type darius windmill	[E71]
E23	Using double airfoil blades	2		[E72]
E24	Dampening system at base of VAWT	2		[E52]
E25	Gearbox insulation	2		
E26	VAWT modified for lower TSR	1		[E67]
E27	Elimination of extra friction and vibrations in all parts	1		
E28	Designing the blades with implemented Riblet coating which is a surface coating that mimics shark denticles	2		[E73]

Concept	Description	Level of Development (1-3)	Image	Reference number
E29	Corrugated blade design based on the corrugated wings of dragonflies	2	 The diagram illustrates a dragonfly wing with three distinct profiles labeled 'profile 1', 'profile 2', and 'profile 3'. Below each profile is a corresponding airfoil shape labeled 'Profile 1A', 'Profile 2A', and 'Profile 3A' respectively. The airfoils show varying degrees of corrugation or ribbing along their length, mimicking the structure of dragonfly wings.	[E74]
E30	Implementing materials like cotton, wood, or bamboo to minimize noise	2		
E31	Using carbon fiber for the blades	2		[E20]
E32	Strengthening the base structure	1		
E33	Implementing a braking system	2		[E12]
E34	Shut off mechanism	1		
E35	Coating/material to protect from hot/cold weather	2		[E12]
E36	Collapsible pole component (changeable height)	1	 M40 Modular system pole for micro wind turbines	[E69]

Concept	Description	Level of Development (1-3)	Image	Reference number
E37	Triangular base	2		[E12]
E38	Columns built into the building to act as a foundation for the VAWT.	1		
E39	Triple Twisted Helical Savonius. Typically	1		
E40	Snack-cup inspired Deformable Helical Savonius	1		
E41	Tightly Twisted Helical Blade for Darrieus	1		

Concept	Description	Level of Development (1-3)	Image	Reference number
E42	Helical and Eggbeater Combined Darrieus Blade	1		
E43	Combined Helical and Eggbeater Darrieus and Internal Savonius	1		
E44	Hybrid with large internal Helical Savonius	1		
E45	Propeller to help push blades with the direction of the drag.	1		

Concept	Description	Level of Development (1-3)	Image	Reference number
E46	Insect wing inspired helical darrieus - in blade shape, material, and veining	1		
E47	Application of Savonius Augmentation on Ice Savonius Type (slits in blades, end plates, shielding plateS)	1		
E48	Further twist to Ice Savonius Type	1		
E49	Two Bladed Ice Savonius Type	1		
E50	Golf ball divots on concave side of Savonius blades (note: may belong on other side)	1		
E51	Collapsing blades to reduce or increase drag depending on type.	1		
E52	Additional material on blades to increase drag.	1		

Concept	Description	Level of Development (1-3)	Image	Reference number
E58	Rubber or ductile polymer for deformable blades	1		
E59	3D Printed blade for speed of production and cost efficiency	1		
E60	Stacked Darrieus in series VAWT with further contributions (Brain Writing)	1		

Conclusion

This memo compiled VAWT concepts from research studies, patents, and commercial technologies, as well as original ideas generated by VAWT Ventures team members, providing descriptions, levels of development, and relevant images for each concept. While the concepts are organized into Darrieus, Savonius, and hybrid categories, there is potential to combine features across these configurations to create new, more effective designs. In particular, hybrid designs offer a promising pathway because they can leverage the efficiency of lift-based Darrieus turbines while incorporating the self-starting capability of drag-based Savonius turbines, mitigating the drawbacks of each individual type. Building on documented concepts, the team should prioritize hybridization studies that combine aspects of lift-based and drag-based turbines, specifically mixed configurations.

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Appendix F: Concept Selection Memo

This appendix is a memo that describes how we narrowed down to our four selected concepts and the reasoning behind the decisions we made.

Appendix F: Concept Selection Memo

To: Susannah Howe and HRI Liaisons

From: VAWT Ventures

Date: December 11th, 2025

Subject: A report on initial concept evaluation techniques, the winnowing process, and the finalized four concepts that will be moving forward to the next phase.

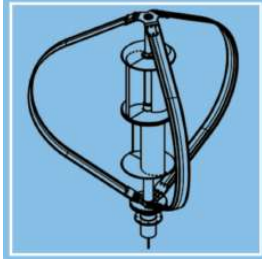
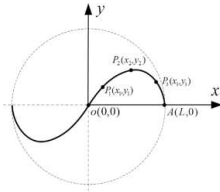
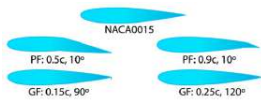
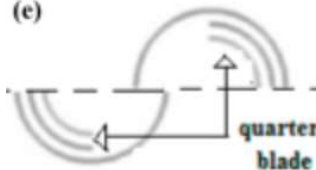
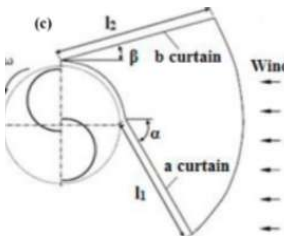
Introduction

As part of our concept generation process, we generated and compiled over 200 concepts for VAWTs. The purpose of this memo is to describe how we narrowed down to our four selected concepts and the reasoning behind the decisions we made.

Concept Organization

Before eliminating concepts, we organized our concepts into the following categories: Skeleton of a VAWT, Blade Shape, Interior Augmentation, Exterior Augmentation, and Other Optimization. A description of each category, and a representative picture are provided in Table F1.

Table F1
Concept categories, descriptions, and representative photos

Concept Category	Description	Representative photos
Skeleton of a VAWT	Skeleton of a VAWT includes broad concepts that encompass the entire rotor, such as an Eggbeater Darrieus, or a hybrid with a Classical Savonius within an H-rotor Darrieus.	 
Blade Shape	Blade shape includes concepts related to blade shape, which might include different airfoil types for Darrieus turbines or the curve of the savonius blades.	 
Interior Augmentation	Interior augmentation includes concepts that modify aspects of the turbine within the rotor blades. An example is additional miniature or quarter blades.	
Exterior Augmentation	Exterior augmentation concepts focus on addition outside of the rotor itself. Many of these concepts are deflector plates or guide vanes that direct wind flow.	
Other Optimization	Other optimization includes any concepts not encompassed by the above categories. For instance, the inclusion of a waterproof enclosure for the electronics is one concept in this category.	

During this process of categorization, we deleted duplicate concepts, removed ideas that did not exist as standalone concepts such as material types, and grouped similar concepts, such as different types of elliptical Savonius blades into one concept to evaluate together.

Concept Evaluation

Throughout the organization of the concepts, the team did additional research to define each concept enough to begin evaluation. After organization and preliminary research, we did an initial pass of all the sorted concepts as individuals to assess whether they were feasible for the project. We each identified “infeasible” concepts from our own perspectives, so when we came together as a group, we could agree upon a shared definition of feasibility. To us, feasibility captured intuitive decisions of what would be capable of generating power comparable to other designs and what was outside our modeling capabilities within the year. A few concepts removed from this section were “a single turbine that runs on lift and drag without passing the limit of a hybrid,” “a form of hybrid where the entire turbine switches skeleton (from Savonius to Darrieus and visa versa) depending on wind speed,” and “the original Persian VAWT.” In addition to edits made based on feasibility, we decided to remove any concepts from the Exterior Augmentation category that would affect the multidirectionality of the wind turbine, therefore damaging the ability of the rotor to produce power from wind in multiple directions. This narrowed our set to around 170 concepts.

From there, we decided that this large number of concepts was out of our scope and difficult to evaluate in comparison to one another. We focused on the Skeleton of VAWT category because the other categories were less fundamental to the base level design of the VAWT and made changes too small to be evaluated. We removed the concepts in the following categories: Internal Augmentation, External Augmentation, Blade Shape, and Other Optimization. Narrowing to the Skeleton of a VAWT category reduced our set to roughly 30 concepts.

The next winnowing process was determined by individual evaluation matrices. Each person evaluated 11 concepts; 3 to 5 of those concepts overlapped with another member's concepts to account for personal biases. The evaluation was on a scale from 1 being the lowest (passable) to 5 being the highest (ideal), and 0 was given to any values that we had no information on. The evaluation criteria used were “Cut-in Speed,” “Expectation of Power Generation in low wind speeds,” “Excitement to Pursue,” “Modeling and Prototyping Confidence,” and “Rotor Height.” Table F2 is the evaluation matrix the team used to evaluate the 30 concepts.

Table F2
Initial evaluation matrix

	Cut-in Speed (m/s)	Expectation of Power Generation in low wind speeds	Excitement to Pursue	Modeling and Prototyping Confidence	Rotor Height (m)
0	No information				No information
1 Passable	>5	Low	Low	Low	>3
2 Fine	(4,5]	Low-medium	Low-medium	Low-medium	(2.5, 3]
3 Good	(3,4]	Medium	Medium	Medium	(1.5, 2]
4 Excellent	(2, 3]	Medium-high	Medium-high	Medium-high	(1,1.5]
5 Ideal	<2	High	High	High	< 1

It should be noted that an error we made in our scaling for rotor height, shown in Table F2 above. There is a 0.5 skip between good and fine, when the scale should be continuous. Since we only used rotor height in our initial evaluation, this error did not matter for the rest of our passes. Table F3 details the rationale behind each chosen evaluation criteria and how we determined the values along the passable to ideal 1-5 scale. The criteria were chosen based on our values, what we believed to be the most important stakeholder needs, and accessible information.

Table F3
Justification of evaluation criteria and scale

Evaluation Criteria	Reasoning for Indicator	Reasoning for Scale	Effectivity of Criteria
Cut-in Speed	Indicates the ability of a VAWT to start and therefore begin to generate power at low wind speeds.	Anemometer wind measurements over Ford Hall balcony indicated wind speeds varying between 0 and 7.1 m/s, hovering in 2-3 m/s range. The average wind speeds were between 2 and 3, so we set <2 as our ideal. We did not set a cap on the passable designs, since the designs with extremely high cut-in speeds were large farm-scale devices and we would be changing this scale and therefore the cut-in speed. Additionally, we awarded no points to any concepts where cut-in speed was not provided.	Not effective. Did not move into the next stage of evaluation because many concepts did not have reported cut-in speeds and could factor it into “Expectation of Power Generation” criteria.
Expectation of Power Generation in Low Wind Speeds	Indicates our team’s belief in the ability of a VAWT to generate power at low wind speeds, based on research about the concept and similar concepts.	This metric assesses the team members belief in the amount of power the VAWT is capable of producing at low wind speeds compared to the broader range of VAWTs. After the cut-in speed criteria was removed, “expectation of power generation in low wind speeds” factored in the cut-in speed when available and other accessible related to power generation.	Effective. Moved into the next stage of evaluation because we identified power generation as our most important performance criteria.
Excitement to Pursue	We included excitement to factor in our passion for the concepts. It was important to us to pursue designs that are interesting to us, which often are not the simplest or most promising ideas.	This metric assesses the team members interest and excitement about the given concept.	Effective. Moved into the next stage of evaluation as we want to pursue ideas we are excited about.

Evaluation Criteria	Reasoning for Indicator	Reasoning for Scale	Effectivity of Criteria
Modeling and Prototyping Confidence	Indicated the feasibility of modeling the concept in phase 1, building in phase 2, and manufacturing. In addition, a more complex design, generally indicates a higher cost.	In assessing the Modeling and Prototyping Confidence, the team's ranking is based on whether we believe ourselves capable of modeling and building the design. Our judgments factor in any complex geometry and complex mechanisms of movement a concept might include.	Effective. Moved into the next stage of evaluation, as this is where we are accounting for the feasibility and cost of the ideas we include.
Rotor Height	The rotor height accounts for how much we would need to alter the design to make it a reasonable size for a rooftop application. We believed this could be a good numerical way to assess simplicity and aesthetic compatibility.	Similar to cut-in speed, the zero was included to factor in amounts of accessible information. The remainder of the scale was based on how tall the turbine could reasonably be to fit onto a rooftop.	Not Effective. Did not move into the next stage of evaluation, because it is an easily adjusted parameter and most of the designs we found were within a passable range which is all we cared about.

Once we reached 23 concepts for Skeleton of a VAWT, we continued winnowing with a goal of selecting no more than four concepts. The goal of four concepts was set to simplify the division of labor, as there are four members on the team. At 23 concepts, the evaluation process became more simplified and critical. All team members evaluated the remaining 23 concepts through a slightly altered evaluation matrix. As described in the last column Table F3, we removed cut-in speed and rotor height as evaluation criteria. For this pass, the Expectation of Power Generation was based on power generation curves, cut in speed, and other information we were able to find about power generation for that particular VAWT. We also took into account our broader understanding of which types of VAWTs are more likely to consistently produce power based on previous research.

Once all members had completed individual tables for all 23 of these designs, we identified concepts that had received a score of one in any column. We discussed and removed upon agreement of two or more members. Each member identified the five concepts with the lowest total score. If two or more members had the same concept in their lowest five, these concepts were removed. Furthermore, we decided to move any concepts with multiple stages as well as

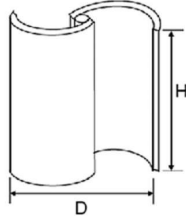
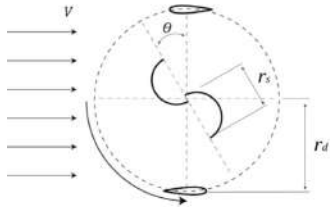
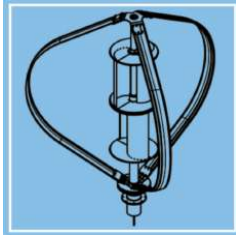
any involving blade twists to the further optimizations section because these were things that did not affect the main skeleton of the VAWT and could be added on later during the optimization phase. This also included the electromagnetic switch, the Darrieus-Savonius hybrid where the Darrieus could be moved closer and further from the rotor, and the Bach and Benesh Savonius. We additionally removed many concepts due to lower overall scores and a lack of information. Some of these concepts included the Double Darrieus hybrid (H-rotor inside an Eggbeater), two stage Savonius inside Eggbeater Darrieus, and the Classical H-Rotor Darrieus. This process resulted in eight remaining concepts.

At this stage, we transitioned into choosing the top four concepts, from the remaining eight. The remaining eight concepts had enough information about the cut in speed and power curve so that we were able to make justified technical decisions about which four to move forward with. Concept excitement levels, diversity of skeleton types, and diversity of risk levels highly impacted our justification for the top four concepts.

The risk scale we implemented for the final eight concepts was based on the amount of available information, the feasibility of modeling each design, and our group's overall understanding of a concept (Table F4). We intentionally included concepts across different risk levels to balance reliability with excitement to ensure that at least one option would be viable while still allowing us to explore more experimental ideas. Of the eight concepts, we categorized five as low risk, two as medium risk, and one as high risk. From these, we selected four to move forward with: one low-risk concept, two medium-risk concepts, and one high-risk concept.

Table F4

Eight final concepts

Concept (from low to high risk)	Visual
1. Classical Savonius	 [6]
2. Classical Savonius within h-type darrieus	 [7]
3. Stacked Savonius inside eggbeater Darrieus	 [1]
4. Single stage Helical Savonius	 [8]
Concept (from low to high risk)	Visual

5. "Tulip" shaped Helical Savonius



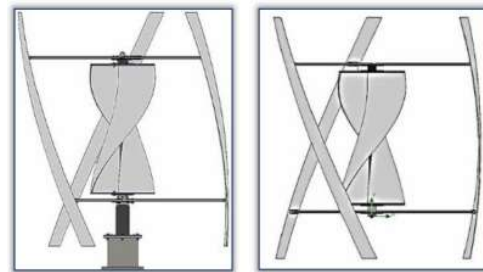
[9]

6. EN0005



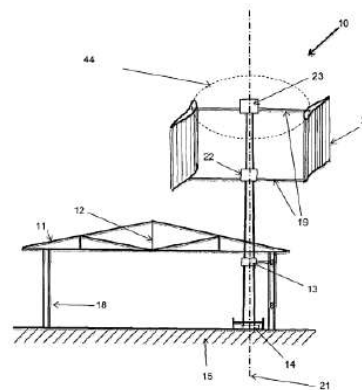
[10]

7. Hybrid with internal Helical Savonius



[11]

8. H-Rotor Darrieus with Savonius Compartments



[12]

Selected Concepts

We selected the final four concepts out of the final eight to diversify the types of VAWTs, by our confidence in the feasibility of each concept, and the flexibility of modifications the team can make. We included two Hybrid designs (one with a typically oriented Savonius, one with the Savonius uniquely oriented within the Darrieus), one Darrieus, and one Savonius. The Hybrid designs consist of an H-type Darrieus, a Helical Darrieus, and a Helical Savonius. With the unique Darrieus and Classical Savonius, this final four provides us with a wide variety of VAWT types, a mix of designs we are excited about pursuing and more standard ones we are confident in our capability to model and push forward.

Of our selected four concepts, the Classical Savonius is the lowest risk option (Fig. F1). We chose this design primarily because of its simplicity and its low cut-in speed, both of which are important for reliable power generation under the wind conditions at Smith. The extensive body of research on Classical Savonius optimization also gives us confidence in our ability to model it accurately and make targeted modifications that could improve its performance. Some of the parameters we plan to adjust include blade shape, the angle of twist, and the number of stages.

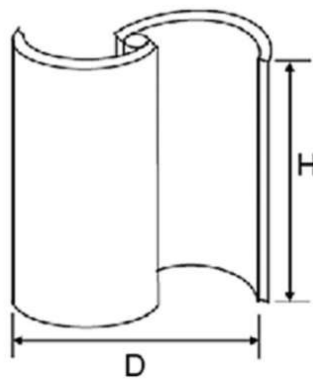


Fig. F1. Classical Savonius [6].

The second selected concept is the EN0005, a distinctive Darrieus design that we categorized as high risk (Fig. F2). The concept is rated at a high risk because it has not been commercially explored and there is minimal research into the design. We chose the EN0005 because it is a standalone Darrieus concept and we wanted to have a diversity of ideas. Notably, the EN0005 has a cut-in speed of 1.25 m/s [F10], which is surprisingly low for a Darrieus VAWT and makes it well-suited for the wind conditions at Smith. The EN0005 also offers many opportunities for optimization including adjustments to blade size and shape, rotor diameter, and the distance of the blades from the center.



Fig. F2. EN0005 [10]

The third selected concept, a Helical Savonius within a Helical Darrieus, was initially rated as medium risk due to its classification as a hybrid VAWT (Fig. F3). We selected this design because hybrid concepts in general have shown strong potential in literature, particularly in how they combine the self-starting reliability of a Savonius with the higher efficiency of a Darrieus. In this case, both components are helical, which is especially promising, given that helical Savonius and helical Darrieus VAWTs both show smoother torque, reduced vibration, and more consistent power output [F11]. Bringing them together could help address the traditional weaknesses of each individual type while improving performance in low wind speeds, which is critical for urban environments.

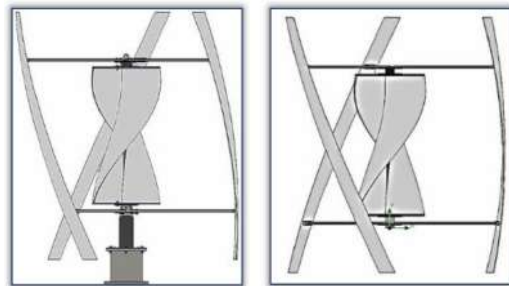


Fig. F3. Helical Savonius within a helical Darrieus [F11].

Although the concept is fairly unique, the helical hybrid also leaves room for adaptation. We can pivot to an H-rotor configuration or modify blade geometry as we learn more about its aerodynamic behavior. At this stage, we are curious about the degree to which the hybrid helical arrangement might enhance efficiency beyond that of a standalone Darrieus.

The fourth and final selected concept, an H-Rotor Darrieus with Savonius Compartments, was the only high risk concept in our final eight (Fig. F4). We classified it as high risk because it has been explored very little in existing literature, which is also what excites us about this design.

Rather than having a full Savonius within a Darrieus, the blades that connect the pole to the H-type blades are made up of Savonius compartments. This is very uncommon in the other technology we researched and are interested to see how it might behave under urban wind conditions.

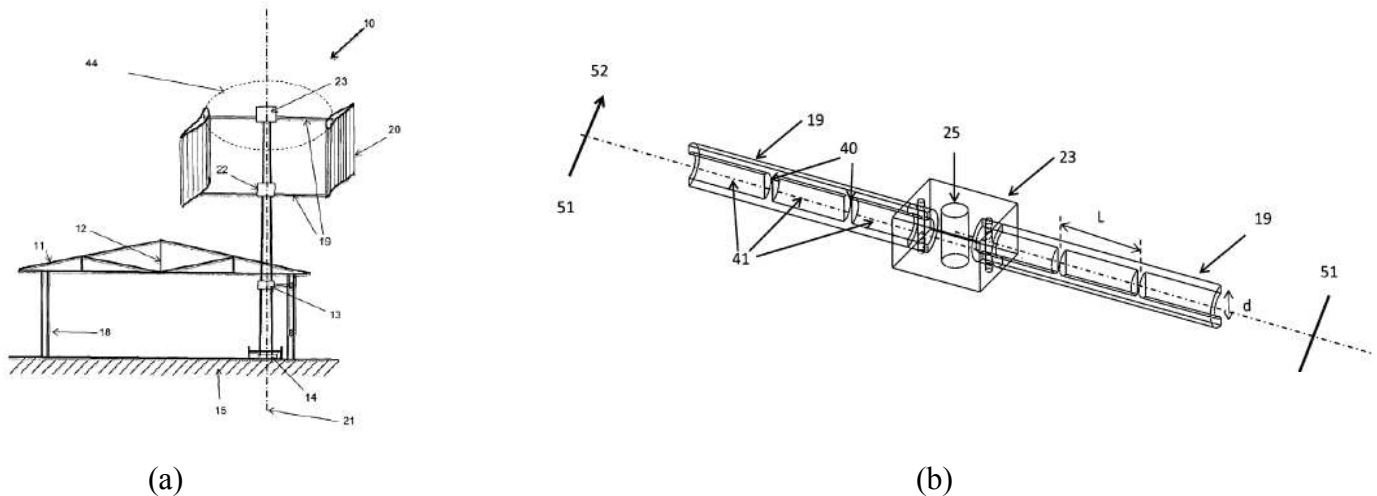


Fig. F4. (a) Full view of H-Rotor Darrieus with Savonius compartments. (b) Zoomed in view of compartments along beams connecting the H-type blades to the central shaft [F12].

Beyond its uniqueness, we wanted to include some form of H-type Darrieus to our lineup because this type is well represented in commercial technology. The patent detailing this concept also reports a low cut-in speed, which is valuable for power generation. At this stage, we are still determining the specific modifications that could be made, as we need a deeper understanding of the aerodynamic interactions within this design. Potential avenues for optimization include adjusting the spacing of the Darrieus blades and varying the number of Savonius compartments, but further research is needed before we develop a concrete improvement plan.

Conclusion and Next Steps

In this memo, we presented our initial concept evaluation techniques, the winnowing process we used to reduce more than two hundred ideas into a manageable set, and the four final concepts we selected to move into the next phase. By organizing all concepts into categories, removing duplicates, and focusing our evaluation on Skeletons of VAWTs, we ensured that our comparisons centered on fundamental structural variations rather than secondary optimizations.

Our multi-stage evaluation process incorporated feasibility, availability of information, expected performance at low wind speeds, simplicity, and team excitement, gradually narrowing the field from 224 concepts to eight. With this smaller set, we were able to make more technically informed decisions using cut-in speeds, power generation curves, and relative risk levels. From

these eight, we selected four concepts that balance feasibility, diversity of ideas, excitement, and potential for optimization.

These four concepts represent the designs we believe are the most viable for further analysis. Moving forward, we will model each design, explore parameter optimizations, and begin determining which concept offers the strongest combination of power output, simplicity, and long-term suitability for our stakeholder needs.

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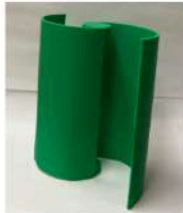
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Appendix G: Prototype Optimization Chart

This appendix documents the progression of 3D printed prototypes and their corresponding cut-in speeds throughout our project.

Appendix G: Prototype Optimization Chart

Table G1 documents the progression of 3D printed prototypes and their corresponding cut-in speeds throughout our project.

Table G1 Prototype optimization chart							
	Round 1	Round 2	Round 3	Round 4	Round 5	Round 6	Round 7
H-Type with Savonius Compartments  Cut in Speed: N/A							
Classical Savonius  Cut in Speed: 5.4 m/s	Added End Caps  8.5 m/s Optimized Overlap Ratio  2.6 m/s Elliptical Blades  2.1 m/s	Twisted Savonius with thin walls  1.7 m/s					
EN0005  Cut in Speed: 2.1 m/s	Optimized Diameter  2.0 m/s		Smoothed Blades (Airfoils and Turns)  1.9 m/s		EN0005-Twisted Savonius Hybrid  1.5 m/s	EN0005 Airfoil Shape  6.7 m/s	
Helical Hybrid  Cut in Speed: N/A	Closed Internal Twisted Savonius  N/A	Classical Savonius in Helical Darrius  N/A Closed Savonius, NACA 0018 Airfoil Shaped Blades  15.2 m/s	Altered Pole Attachment  N/A Reversed Darrieus Airfoils  9.8 m/s	Taller Savonius  6.3 m/s Asymmetric Airfoil  7.15 m/s Wider Savonius  4.6 m/s	Combination 1: Asymmetric, Wider, Taller  4.4 m/s Closed Wider Savonius  3.3 m/s	Altered Pitch of Darrieus Blades  5°: 11 m/s  20°: N/A	Combination 2: EN0005 Airfoil, Wider Closed, Taller  3.8 m/s

Appendix H: Cut-In Speed Measurements

This appendix presents the cut-in speeds of all 3D printed prototypes developed throughout our project.

Appendix H: Cut-In Speed Measurements

Table H1 presents the cut-in speeds of all 3D printed prototypes developed throughout our project.

Table H1
Cut-in speed measurements for all 3D printed prototypes

Category	Prototype Name	Avg Cut-In Speed (Hz)	Avg Cut-In Speed (m/s)	Notes
Savonius	Classical Savonius	7.9	5.4	
	Helical Savonius	2.85	1.7	Different thickness than other prototypes
	Savonius w/ End Caps	11.95	8.5	
	Savonius w/ Optimized OR	3.95	2.6	
	Elliptical Savonius	3.3	2.1	
Helical Hybrid	Helical Hybrid	N/A		
	Helical Hybrid w/ Classical Savonius	N/A		
	Helical Hybrid Closed Savonius	N/A		
Helical Hybrid w/ backwards airfoil	Helical Hybrid w/ Airfoil (backwards)	19.9	15.2	
	Helical Hybrid w/ Poles	N/A		
	Helical Hybrid w/ Poles and Smaller Chord Length	N/A		
Helical Hybrid w/ correct airfoils	Helical Hybrid w/ Reversed Airfoils	13.6	9.8	
	Helical Hybrid w/ Taller Savonius	9.3	6.3	
	Helical Hybrid w/ Larger Savonius Diameter	6.6	4.6	
	Helical Hybrid w/ Non-Symmetrical Airfoils	10.45	7.2	
	Helical Hybrid w/ Smaller Bearing Slits	10.5	7.2	
EN0005	EN0005	3.25	2.1	
	EN0005 v2	3.2	2	
	EN0005 Smooth Top	3.1	1.9	
Final Concept	Helical Savonius + EN0005	3.6	2.3	Blade were opposing each other
	Combined Alterations	6.4	4.4	
	Savonius Diameter Increase + Closed	N/A		First iteration closed the savonius too much and it was causing friction against the pole
Final Concept	Helical Savonius + EN0005 (facing the same direction)	15.2	11.1	Hole for pole was off center, pole rubbing against savonius blade
	HH 5° Pitch	15.1	11	
	HH 20° Pitch	N/A		
	HH Savonius Diameter Increased + Closed	4.8	3.3	
	HH w/ EN0005 Airfoil	9.8	6.7	
Final Round of Optimization	Final HH	5.35	3.8	
	Final EN0005 w/ Helical Savonius	2.6	1.5	
Scale Testing	HH Savonius Diameter Increased + Closed Big	3.8	2.5	
	HH Savonius Diameter Increased + Closed Small	20.75	16	

Appendix I: Angular Velocity Measurements

This appendix presents angular velocity measurements for select 3D printed prototypes, including those we used for scaling calculations.

Appendix I: Angular Velocity Measurements

Table I1 presents angular velocity measurements for select 3D printed prototypes, including those we used for scaling calculations.

Table I1
Angular Velocity Measurements for Select 3D Printed Prototypes

Concept	File Name	Radius (m)	Wind Speed (Hz)	Wind Speed (m/s)	Revolutions Per Minute (avg)	Angular Velocity (rad/s)	TSR
Elliptical Savonius		0.053	10	6.8	805	84.257	0.657
HH Savonius Diameter Increased + Closed		0.055	10	6.8	72	7.536	0.061
Final HH		0.055	10	6.8	261	27.318	0.221
Final EN0005 w/ Helical Savonius		0.0775	10	6.8	131	13.711	0.156
HH Savonius Diameter Increased + Closed		0.055	10	6.8	135	14.130	0.114
HH Savonius Diameter Increased + Closed Big		0.08	6.8	4.7	162.5	17.008	0.290
HH Savonius Diameter Increased + Closed Small		0.035	14.6	10.7	0	0.000	0.000

Appendix J: Concept Selection Sensitivity Analysis

This appendix includes all versions of the evaluation matrix we used to determine the selected design.

Appendix J: Concept Selection Sensitivity Analysis

Figs. J1-J4 include all versions of the evaluation matrix we used to determine the selected design.

Original Weights							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%		0		0		0
Cut-in Speed	30%		0		0		0
Moment of Inertia	15%		0		0		0
Sentiment from Researchers	25%		0		0		0
Cost of Manufactuirng	10%		0		0		0
Total	100%	N/A	0	N/A	0	N/A	0
Rank		2		2		2	

Angelina							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	15%	1	0.15	5	0.75	3	0.45
Sentiment from Researchers	25%	2	0.5	4	1	5	1.25
Cost of Manufacturing	10%	4	0.4	2	0.2	2	0.2
Total	100%	N/A	3.25	N/A	3.65	N/A	3.5
Rank		3		1		2	

Keona							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	15%	1	0.15	5	0.75	3	0.45
Sentiment from Researchers	25%	2	0.5	3	0.75	4	1
Cost of Manufacturing	10%	4	0.4	3	0.3	3	0.3
Total	100%	N/A	3.25	N/A	3.5	N/A	3.35
Rank		3		1		2	

Ginger							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	15%	1	0.15	5	0.75	3	0.45
Sentiment from Researchers	25%	2	0.5	3	0.75	5	1.25
Cost of Manufactuirng	10%	4	0.4	3	0.3	3	0.3
Total	100%	N/A	3.25	N/A	3.5	N/A	3.6
Rank		3		2		1	

Elliot							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	15%	1	0.15	5	0.75	3	0.45
Sentiment from Researchers	25%	1	0.25	3	0.75	5	1.25
Cost of Manufacturing	10%	4	0.4	3	0.3	2	0.2
Total	100%	N/A	3	N/A	3.5	N/A	3.5
Rank		3		2		2	

Higher Cut-in							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	15%		0		0		0
Cut-in Speed	45%		0		0		0
Moment of Inertia	10%		0		0		0
Sentiment from Researchers	25%		0		0		0
Cost of Manufacturing	5%		0		0		0
Total	100%	N/A	0	N/A	0	N/A	0
Rank		2		2		2	

Angelina							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	15%	5	0.75	1	0.15	2	0.3
Cut-in Speed	45%	4	1.8	5	2.25	4	1.8
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	4	1	5	1.25
Cost of Manufacturing	5%	4	0.2	2	0.1	2	0.1
Total	100%	N/A	3.35	N/A	4	N/A	3.75
Rank		3		1		2	

Keona							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	15%	5	0.75	1	0.15	2	0.3
Cut-in Speed	45%	4	1.8	5	2.25	4	1.8
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	3	0.75	4	1
Cost of Manufacturing	5%	4	0.2	3	0.15	3	0.15
Total	100%	N/A	3.35	N/A	3.8	N/A	3.55
Rank		3		1		2	

Ginger							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	15%	5	0.75	1	0.15	2	0.3
Cut-in Speed	45%	4	1.8	5	2.25	4	1.8
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	3	0.75	5	1.25
Cost of Manufacturing	5%	4	0.2	3	0.15	3	0.15
Total	100%	N/A	3.35	N/A	3.8	N/A	3.8
Rank		3		2		2	

Elliot							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	15%	5	0.75	1	0.15	2	0.3
Cut-in Speed	45%	4	1.8	5	2.25	4	1.8
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	1	0.25	3	0.75	5	1.25
Cost of Manufacturing	5%	4	0.2	3	0.15	2	0.1
Total	100%	N/A	3.1	N/A	3.8	N/A	3.75
Rank		3		1		2	

Higher Angular Velocity + MOI							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	30%		0		0		0
Cut-in Speed	25%		0		0		0
Moment of Inertia	20%		0		0		0
Sentiment from Researchers	20%		0		0		0
Cost of Manufacturing	5%		0		0		0
Total	100%	N/A	0	N/A	0	N/A	0
Rank		2		2		2	

Angelina							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	30%	5	1.5	1	0.3	2	0.6
Cut-in Speed	25%	4	1	5	1.25	4	1
Moment of Inertia	20%	1	0.2	5	1	3	0.6
Sentiment from Researchers	20%	2	0.4	4	0.8	5	1
Cost of Manufacturing	5%	4	0.2	2	0.1	2	0.1
Total	100%	N/A	3.3	N/A	3.45	N/A	3.3
Rank		2		1		2	

Keona							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	30%	5	1.5	1	0.3	2	0.6
Cut-in Speed	25%	4	1	5	1.25	4	1
Moment of Inertia	20%	1	0.2	5	1	3	0.6
Sentiment from Researchers	20%	2	0.4	3	0.6	4	0.8
Cost of Manufacturing	5%	4	0.2	3	0.15	3	0.15
Total	100%	N/A	3.3	N/A	3.3	N/A	3.15
Rank		2		2		2	

Ginger							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	30%	5	1.5	1	0.3	2	0.6
Cut-in Speed	25%	4	1	5	1.25	4	1
Moment of Inertia	20%	1	0.2	5	1	3	0.6
Sentiment from Researchers	20%	2	0.4	3	0.6	5	1
Cost of Manufacturing	5%	4	0.2	3	0.15	3	0.15
Total	100%	N/A	3.3	N/A	3.3	N/A	3.35
Rank		2		2		1	

Elliot							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	30%	5	1.5	1	0.3	2	0.6
Cut-in Speed	25%	4	1	5	1.25	4	1
Moment of Inertia	20%	1	0.2	5	1	3	0.6
Sentiment from Researchers	20%	1	0.2	3	0.6	5	1
Cost of Manufacturing	5%	4	0.2	3	0.15	2	0.1
Total	100%	N/A	3.1	N/A	3.3	N/A	3.3
Rank		3		2		2	

Fig. J1. Original categories for evaluation criteria with varying weights.

Taking from Cost of Maufacturing and MOI							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%		0		0		0
Cut-in Speed	30%		0		0		0
Moment of Inertia	10%		0		0		0
Sentiment from Researchers	25%		0		0		0
Cost of Manufactuirng	5%		0		0		0
Team Contributions	10%						
Total	100%	N/A	0	N/A	0	N/A	0
Rank		2		2		2	
Angelina							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	4	1	5	1.25
Cost of Manufactuirng	5%	4	0.2	2	0.1	2	0.1
Team Contributions	10%	1	0.1	3	0.3	4	0.4
Total	100%	N/A	3.1	N/A	3.6	N/A	3.65
Rank		3		2		1	
Keona							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	3	0.75	4	1
Cost of Manufactuirng	5%	4	0.2	3	0.15	3	0.15
Team Contributions	10%	1	0.1	3	0.3	4	0.4
Total	100%	N/A	3.1	N/A	3.4	N/A	3.45
Rank		3		2		1	
Ginger							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	3	0.75	5	1.25
Cost of Manufactuirng	5%	4	0.2	3	0.15	3	0.15
Team Contributions	10%	1	0.1	3	0.3	4	0.4
Total	100%	N/A	3.1	N/A	3.4	N/A	3.7
Rank		3		2		1	
Elliot							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	1	0.25	3	0.75	5	1.25
Cost of Manufactuirng	5%	4	0.2	3	0.15	2	0.1
Team Contributions	10%	1	0.1	2	0.2	4	0.4
Total	100%	N/A	2.85	N/A	3.3	N/A	3.65
Rank		3		2		1	

Second Possible Weight							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	17.5%		0		0		0
Cut-in Speed	40.0%		0		0		0
Moment of Inertia	7.5%		0		0		0
Sentiment from Researchers	20.0%		0		0		0
Cost of Manufactuirng	5.0%		0		0		0
Team Contributions	10.0%						
Total	100.0%	N/A	0	N/A	0	N/A	0
Rank		2		2		2	
Angelinaa							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	17.5%	5	0.875	1	0.175	2	0.35
Cut-in Speed	40.0%	4	1.6	5	2	4	1.6
Moment of Inertia	7.5%	1	0.075	5	0.375	3	0.225
Sentiment from Researchers	20.0%	2	0.4	4	0.8	5	1
Cost of Manufactuirng	5.0%	4	0.2	2	0.1	2	0.1
Team Contributions	10.0%	1	0.1	3	0.3	4	0.4
Total	100.0%	N/A	3.25	N/A	3.75	N/A	3.675
Rank		3		1		2	
Keona							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	17.5%	5	0.875	1	0.175	2	0.35
Cut-in Speed	40.0%	4	1.6	5	2	4	1.6
Moment of Inertia	7.5%	1	0.075	5	0.375	3	0.225
Sentiment from Researchers	20.0%	2	0.4	3	0.6	4	0.8
Cost of Manufactuirng	5.0%	4	0.2	3	0.15	3	0.15
Team Contributions	10.0%	1	0.1	3	0.3	4	0.4
Total	100.0%	N/A	3.25	N/A	3.6	N/A	3.525
Rank		3		1		2	
Ginger							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	17.5%	5	0.875	1	0.175	2	0.35
Cut-in Speed	40.0%	4	1.6	5	2	4	1.6
Moment of Inertia	7.5%	1	0.075	5	0.375	3	0.225
Sentiment from Researchers	20.0%	2	0.4	3	0.6	5	1
Cost of Manufactuirng	5.0%	4	0.2	3	0.15	3	0.15
Team Contributions	10.0%	1	0.1	3	0.3	4	0.4
Total	100.0%	N/A	3.25	N/A	3.6	N/A	3.725
Rank		3		2		1	
Elliot							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	17.5%	5	0.875	1	0.175	2	0.35
Cut-in Speed	40.0%	4	1.6	5	2	4	1.6
Moment of Inertia	7.5%	1	0.075	5	0.375	3	0.225
Sentiment from Researchers	20.0%	1	0.2	3	0.6	5	1
Cost of Manufactuirng	5.0%	4	0.2	3	0.15	2	0.1
Team Contributions	10.0%	1	0.1	2	0.2	4	0.4
Total	100.0%	N/A	3.05	N/A	3.5	N/A	3.675
Rank		3		2		1	

Fig. J2. Evaluation matrix including team contribution criterion at various weights.

Taking from Cost of Maufacturing and MOI							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%		0		0		0
Cut-in Speed	30%		0		0		0
Moment of Inertia	10%		0		0		0
Sentiment from Researchers	25%		0		0		0
Cost of Manufactuirng	5%		0		0		0
Potential for Improvement	10%						
Total	100%	N/A	0	N/A	0	N/A	0
Rank		2		2		2	
Angelina							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	4	1	5	1.25
Cost of Manufactuirng	5%	4	0.2	2	0.1	2	0.1
Potential for Improvement	10%	3	0.3	1	0.1	4	0.4
Total	100%	N/A	3.3	N/A	3.4	N/A	3.65
Rank		3		2		1	
Keona							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	3	0.75	4	1
Cost of Manufactuirng	5%	4	0.2	3	0.15	3	0.15
Potential for Improvement	10%	2	0.2	1	0.1	3	0.3
Total	100%	N/A	3.2	N/A	3.2	N/A	3.35
Rank		2		2		1	
Ginger							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	3	0.75	5	1.25
Cost of Manufactuirng	5%	4	0.2	3	0.15	3	0.15
Potential for Improvement	10%	4	0.4	2	0.2	4	0.4
Total	100%	N/A	3.4	N/A	3.3	N/A	3.7
Rank		2		3		1	
Elliot							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	20%	5	1	1	0.2	2	0.4
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	1	0.25	3	0.75	5	1.25
Cost of Manufactuirng	5%	4	0.2	3	0.15	2	0.1
Potential for Improvement	10%	4	0.4	2	0.2	4	0.4
Total	100%	N/A	3.15	N/A	3.3	N/A	3.65
Rank		3		2		1	

Making Cut-in More Important							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	17.5%		0		0		0
Cut-in Speed	40.0%		0		0		0
Moment of Inertia	7.5%		0		0		0
Sentiment from Researchers	20.0%		0		0		0
Cost of Manufactuirng	5.0%		0		0		0
Potential for Improvement	10.0%						
Total	100.0%	N/A	0	N/A	0	N/A	0
Rank		2		2		2	
Angelina							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	17.5%	5	0.875	1	0.175	2	0.35
Cut-in Speed	40.0%	4	1.6	5	2	4	1.6
Moment of Inertia	7.5%	1	0.075	5	0.375	3	0.225
Sentiment from Researchers	20.0%	2	0.4	4	0.8	5	1
Cost of Manufactuirng	5.0%	4	0.2	2	0.1	2	0.1
Potential for Improvement	10.0%	3	0.3	1	0.1	4	0.4
Total	100.0%	N/A	3.45	N/A	3.55	N/A	3.675
Rank		3		2		1	
Keona							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	17.5%	5	0.875	1	0.175	2	0.35
Cut-in Speed	40.0%	4	1.6	5	2	4	1.6
Moment of Inertia	7.5%	1	0.075	5	0.375	3	0.225
Sentiment from Researchers	20.0%	2	0.4	3	0.6	4	0.8
Cost of Manufactuirng	5.0%	4	0.2	3	0.15	3	0.15
Potential for Improvement	10.0%	2	0.2	1	0.1	3	0.3
Total	100.0%	N/A	3.35	N/A	3.4	N/A	3.425
Rank		3		2		1	
Ginger							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	17.5%	5	0.875	1	0.175	2	0.35
Cut-in Speed	40.0%	4	1.6	5	2	4	1.6
Moment of Inertia	7.5%	1	0.075	5	0.375	3	0.225
Sentiment from Researchers	20.0%	2	0.4	3	0.6	5	1
Cost of Manufactuirng	5.0%	4	0.2	3	0.15	3	0.15
Potential for Improvement	10.0%	4	0.4	2	0.2	4	0.4
Total	100.0%	N/A	3.55	N/A	3.5	N/A	3.725
Rank		2		3		1	
Elliot							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	17.5%	5	0.875	1	0.175	2	0.35
Cut-in Speed	40.0%	4	1.6	5	2	4	1.6
Moment of Inertia	7.5%	1	0.075	5	0.375	3	0.225
Sentiment from Researchers	20.0%	1	0.2	3	0.6	5	1
Cost of Manufactuirng	5.0%	4	0.2	3	0.15	2	0.1
Potential for Improvement	10.0%	4	0.4	2	0.2	4	0.4
Total	100.0%	N/A	3.35	N/A	3.5	N/A	3.675
Rank		3		2		1	

Fig. J3. Evaluation matrix including potential for improvement criterion at various weights.

Taking from Cost of Maufacturing and MOI							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	25%		0		0		0
Cut-in Speed	30%		0		0		0
Moment of Inertia	10%		0		0		0
Sentiment from Researchers	20%		0		0		0
Cost of Manufacturing	5%		0		0		0
Team Contributions	5%		0		0		0
Potential for Improvement	5%		0		0		0
Total	100%	N/A	0	N/A	0	N/A	0
Rank		2		2		2	
Angelina							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	25%	5	1.25	1	0.25	2	0.5
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	20%	2	0.4	4	0.8	5	1
Cost of Manufacturing	5%	4	0.2	2	0.1	2	0.1
Team Contributions	5%	1	0.05	3	0.15	4	0.2
Potential for Improvement	5%	3	0.15	1	0.05	4	0.2
Total	100%	N/A	3.35	N/A	3.35	N/A	3.5
Rank		2		2		1	
Keona							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	25%	5	1.25	1	0.25	2	0.5
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	20%	2	0.4	3	0.6	4	0.8
Cost of Manufacturing	5%	4	0.2	3	0.15	3	0.15
Team Contributions	5%	1	0.05	3	0.15	4	0.2
Potential for Improvement	5%	2	0.1	1	0.05	3	0.15
Total	100%	N/A	3.3	N/A	3.2	N/A	3.3
Rank		2		3		2	
Ginger							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	25%	5	1.25	1	0.25	2	0.5
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	20%	2	0.4	3	0.6	5	1
Cost of Manufacturing	5%	4	0.2	3	0.15	3	0.15
Team Contributions	5%	1	0.05	3	0.15	4	0.2
Potential for Improvement	5%	3	0.15	2	0.1	4	0.2
Total	100%	N/A	3.35	N/A	3.25	N/A	3.55
Rank		2		3		1	
Elliot							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	25%	5	1.25	1	0.25	2	0.5
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	20%	1	0.2	3	0.6	5	1
Cost of Manufacturing	5%	4	0.2	3	0.15	2	0.1
Team Contributions	5%	1	0.05	2	0.1	4	0.2
Potential for Improvement	5%	3	0.15	2	0.1	4	0.2
Total	100%	N/A	3.15	N/A	3.2	N/A	3.5
Rank		3		2		1	

Making Novelty and Potential for Improvement Less Important							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	25%		0		0		0
Cut-in Speed	30%		0		0		0
Moment of Inertia	10%		0		0		0
Sentiment from Researchers	25%		0		0		0
Cost of Manufacturing	5%		0		0		0
Team Contributions	2.5%		0		0		0
Potential for Improvement	2.5%		0		0		0
Total	100%	N/A	0	N/A	0	N/A	0
Rank		2		2		2	
Angelina							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	25%	5	1.25	1	0.25	2	0.5
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	4	1	5	1.25
Cost of Manufacturing	5%	4	0.2	2	0.1	2	0.1
Team Contributions	2.5%	1	0.025	3	0.075	4	0.1
Potential for Improvement	2.5%	3	0.075	1	0.025	4	0.1
Total	100%	N/A	3.35	N/A	3.45	N/A	3.55
Rank		3		2		1	
Keona							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	25%	5	1.25	1	0.25	2	0.5
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	3	0.75	4	1
Cost of Manufacturing	5%	4	0.2	3	0.15	3	0.15
Team Contributions	2.5%	1	0.025	3	0.075	4	0.1
Potential for Improvement	2.5%	2	0.05	1	0.025	3	0.075
Total	100%	N/A	3.325	N/A	3.25	N/A	3.325
Rank		2		3		2	
Ginger							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	25%	5	1.25	1	0.25	2	0.5
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	2	0.5	3	0.75	5	1.25
Cost of Manufacturing	5%	4	0.2	3	0.15	3	0.15
Team Contributions	2.5%	1	0.025	3	0.075	4	0.1
Potential for Improvement	2.5%	3	0.075	2	0.05	4	0.1
Total	100%	N/A	3.35	N/A	3.275	N/A	3.6
Rank		2		3		1	
Elliot							
		Savonius		EN0005		Helical Hybrid	
Criteria	Weight	Raw score	Weighted Score	Raw score	Weighted Score	Raw score	Weighted Score
Angular Velocity	25%	5	1.25	1	0.25	2	0.5
Cut-in Speed	30%	4	1.2	5	1.5	4	1.2
Moment of Inertia	10%	1	0.1	5	0.5	3	0.3
Sentiment from Researchers	25%	1	0.25	3	0.75	5	1.25
Cost of Manufacturing	5%	4	0.2	3	0.15	2	0.1
Team Contributions	2.5%	1	0.025	2	0.05	4	0.1
Potential for Improvement	2.5%	3	0.075	2	0.05	4	0.1
Total	100%	N/A	3.1	N/A	3.25	N/A	3.55
Rank		3		2		1	

Fig. J4. Evaluation matrix including team contribution and potential for improvement criteria at various weights.

Appendix K: CFD Best Practices and Set-Up

This appendix starts by outlining the ideal set-up based on our research and then details our actual set-up, explaining how and why it differs from our research.

Appendix K: CFD Best Practices and Set-Up

To determine how to set-up our CFD, we began by conducting research into best practices for CFD for VAWTs and based our set-up in large part on this research. Due to time constraints and tradeoffs between computational efficiency and accuracy, our set-up differs at times from these best practices. This appendix starts by outlining the ideal set-up based on our research and then details our actual set-up, explaining how and why it differs from our research.

CFD Best Practices for VAWTs

In general, it is necessary to use 3D simulations for VAWTs because 2D simulations fail to capture flow phenomena that impact VAWT aerodynamic performance. In particular, 2D studies ignore tip losses and parasitic drag from support struts causing them to overpredict peak C_p by 30% to 50% compared to 3D simulations and experimental data [K1]. 2D simulations can still be useful for qualitative trend identification and preliminary design comparative assessments, but 3D analysis is necessary for accurate performance prediction [K1].

The size of the outer domain is critical to minimize the influence of artificial boundaries on the flow around the turbine and its wake development. Table K1 summarizes recommended minimum distances from the turbine center compiled by [K1] based on systematic sensitivity studies.

Table K1

Minimum recommended outer domain dimensions to minimize influence of artificial boundaries [K1]

Upstream inlet	Minimum distance from turbine center of 10 to 15 times the turbine diameter (D) with 15D necessary to fully contain upstream induction zone
Downstream outlet	Minimum distance from turbine center of 10 to 14 times the turbine diameter. 10D is often sufficient for wake development
Domain width	A width of at least 20D is recommended to ensure the blockage ratio (turbine frontal area divided by domain cross-sectional area) stays below 5%
Domain height	Sufficient height to avoid boundary influence, 2.5D was used in one large-scale VAWT study, but there were not specific guidelines

In addition to setting the computational domain dimensions, setting appropriate boundary conditions, which define how the fluid behaves at the edges of the computation domain, is

necessary to achieve realistic results. The recommended boundary conditions are summarized in Table K2.

Table K2
Recommended boundary conditions, adapted from [K1]

Inlet	Specifies the incoming flow conditions. This is often a uniform velocity with a prescribed turbulence intensity and turbulent length scale, or a more
Outlet	Usually set to a zero-gauge pressure to allow the flow to exit the domain naturally
Side, top, and bottom boundaries	These are often symmetry planes to reduce computational cost.
Turbine surfaces	A no-slip wall condition is applied, meaning the fluid velocity at the surface is equal to the surface velocity.

Another key aspect of CFD set-up is appropriately choosing a turbulence model. Turbulence is characterized by chaotic, irregular flow occurring across diverse spatial and temporal scales. The free-stream air velocity is often turbulent, particularly in urban environments. In addition, as the fluid interacts with the rotating blades, it develops turbulent characteristics as boundary layers form, potentially separate and undergo a transition from laminar to turbulent flow [K1]. These factors make it necessary to treat the flow as turbulent. While directly resolving turbulence is possible, it requires numerically solving turbulent flows at a large range of temporal and spatial scales, making it nearly impossible for engineering applications. Instead, engineers use simplified turbulence models that are less computationally expensive, but still predict the main impact of turbulence on the flow [K2]. Choosing an appropriate turbulence model is an important decision to balance accuracy and computational cost.

There are two main families of turbulence models: Reynolds-averaged Navier Stoke (RANS) and Large Eddy Simulations (LES). RANS models focus on time-averaged flow properties and then model the effect of all turbulent eddies. RANS models are fast and computationally inexpensive, making them useful for applications where large-scale turbulent structures are not the primary interest. However, they are unsuitable for applications where flow instabilities, detailed vortex shedding, or transient phenomena are critical [K3]. Three common types of RANS models are k-epsilon ($k-\epsilon$), k-omega ($k-\omega$), and k- ω Shear Stress Transport (SST). K-epsilon is good when flow is fully turbulent and far from the walls or when computational cost is a major constraint. However, it is typically not suitable for VAWTs because of its inability to accurately model flows with strong pressure gradients and boundary layer separation [K1]. K-omega models are preferred for wall-bounded functions and flows with strong boundary layer effects, adverse pressure gradients, or mild flow separation. They resolve flow all the way to the wall, but require

a much finer mesh in the near wall region, increasing computational cost [K3]. The k- ω Shear Stress Transport (SST) model uses k- ω modeling in the inner parts of the boundary layer and switches to k- ϵ in the free-stream to avoid the k- ω model's sensitivity to freestream turbulence properties. It also contains a modification to improve its predictions of flow separation and pressure gradients [K3]. K- ω SST is widely regarded as the most suitable RANS model for VAWT simulations as it can accurately predict power coefficients and torque and provides reasonable agreement with experimental data and wake characteristics across various TSRs [K1]. It is recommended for initial design exploration and parametric studies, capturing the focus on our project.

In contrast to RANS models, LES simulations spatially filter out the smallest scales of turbulence and resolve the large scales of turbulence with the most energy directly. LES models are much higher fidelity than RANS models and capture transient flow structures, but they are much higher computational cost and require very fine meshes and small time steps to resolve large eddies. LES models are well suited for acoustics, combustion, and flows with large separation where RANS models fail [K3]. Due to their high computational costs, pure LES models are often used only in fundamental research, benchmarking studies, or simulations with simple geometry [K1].

In addition to pure RANS and LES models, there are hybrid models that aim to reduce computational cost of LES while maintaining some of the increased accuracy. One example is Detached Eddy Simulation (DES) which uses RANS in the boundary layer near the walls where it is efficient and accurate and switches to LES in regions away from the wall where the flow separates and large, unsteady eddies form [K3]. Hybrid models reflect ongoing efforts to resolve time-dependent features like dynamics stall and wake dynamics while minimizing computational cost [K1]. Fig. K1 shows how fidelity and computational cost often increase together for turbulence models.

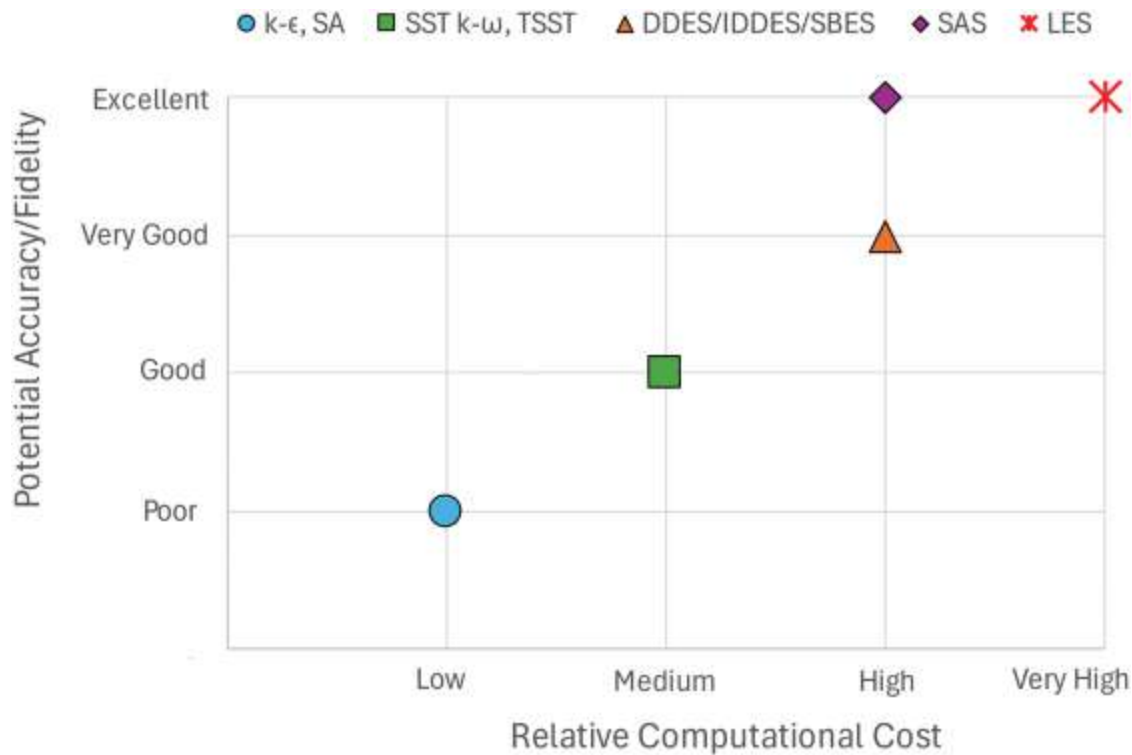


Fig. K1. Tradeoffs between computational cost and potential accuracy for common turbulence models [K1].

Another key aspect of CFD set-up is meshing, which is the process of dividing the continuous fluid domain into smaller, discrete cells, where the governing equations are solved at specific locations. In general, the smaller the cells and the greater the number of cells, the higher the computational cost. There are three broad categories of meshes: structured meshes, unstructured meshes, and hybrid meshes. Structured meshes have a regular grid pattern that allows for precise control of cell quality. They have high computational efficiency and are ideal for resolving the critical boundary layer region around VAWT airfoils where high orthogonality and smooth cell transitions are important. However, generating structured meshes for VAWTs can be difficult and time-consuming [K1]. Unstructured meshes typically use triangles in 2D or tetrahedra in 3D. They provide greater flexibility to handle the complex and irregular geometries of VAWTs and their generation can be automated. However, they can be more computationally expensive and can produce lower-quality cells if they are not generated carefully, which can impact solver convergence and solution accuracy [K1]. Finally, hybrid meshes use a structured mesh near the blade surface to accurately capture the boundary layer and a flexible, unstructured mesh for the rest of the computational domain. This ensures high fidelity results in the critical flow regions while minimizing computational cost. Hybrid meshes are the most common and effective strategy for high-fidelity aerodynamic studies of VAWTs [K1]. Fig. K2 shows an example of a structured, unstructured, and hybrid mesh.

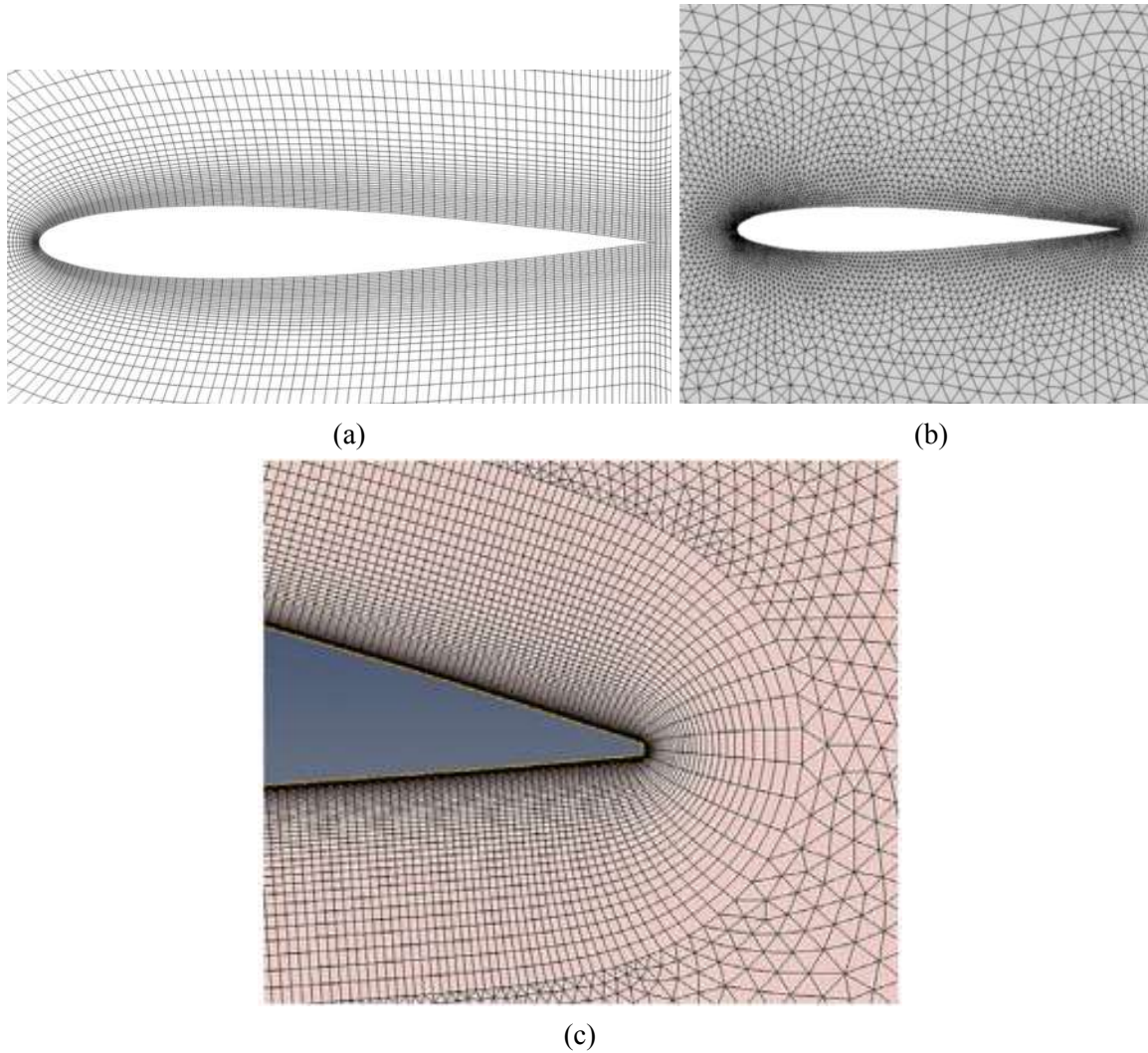


Fig. K2. (a) structured mesh [K4](b) unstructured mesh [K5] (c) hybrid mesh with structured mesh near the airfoil surface and unstructured mesh in the rest of the computational domain [K1].

It is particularly important to accurately capture the flow in the boundary layer in order to predict forces on the blades such as lift, drag, and torque and phenomena like flow separation and stall [K1]. This requires careful control of the mesh quality and resolution near the blades. A key parameter related to meshing in the boundary layer is the non-dimensional wall distance, y^+ , which represents the distance from the wall to the center of the first mesh cell, normalized by viscous scales. There are two ways to deal with this critical area near the blades: directly resolving the boundary layer and using wall modeling functions. Directly resolving the boundary layer uses a very fine mesh to directly compute turbulence viscous effects in the boundary layer without using approximations. This strategy typically requires $y^+ \leq 1$ to capture all the flow details, leading to higher accuracy potential and higher computational cost [K1]. Wall modeling functions approximate near wall behavior and can significantly reduce computational cost

because they do not require a fine mesh near the wall. However, there are potential accuracy limitations. When using wall functions, the y^+ values should typically be kept between 30 and 300 [K6]. Fig. K3 shows the mesh near the leading edge of an airfoil for both approaches to wall treatment.

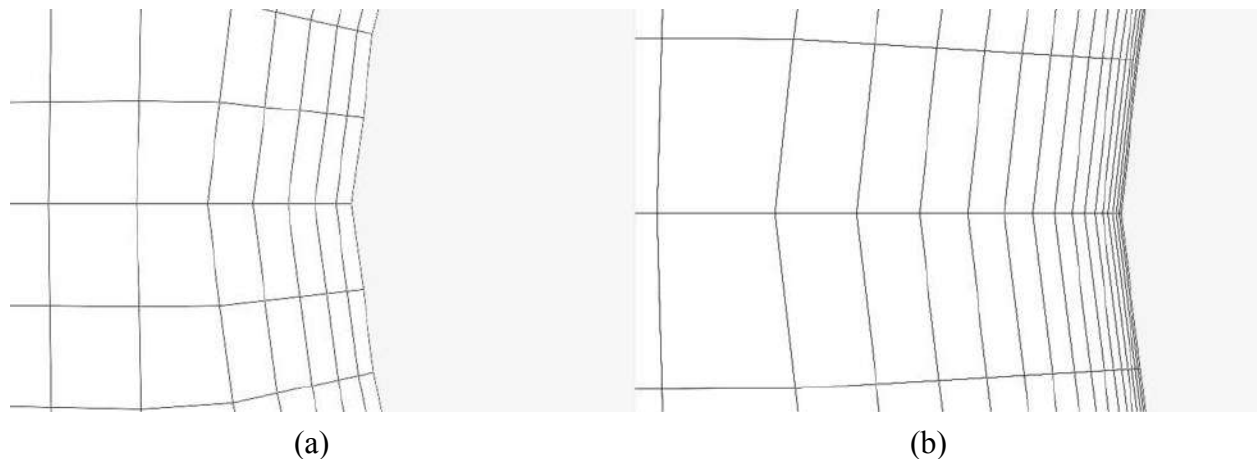


Fig. K3. (a) Wall modeling with 5 layers. The first layer follows the $y^+ > 30$ condition. (b) Full resolution of the wall boundary with 15 layers. The first layer follows the $y^+ < 1$ condition [K6].

The method of boundary layer meshing that is most appropriate for a given situation heavily depends on the chosen turbulence model. For Low-Re turbulence models like K-omega SST, very fine mesh resolution is needed near the walls so it is often necessary to directly resolve the boundary layer. High-Re turbulence models, such as standard k-epsilon models can use wall functions with coarser near wall meshes and higher y^+ values. For VAWT simulations, especially for those involving dynamic stall, it has been shown that accurately capturing the boundary layer development and separation requires fine near-wall resolutions. This means that for reliable torque and C_p predictions, it is often necessary to directly resolve the boundary layer [K1].

The last aspect of CFD set-up for VAWTs is the method for simulating the rotation of the turbine. Two types of rotating zones are Multiple Reference Frames (MRF) and Arbitrary Mesh Interface (AMI). The MRF approach is a steady-state approximation that uses a rotating reference frame that modifies the governing equations in the rotating zone to simulate the rotation of the turbine [K7]. In this approach, the mesh is not physically rotated. MRF simulations are much less computationally expensive than transient models, but fail to capture highly unsteady phenomena like dynamic stall, wake interaction, and vortex shedding [K1]. The AMI approach is a fully transient simulation that creates a mesh interface between the moving and stationary parts of the mesh and physically rotates the rotating domain at each time step, interpolating at the interface to allow for realistic movement. It is much more computationally expensive, but it takes all transient effects into account [K7]. For VAWT simulations, MRF can be used for initial design iterations, but it is less well suited for higher fidelity studies due to the inherent unsteadiness of VAWTs [K1]. For both MRF and AMI, the inner rotating domain is typically a cylinder that fully

encompasses the turbine blades. The diameter of this cylinder should be approximately 1.5 times the diameter of the turbine [K1].

Our Set-up

Our set-up took into account the best practices outlined in the previous section. All of our simulations used incompressible flow because VAWTs operate at low wind speeds where the density changes in air are negligible. In all of our simulations, we subtracted the blades from the flow volume to create a domain with only fluid and treated the resulting surfaces as walls with a no-slip condition. Table K3 summarizes the dimensions and boundary conditions we used in our CFD simulations.

Table K3
CFD set-up specifications

Parameter	Value
Radius of turbine (ft)	7
Height of turbine (ft)	7.78
Computational domain dimensions (ft)	
Distance from inlet to center of turbine (ft)	105
Distance from outlet to center of turbine (ft)	70
Distance from sides to center of turbine (ft)	70
Distance from top and bottom to center of turbine (ft)	77.8
Inner rotating domain dimensions	
Radius (ft)	5.25
Height (ft)	11.67
Turbulence model	K-omega SST
Boundary conditions	
Inlet	Fixed velocity of 2m/s with 5% turbulence intensity
Outlet pressure	Zero gauge pressure
Sides, top, and bottom	Symmetry

The main difference between our set-up and the best practices explained above relates to meshing. We initially attempted to directly resolve the boundary layer, but as we added more layers, we increasingly got warnings that our mesh quality was low, and in particular, that many cells had high non-orthogonality. Given our time constraints, we were not able to address this issue. In addition, we were not able to plot the y^+ values on the blades of the turbine and thus,

could not determine whether they were less than or equal to one. Because of all this, we used SimScale's physics-based mesh with three layers, an overall relative thickness of 0.4, and a growth rate of 1.5. This is an unstructured mesh that likely uses wall functions, but since we were not able to plot y^+ values, we could not verify that they were in the correct range. A key area of future work is improving the mesh quality by directly resolving the boundary layer and switching to a hybrid mesh for more control in the area near the blades. Fig. K5 shows our mesh around the Savonius and Helical Hybrid blades.

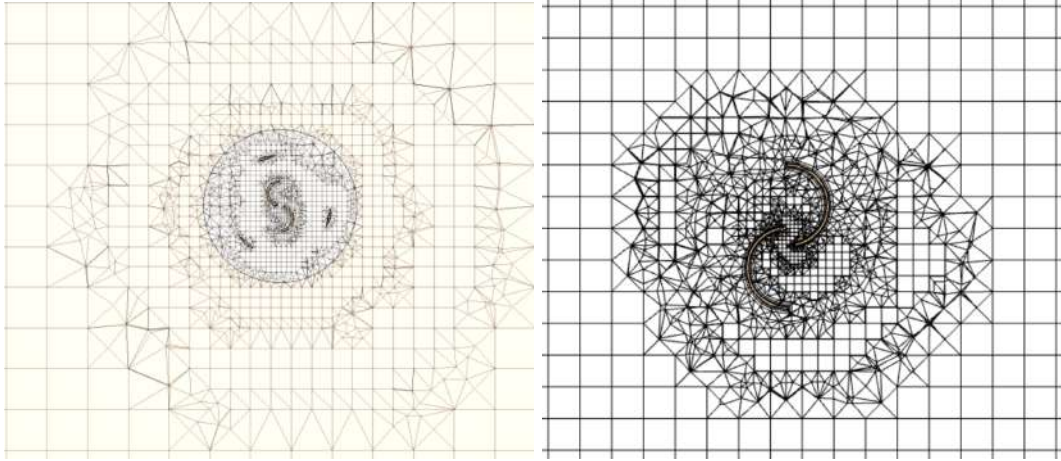


Fig. K5. Automatic physics-based boundary layer mesh for (a) a Helical Hybrid and (b) our classical Savonius.

To calculate the forces and moments on the blades, we had SimScale perform a line integral on the surfaces of the blades to calculate the forces and moments. We used the resulting torque to calculate a torque coefficient (C_T) and coefficient of power (C_P).

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Appendix L: CFD Preliminary Analysis

This appendix is an overview of our completed CFD work, including our initial goals and efforts, initial simulation set up, preliminary results, CFD validation, performance evaluation, and limitations and challenges.

Appendix L: CFD Preliminary Analysis

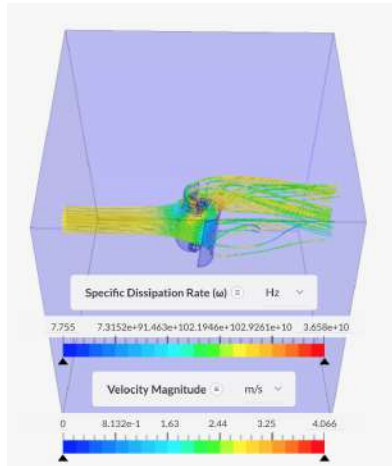
Purpose

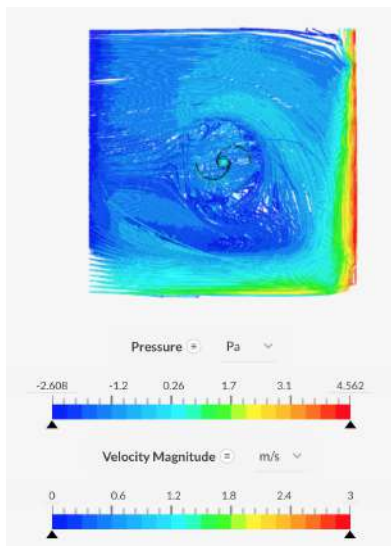
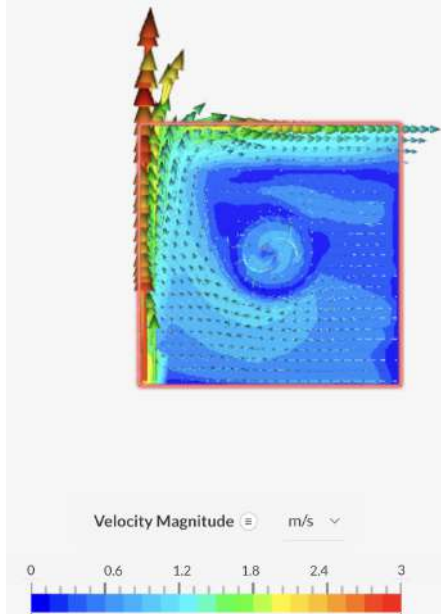
This appendix is an overview of the CFD work completed by VAWT Ventures, including initial goals and efforts, initial simulation set up, preliminary results, CFD validation, performance evaluation, and limitations and challenges. This appendix will include compiled tables of the principal studies run and the results of these studies. The order of this appendix is as follows: Preliminary Classical Savonius Study, Airfoil Validation, Complete Set Up of Classical Savonius.

Preliminary Classical Savonius Study

The goal of this initial classical Savonius was to gain familiarity with the software, as well as the user interface, and retrieve an initial set of preliminary results. This was our first study using Simscale, and we wanted to learn more about the set up methods for 3D models, and we wanted to get our first set of results. The first step was importing the VAWT geometry in the form of a STEP file from Fusion. The rotor diameter was 0.1 meters for this study. The study number, brief description, flow visualization, and results are given below in Table L1.

Table L1
Preliminary classical Savonius studies

Study #	Description	Flow Visualization	Results
1	- Rotating walls boundary conditions assigned to the blades set to 20 rad/s along z axis - Velocity inlet set to 3 m/s - No slip wall boundary conditions for the external flow volume sides (excluding velocity inlet and pressure outlet)	 The image shows a 3D CFD simulation of a Savonius rotor. The rotor is a two-bladed vertical-axis wind turbine. The flow field is visualized with streamlines and color-coded velocity magnitude. A color bar at the bottom indicates velocity magnitude in m/s, ranging from 0 to 4.066. Another color bar above it indicates specific dissipation rate in Hz, ranging from 7.755 to 3.658e+10. The rotor is shown in a cross-section, with the blades and the surrounding flow field.	C_t near zero

Study #	Description	Flow Visualization	Results
2	- Instead of rotating walls, used a MRF set to 20 rad/s - No slip wall boundary conditions assigned to the blades		C_t near zero
3	- Higher mesh quality - Using vectors for flow visualization		C_t near zero

Results

From these three studies, we learned best practices for flow visualization, how to interpret velocity profiles, how to interpret our results, and best practices for set up which would inform all of our future studies. For result interpretation, we learned about convergence plots, which are useful for numerical stability visualization to show if a simulation is running correctly. To do this we had to check the residuals and make sure that all of the plots converge to some value, and if the residuals showed diverging it would indicate an unstable model. The residuals of a well performing and accurate model should drop and converge to approximately $10e-4$, per

recommendation from Tom Ramsay from the Honda Automotive Laboratories of Ohio (HALO). For the set up methodology, we learned that the external flow domain, or virtual wind tunnel, should be at least 20 rotor diameters away from all sides of the rotating domain. We also learned about using wall symmetry instead of wall no slip conditions and began to apply that to all of our future studies. Furthermore, after study 2, we learned that the best way to visualize flow is to use vectors and not streamlines. This helped us to determine the issue in our set up model for study 3: the angular velocity of the turbine was overpowering the velocity inlet as can be seen in the flow visualization image in Table L1 under study 3. We also learned about meshing and standard wall functions which we looked into further for our next study. We also learned that any discontinuity around the contours of the rotating domain would indicate a calculation issue. Further we learned that, if the set TSR was greater than the inlet velocity we would expect to see swirling in the wake, but if the TSR was less than the inlet velocity we would see a wake.

Airfoil Validation

The goal of the airfoil validation was to gain confidence in our CFD results and to validate our lift and drag forces with recorded data. We were using values reported in NACA airfoil tools [L1] to validate our results. We validated our results to aerodynamic properties of a NACA 0012 airfoil at a Reynolds number of 50,000 and a 5 degree angle of attack. We would expect a lift coefficient of about 0.6, and a drag coefficient of about 0.025. The expected plots for the coefficient of lift and drag can be seen below in Fig. L1.

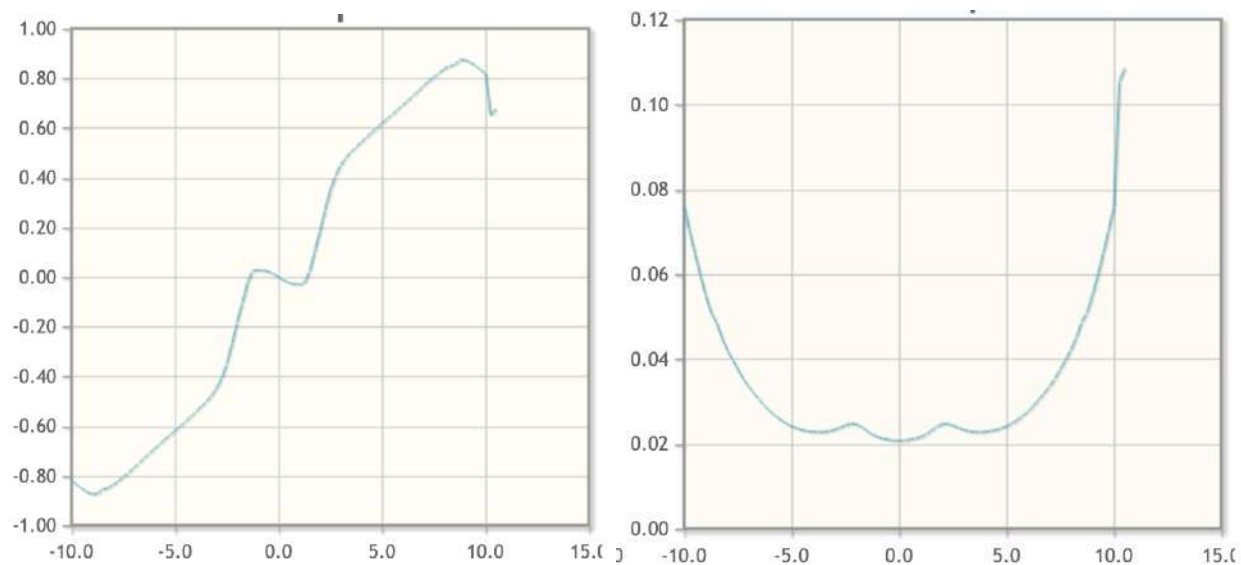


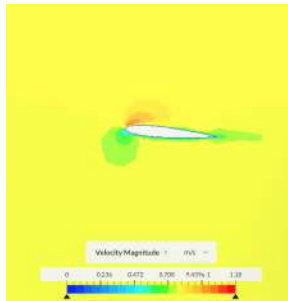
Fig. L1. Coefficient of Lift (Left) and Coefficient of Drag (Right) vs. angle of attack for a NACA 0012 airfoil [L1].

We began our validation by importing our NACA 0012 geometry that we had constructed in Fusion into simscale. This airfoil had a chord of 1 meter. Then we proceeded to calculate our inlet velocity by performing Reynolds number scaling, using Equation L1 provided below, where Re is the Reynolds number, ρ is the density, v is the velocity, L is the chord length, and μ is the kinematic viscosity.

$$Re = \frac{\rho v L}{\mu} \quad (L1)$$

Our known values were the density of the air, the kinematic viscosity of air, our set Reynolds number of 50,000, and our chord length which was 1 meter long. By plugging in our known values and rearranging for v , the inlet velocity, we were able to set an inlet velocity of 0.7645 m/s. The results from our studies are shown below in Table L2.

Table L2
Airfoil validation runs

Study #	Description	Flow Visualization	Results
1	- Set inlet velocity of 0.7645 m/s - Wall symmetry boundary conditions - Standard Mesh		Lift Coefficient ~ 0.012 Drag Coefficient ~ 0
2	Matched the inlet velocity with the free stream velocity given in the forces and moment coefficient calculations		Lift Coefficient ~ 0.57 Drag Coefficient ~ 0.04
3 (Validated)	- Used an inflated boundary layer mesh refinement with a growth rate of 1.15 - Used physics based meshing with hex core element		Lift Coefficient ~ 0.57 Drag Coefficient ~ 0.025

Results

From the Airfoil Validation studies we were able to validate our CFD results with recorded data online, we gained confidence in our CFD modeling, and we learned about inflated boundary layers. For the third study, we were able to get the expected results of approximately 0.6 for the coefficient of lift and about 0.025 for the coefficient of drag. Going from study 2 into study 3, we tried an inflated boundary layer to see if the model would more accurately compute the drag forces acting on the surface of the airfoil, because in study 2, the model was over predicting the coefficient of drag value to be closer to 0.04, while we would expect 0.025. This attempt proved successful, as our final recorded drag coefficient was closer to 0.025.

Complete Set up of the Classical Savonius

The complete set up of the classical Savonius was our second attempt at modeling the classical Savonius. This was done for the purpose of validation and matching our coefficient of power and coefficient of torque values with recorded values in literature. Our process for these studies involved matching approximate TSR values with the values recorded in literature, and then solving the model to compare our results with recorded values from past studies in literature. We set TSR values based on the optimal TSR operating range for a classical Savonius (0.7-0.8) which can be referenced in Appendix M. Then using Equation L2 below, we solved for the angular velocity, where TSR is the tip speed ratio, ω is the angular velocity, R is the rotor radius, and U is the freestream velocity.

$$TSR = \frac{\omega * R}{U} \quad (L2)$$

We would expect to see a C_p of around 0.2 - 0.25 for a TSR range of 0.7-0.8, as can be seen in Fig. L2, our validation source. Our studies, their descriptions, flow visualization, and results can all be seen in Table L3.

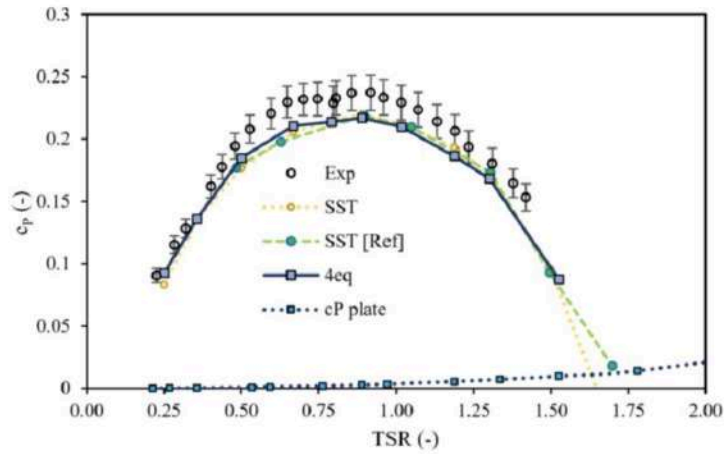
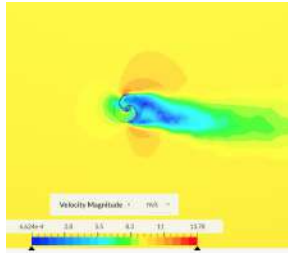
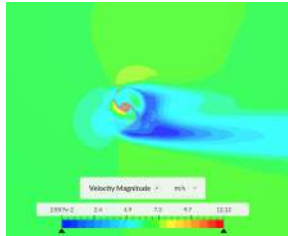
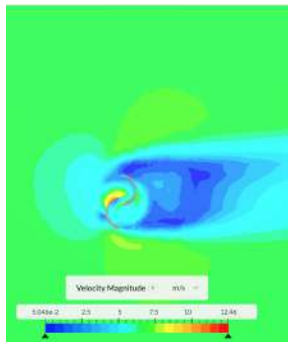


Fig. L2. C_p vs TSR for a Classical Savonius Model [L2].

Table L3
Complete Set up of the Classical Savonius Studies

Study #	Description	Flow Visualization	Results
Study 1 (Rotor Diameter = 2.134 meters) (TSR = 7)	- Set velocity inlet of 2 m/s - Set angular velocity of 1.4 rad/s		$C_T \sim 0.9$ $C_p = C_t \cdot \text{TSR} \sim 0.63$
Study 2 (Rotor Diameter = 2.134 meters) (TSR = 0.7)	- Matched the inlet velocity with the free stream velocity in the forces and moments coefficient calculations - Set an accurate reference length		$C_T \sim 1.82$ $C_p \sim 1.274$ (physically impossible)

Study #	Description	Flow Visualization	Results
Study 3 (Rotor Diameter = 2.134 meters) (TSR = 0.8)	- Increased the inlet velocity to 10 m/s - Set the angular velocity to 3.29 rad/s		$C_T \sim -0.04$
Study 4 (Fixed the overlap ratio in our geometry to match that of the validation study) (Rotor Diameter = 1.096 meters) (TSR = 0.8)	Angular velocity set to 9.6 rad/s to match the TSR of 0.8		$C_T \sim 0$
Study 5 (Fixed the overlap ratio in our geometry to match that of the validation study) (Rotor Diameter = 1.096 meters) (TSR = 0.8)	Experimented with the lift and drag vectors in the lift and drag moment coefficient calculations		$C_T \sim 0.29$

Results

We were ultimately able to validate our results from our classical Savonius model with what would be expected at a TSR of 0.8. The moment coefficient we got can be seen below in Fig. L3, where the torque oscillates with a mean value of about 0.3. At a TSR of 0.8 we can calculate the coefficient of power by multiplying the moment coefficient with 0.8 to get a C_p of 0.24 which is what we would expect based on recorded values.

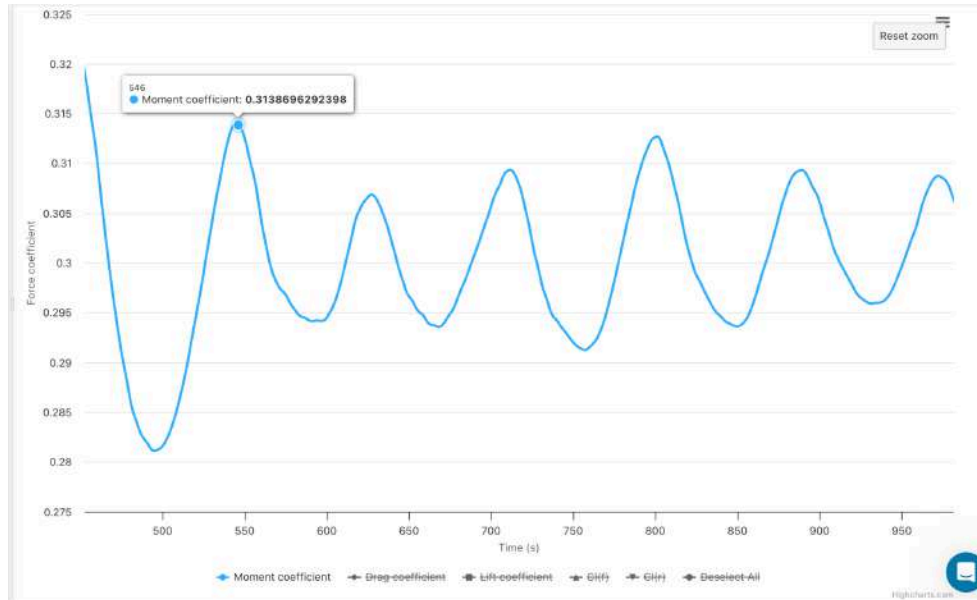


Fig. L3. Moment coefficient for the validated study of classical Savonius.

There were numerous studies that have not been recorded as we experimented with different mesh qualities, and we tried to directly resolve the boundary layer, and did mesh refinements. Those studies were not included in Table L3 due to inconclusive results. Further, there were numerous studies performed due to minor changes within the set up and the results did not seem to change. These minor changes included things like removing the top and bottom caps from our geometry to see how the aerodynamic properties would be affected, setting really high outliers to see if the torque coefficient would increase in value, experimenting with different TSR values, and inflating the boundary layers, however for all of these studies our torque coefficient results were inconclusive. The main takeaways we learned from this experiment was that the lift and drag vectors have to be set in the correct orientation, where the lift force is not in the z direction towards the shaft of the rotor, but instead faces into the blades and with the MRF the lift vector gets “moved” around in approximated time frames. We also learned about setting correct reference areas and reference lengths within the force and moment coefficient calculations as well as setting the correct axis of rotations centered specifically about the rotor. While our results seem to have matched our expected results from literature, we would still like to note our model limitations including boundary layer mashing. While we ran numerous simulations altering the mesh settings and trying to directly resolve the boundary layer, our model would produce inconclusive results, so we were ultimately unable to find an appropriate mesh for our model.

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Appendix M: CFD TSR Analysis

This appendix includes all of the results for both the classical Savonius and the helical hybrid tip speed ratio (TSR) analyses, including the set up, validation, and discussion.

Appendix M: CFD TSR Analysis

Introduction

A tip speed ratio (TSR) analysis is useful in determining an optimal TSR operating range for a VAWT. VAWTs tend to have an optimal operating range where the C_p is the highest, and when the TSR is out of this range, the C_p declines rapidly. The purpose of the TSR analysis was to determine the optimal range, as well as determine how the C_p was behaving with respect to altered TSR, and if our C_p matched what would be expected from literature. This appendix includes all of the results for both the classical Savonius and the helical hybrid TSR analyses including the set up, validation, and discussion.

Classical Savonius TSR Analysis

For the classical Savonius we wanted to test a TSR range from zero to 1.4 in increments of 0.2. It is reported in literature that the optimal TSR range for a classical savonius falls between 0.7-0.8, which is why we wanted to include those values in our range, while also having outliers. The outliers would help us determine if the model was accurately calculating the parasitic forces, which account for skin friction and drag forces. We would expect a parabolic C_p curve with a decline once the VAWTs TSR was out of the optimal TSR range (0.7-0.8). An example of this curve is shown below in Fig. M1 from the studies conducted on a classical Savonius by Milas et al. in 2022 using Ansys (an alternate CFD software) [M1]. In the figure we can see a parabolic curve with highest C_p values around 0.7-0.8 TSR, which is what we would have expected for our own study.

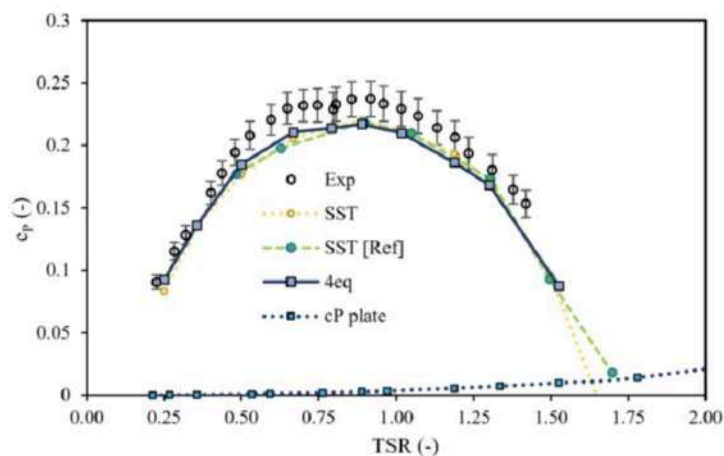


Fig. M1. Classical Savonius TSR analysis study [M1].

We began our study with the same workflow that had been set up previously (described in Appendix K). The differences included a parametric sweep of TSR values; however, since Simscale does not have the option of manually setting a TSR range, we instead calculated the corresponding angular velocities based on our TSR values while maintaining constant rotor radius and incoming velocity. We used Equation M1 to calculate the angular velocity, where ω is the angular velocity, TSR is the tip speed ratio, R is the rotor radius, and U_x is the free stream velocity. The output values are provided below in Table M1.

$$\omega = \frac{TSR * R}{U_x} \quad (M1)$$

Table M1
Parametric inputs for TSR analysis classical Savonius

Parameter	Value
Inlet Velocity	6 m/s
Rotor Radius	0.5 meters
TSR Values	{0, 0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4}
Angular Velocity Values	{0, 2.4, 4.8, 7.2, 9.6, 12, 14.4, 16.8}(rad/s)

Our results, shown below in Fig. M2, indicated a calculation flaw because our C_p continued to rise even though we would expect the C_p to increase until an optimal TSR range, and then rapidly decrease again due to the drag nature of Savonius rotors. The decrease in C_p at higher TSRs would be expected also due to parasitic forces, which accounts for skin friction and pressure drag. The C_p value at a TSR of approximately 0.8 still seemed to be within the expected range (0.15-0.25), which indicated an issue related to higher TSR values.

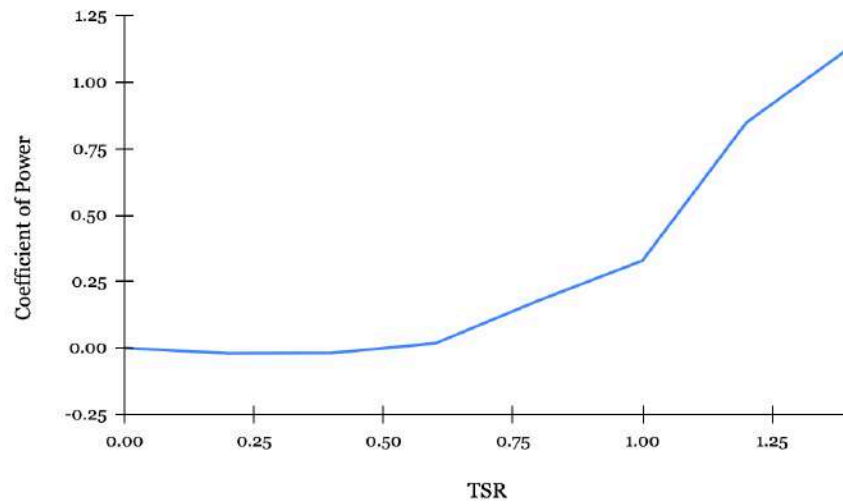


Fig. M2. Coefficient of power vs TSR for classical Savonius

Helical Hybrid TSR Analysis

After the Classical Savonius TSR analysis, we wanted to run a similar analysis of our selected concept, the full scale helical hybrid model, for validation purposes. The same procedure was followed except that the TSR ranged from 0.5 to 2.5 in increments of 0.5. While limited, current research shows that optimal TSR for helical hybrids can range from 0.5 to 2.5, and higher depending on the configuration [M2][M3]. Our set up parameters can be seen below in Table M2.

Table M2
Parametric inputs for TSR analysis helical hybrid

Parameter	Value
Inlet Velocity	2 m/s
Rotor Radius	1.077 meters
TSR Values	{0.5, 1, 1.5, 2, 2.5}
Angular Velocity Values	{0.9285, 1.857, 2.7855, 3.714, 4.6425}(rad/s)

This study resulted in the same inconclusive results, as the C_p continuously kept rising even though we would expect a decrease out of optimal range. The results are shown below in Fig. M3.

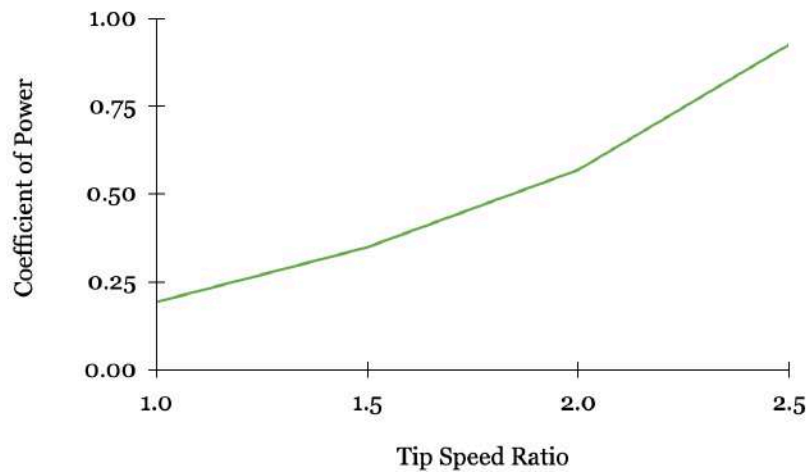


Fig. M3. Coefficient of power vs TSR for helical hybrid.

After coming across the same algorithmic flaw in our results, and upon advice from an external source with CFD expertise, the team subsequently decided to attempt a transient study. The main difference was that we set our rotating domain to be an Arbitrary Mesh Interface (AMI), and set our simulation control as shown below in Fig. M4.

Simulation control		
End time	1.8	s
Delta t	0.01	s
Adjustable time step	True	▼
Maximal Courant number	100	
Maximal step	1	
Write control	Adjustable runtime	▼
Write interval	0.05	s
Preferred number of CPUs	Automatic	▼
Maximum runtime	1.728e+5	s
Potential flow initialization	☐	
Decompose algorithm	Scotch	▼

Fig. M4. Simulation control set-up for transient studies

The results from the transient simulation had the same computational error. The C_p continuously rose to physically unrealistic values, higher than one. We also ran a simulation with a very extreme outlier for TSR to see if the C_p had decreased. Fig. M5 shows the results from this study below, plotting the total moment about the Z axis, or the moment about the shaft of the VAWT.

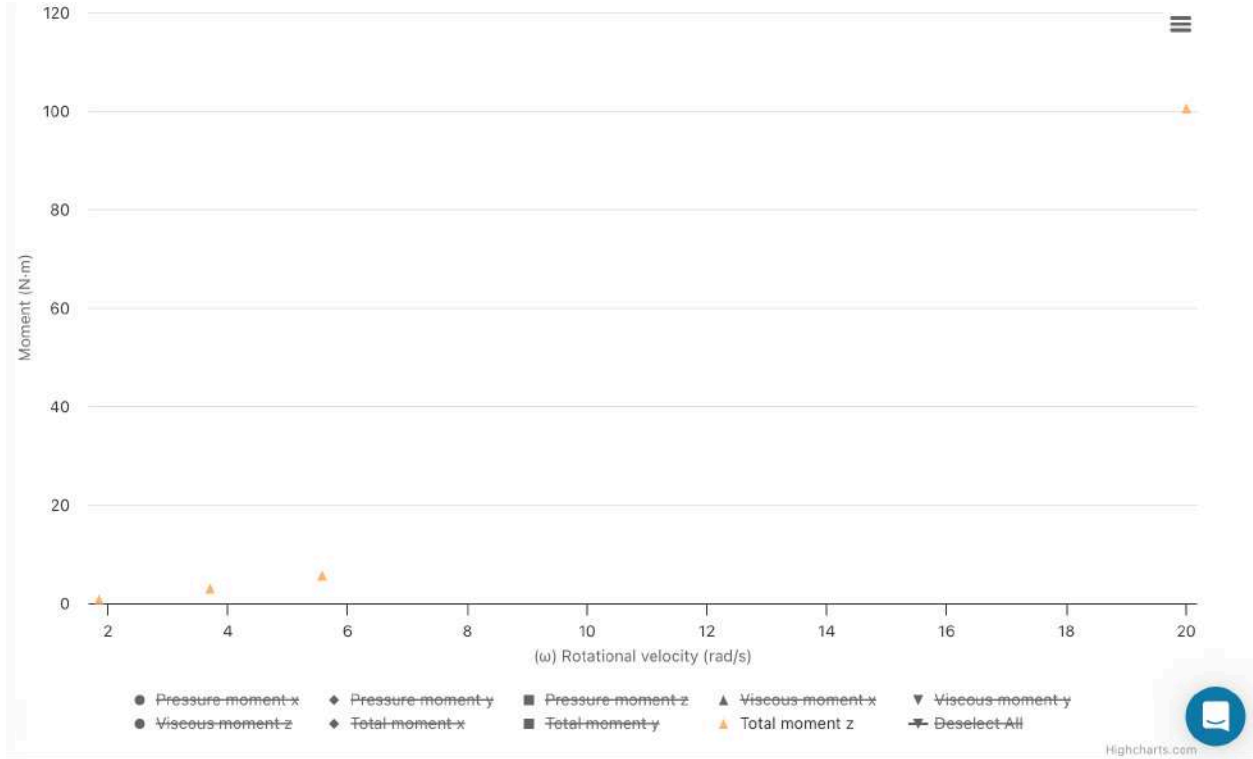


Fig. M5. Total moment (N*m) about the z-axis of our helical hybrid (shown by yellow triangles).

It is evident that the moment force rapidly rises to an unrealistic value, since if we use Equation M2 and M3, where C_M is the coefficient of moment, ρ is the density, S is the swept area, R is the rotor radius, V is the velocity, C_p is the coefficient of power, and TSR is the tip speed ratio, to calculate the C_p , we get a value much greater than 1 (not physically possible for any machine.)

$$C_m = \frac{\text{Total Moment } Z}{1/2(\rho)(S)(R)V^2} \quad (\text{M2})$$

$$C_p = C_m * \text{TSR} \quad (\text{M3})$$

However, we did notice more oscillation within the torque coefficient calculation, and we were able to use our flow profile animation to visualize fluid flow over the 3D rotating model.

Validation for TSR of 1

In the following study, a hybrid helical (outer Darrieus inner Savonius) was tested under different TSR's and the velocity profiles were compared [M4]. In Fig. M6. Asadi and Hassanzadeh were testing lower wind conditions in their study. This means that the internal Savonius rotor is the dominant mechanism, and so they performed a validation of the Savonius rotor, plotting C_p vs TSR study, shown below.

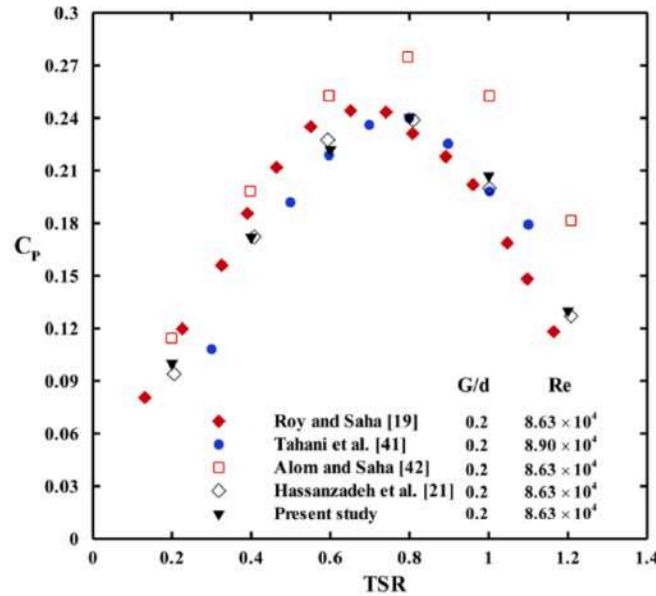


Fig. M6. Savonius validation TSR analysis [M4].

From this study, we can see that at a TSR of 1, the C_p of the VAWT is approximately 0.20. Furthermore, Fig. M7 below shows the results of a different study conducted on a similar outer Darrieus inner Savonius hybrid VAWT, where the blue shows just the results from the external Darrieus, orange shows the Savonius, and purple and green show the hybrid combination. It is evident from these results that the external Darrieus contributes very little power compared to the Savonius at such a low TSR value.

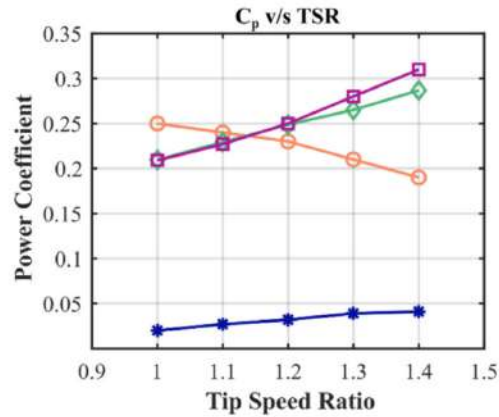


Figure M7. C_p vs TSR for a hybrid VAWT (blue showing solely the Darrieus) (orange solely the Savonius) and (purple and green showing hybrid configuration) [M5].

Using Fig. M7, above, we were able to determine that the C_p at a TSR of 1 for the helical combination was approximately 0.2. These sources helped us validate our own value of 0.19 at TSR of 1 and also helped us determine that the majority of the C_p is coming solely from the inner Savonius at a low TSR. This conclusion is helpful in understanding the functionality of hybrid VAWTs, and how the TSR is critical in determining the performance of the VAWT. The results from these studies also helped us validate our own value of 0.19 for C_p at a TSR of 1.

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Appendix N: Wind Tunnel Wake Analysis Set-Up

This appendix presents the setup, experimental methods, and results of the wind tunnel wake analysis conducted to compare with CFD simulations.

Appendix N: Wind Tunnel Wake Analysis Set-Up

This appendix presents the setup, experimental methods, and results of the wind tunnel wake analysis conducted to compare with CFD simulations.

Experimental Setup

We designed the wind tunnel setup to measure airflow characteristics across the horizontal plane of a VAWT prototype while it was in the wind tunnel. The prototype was placed within the test section of the wind tunnel, which was covered by a lid containing five evenly spaced holes as shown in Fig. N1. These holes allowed for the insertion of a pitot tube to collect voltage data at multiple positions across the test section.



Fig. N1. Wind tunnel test section with lid and pitot tube access holes.

The pitot tube was positioned manually through the holes to measure airflow conditions at specific locations relative to the prototype.

Voltage Measurements

We collected voltage readings at a wind tunnel operating speed of approximately 11 m/s (corresponding to 15 Hz speed setting on the wind tunnel control panel) and recorded two key measurements:

- Static Pressure Voltage (V_1): The tube opening was oriented perpendicular to the airflow, with the opening positioned at the top and extending slightly downward into one of the holes.
- Dynamic Pressure Voltage (V_2): The tube opening was aligned parallel to the airflow and faced upstream (toward the wind source).

Figs. N2 through N4 show the equipment and initial set up for this process.

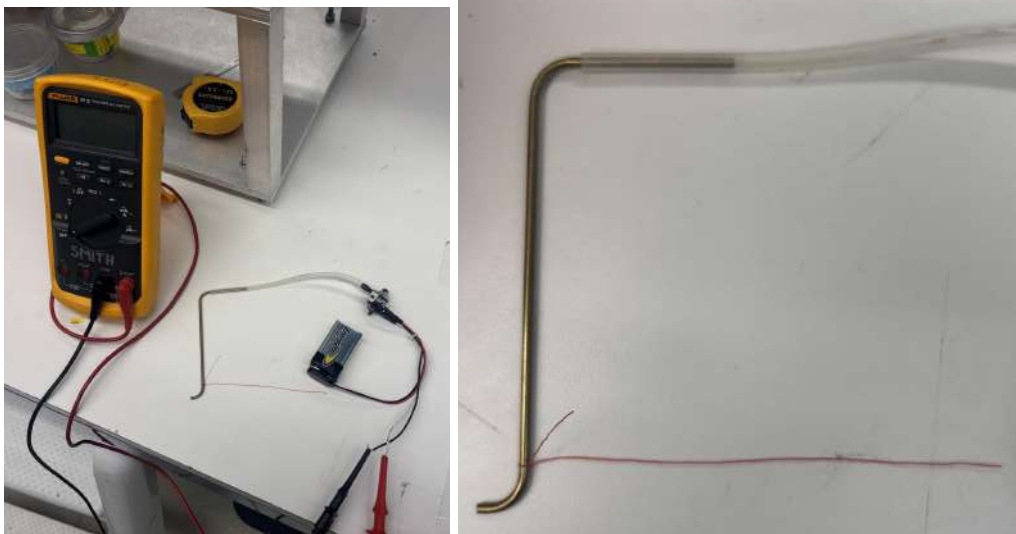


Fig. N2. Testing equipment: multimeter (left) and pitot tube with string attached for angle measurements (right).



Fig. N3. Static voltage measurement setup.

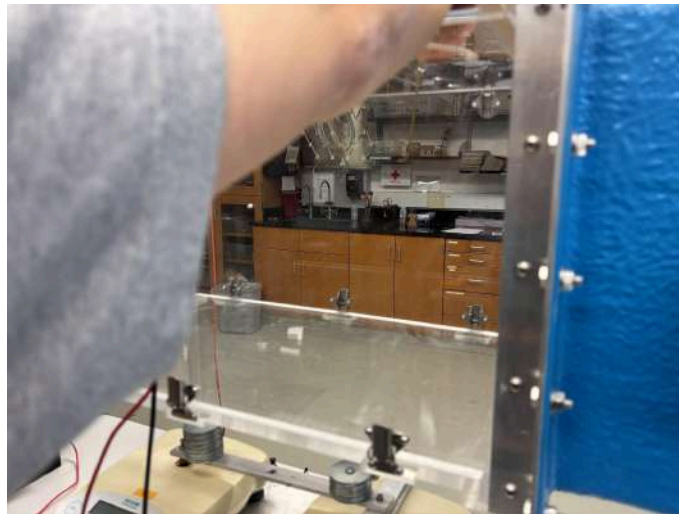


Fig. N4. Dynamic voltage measurement setup.

Voltage-to-Pressure Conversion

We converted voltage readings to pressure using the calibration relationship shown in (N1), where V_{out} is the nominal transfer value, V_s is the supply voltage, and P is pressure:

$$V_{out} = V_s (0.009 P + 0.04) \quad (N1)$$

The equation to solve for pressure is shown below in (N2):

$$P = ((V_s - 0.2) * (100000 / 4.5)) + 15000 \quad (N2)$$

We converted both static (V_1) and dynamic (V_2) voltage readings into pressures using equation (N2). We then used these pressures to determine airflow velocity through a simplified Bernoulli's equation (N3) where ρ is the density of air.

$$P_1/\rho = P_2/\rho + V_2^2/2 \quad (\text{N3})$$

Velocity Calculation

We calculated air velocity at each measurement point using Bernoulli's equation:

- $V_1 = 0$ m/s (ambient air outside the tunnel)
- Air density $\rho = 1.204$ kg/m³ (room temperature)

We determined velocity within the wind tunnel from the pressure difference between static and dynamic measurements.

Experimental Data

We collected measurements at a wind tunnel setting of 11 m/s (15 Hz) across the five holes in the test section lid, recording static voltage (V_1), dynamic voltage (V_2), flow angle, and resulting velocity at each location as shown in Table N1.

Table N1
Experimental data

Hole Location	V_1 (Static)	V_2 (Dynamic)	Flow Angle	Velocity (m/s)
Hole 1 (laser cutter side)	4.101 V	4.107 V	0°	14.88
Hole 2	4.100 V	4.106 V	~5° toward control panel	14.88
Hole 3	4.099 V	4.103 V	~15° toward control panel	12.15
Hole 4	4.099 V	4.104 V	~5° toward control panel	13.59
Hole 5 (control panel side)	4.099 V	4.104 V	0°	13.59

Measurement Workflow

The data processing workflow for each measurement location is summarized as:

Voltage $\rightarrow$ Pressure $\rightarrow$ Velocity

1. Record V_1 (static) and V_2 (dynamic)
2. Convert both voltages to pressure using the calibration equation
3. Compute velocity from the pressure difference using Bernoulli's equation

We used Desmos for all computations.

Flow Visualization

The visual results of the wind tunnel testing can be seen in Fig. N5.

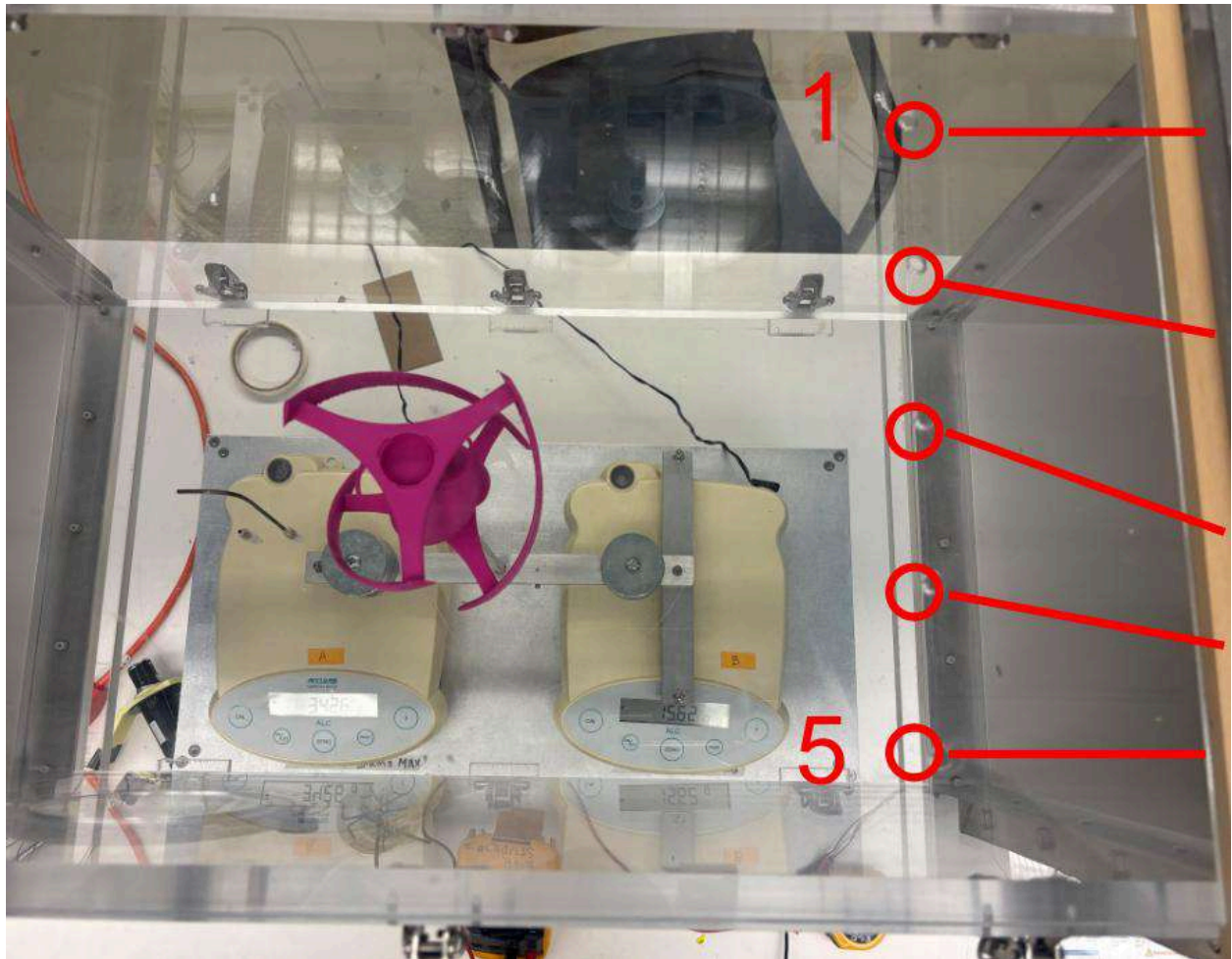


Fig. N5. Compiled results of wind tunnel testing.

Appendix O: Scaling

This appendix explores how scaling the selected VAWT geometry may affect its performance, specifically cut-in speed and tip speed ratio.

Appendix O: Scaling

Introduction

It is important to understand how the prototype of a VAWT will act at its full scale on a rooftop. Urban wind conditions make the turbine's behavior fairly unpredictable and realistic scaling is out of scope for this phase of the project. We determined it could still be useful to future phases for us to predict how cut-in speed and TSR may change as scaling occurs under one directional, constant velocity flow. In many fluid dynamics problems, the Reynolds number and Mach number can be used to create dynamic similarity between small models and full size configurations, allowing for experimental data from scaled models to be used to accurately predict full-scale aerodynamics forces such as lift and drag.

Scaling Factor

We scaled the size of our selected turbine up and down from the prototype with a 4.5 in diameter and 5 in height in Fusion and printed the three models shown in Fig. O1 below.



Fig. O1. The three prototypes used in scaling testing. From left to right the dimensions of the models are 7 x 6.3 in², 5 x 4.5 in², and 3x6.7 in².

The wind tunnel was the main constraint on the size of the turbine. At Smith College, our wind tunnel has a one foot by one foot cross section. We needed to keep the turbine within at least one inch from the walls of the tunnel, as the flow would be inconsistent near the boundaries (Fig. O2).

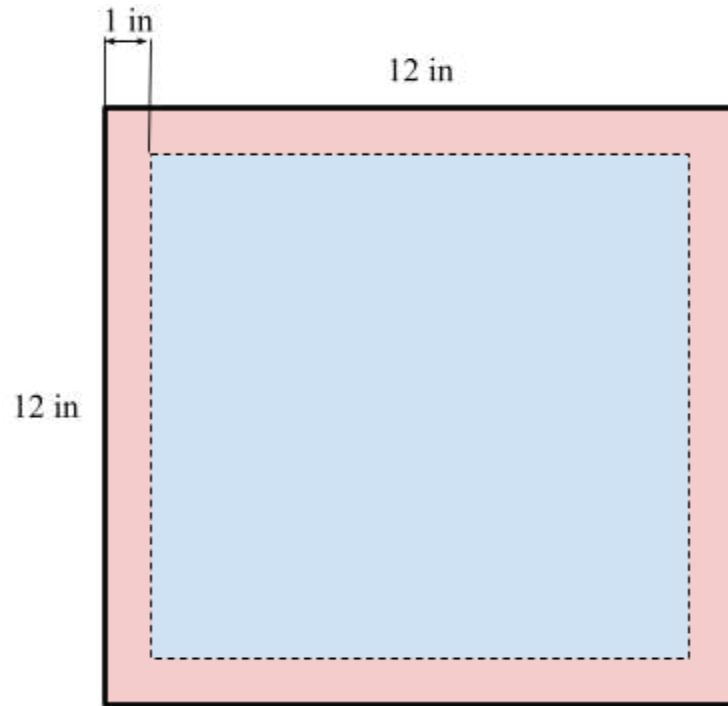
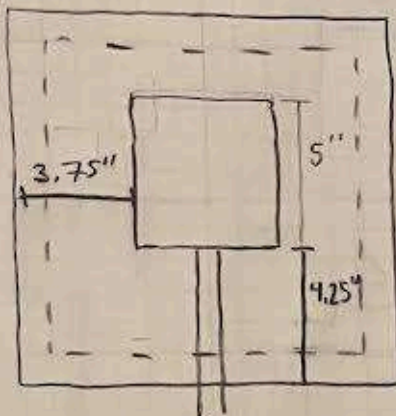


Fig. O2. Wind tunnel cross section 12x12 in² with 1 in of unusable space.

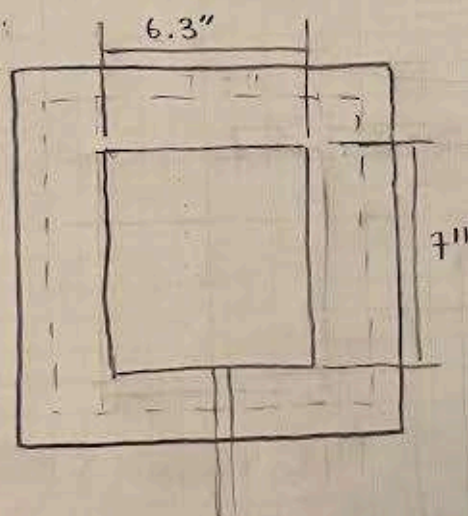
Since the models balance on the top of the pole, the top of each model will be at the same height. We determined the height was the limiting factor and that the tallest the model could be without bordering on the edges of the tunnel is 7 inches, then we scaled the width proportionally. These calculations are shown in Fig. O3. After scaling the larger turbine, we scaled down to the smaller turbine by the same amount. This led to heights of 7 in and 3 in respectively.

3/24/26
GS Scaling

original:



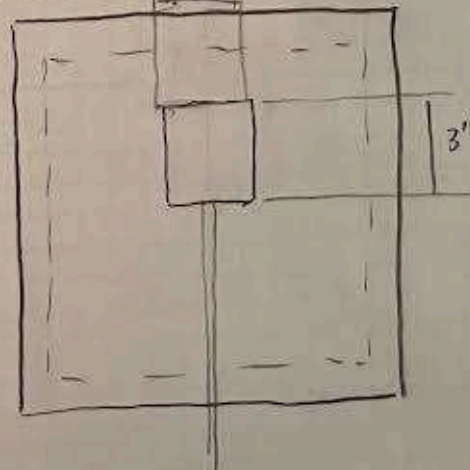
big:



Thought abt 8"
but small
@ 2" diam
seems
right
small

max h = 7"
max d = $4.5 \left(\frac{7}{5} \right) = 6.3"$

Small (same scale down):



small h = 3"
small d = $4.5 \left(\frac{3}{5} \right) = 2.7"$

Fig. O3. Calculations determining the sizes of scaled prototypes.

Testing and Results

In addition to determining the sizes of the turbines we wanted to test, we also needed to determine what tests we wanted to run on the turbine to gain insight on the effects of scaling. We knew the most important determination was cut-in speed, since we have been working to get the turbine to produce power at low wind speeds due to urban airflow conditions. We tested for cut-in speed by increasing the wind speed in the wind tunnel until the turbine began spinning. We performed two trials of this per model. We were only able to use the results from the original and larger models due to an issue with the smaller model we were unable to resolve due to time constraints.

We calculated the Reynolds number from the medium sized model by experimentally finding its cut-in speed. We then changed the velocity to match this Reynolds number for the large model. This is the theoretical cut-in speed for the large model. From there, we experimentally found the cut-in of the large model and compared the theoretical and experimental results (Table O1). The calculations for predicting cut-in speed using Reynolds number as a scaling factor are shown in Fig. O4.

Table O1

Results for cut-in speed for large (7 in x 6.3 in) VAWT model using Reynolds number calculated from experimental results for medium (5 in x 4.5 in) turbine

Size (height x diameter)	Experimental Cut-in Speed	Predicted Cut-in Speed by $Re = 2.5 \times 10^4$
7 in x 6.3 in	2.5 m/s	2.3 m/s

Cut-in Speed Scaled via Reynold's Number		GS
medium from testing: cut-in = 3.3 m/s D = 4.5 in = 0.1143 m	knowns about air: $\rho = 1.225 \text{ kg/m}^3$ $\mu = 1.8 \times 10^{-5} \text{ kg/m}\cdot\text{s}$ (at $\approx 20^\circ\text{C}$)	
$Re = \frac{\rho v D}{\mu} = \frac{(1.225 \text{ kg/m}^3)(3.3 \text{ m/s})(0.1143 \text{ m})}{1.8 \times 10^{-5} \text{ kg/m}\cdot\text{s}}$ $= 25,670 \approx 2.5 \times 10^4$		
cut-in for 6.3 in diameter model using $Re = 2.5 \times 10^4$:		
$Re = \frac{\rho v D}{\mu} \rightarrow v = \frac{Re \mu}{\rho D}$ $v = \frac{(2.5 \times 10^4)(1.8 \times 10^{-5} \text{ kg/m}\cdot\text{s})}{(1.225 \text{ kg/m}^3)(0.16 \text{ m})} = 2.3 \text{ m/s}$		
cut-in for 7ft diameter using $Re = 2.5 \times 10^4$:		
$v = \frac{(2.5 \times 10^4)(1.8 \times 10^{-5} \text{ kg/m}\cdot\text{s})}{(1.225 \text{ kg/m}^3)(7/3.281 \text{ m})} = 0.17 \text{ m/s}$		

Fig. O4. Calculations to predict cut-in speed using Reynolds number as a scaling factor

From these results, we can see the experimental cut-in matches the predicted cut-in closely. This tells us that it may be possible to use Reynolds number to scale to a full sized wind turbine. The other factor we wanted to understand was whether TSR would stay consistent using a wind speed scaled by Reynolds number.

In Tip Speed Ratio testing, we calculated the applied wind speed for the larger turbine by matching its Reynolds number to that of the medium turbine using its experimental wind speed. We then did angular velocity testing and calculated the TSR using those experimental values. The Tip Speed Ratio values were found using equation (O1).

$$TSR = \frac{\omega \cdot R}{v} \quad (O1)$$

Table O2
Results for TSR testing

Size (height x diameter)	Wind Speed	TSR
5" x 4.5"	6.8 m/s	0.11
7" x 6.3"	4.7 m/s	0.29

The results from TSR testing indicate that TSR does not remain the same at varying scales, even when keeping Reynolds number constant. This indicates that aerodynamic behavior and therefore C_p and power generation cannot be scaled using Reynolds number alone.

Conclusions and Recommendations

From the testing, we determined that it may be possible to predict cut-in speed with Reynolds number scaling, however TSR does not remain constant when scale is altered, even when Reynolds number is kept the same. This indicates that Reynolds number alone cannot be used to predict the dynamic behavior of a larger scale prototype from a smaller one.

In the future, we recommend continuing to test differently sized prototypes to confirm the results of our preliminary testing. It may also be useful to test different sizes of turbine with an oscillating fan to more closely mimic the conditions of a rooftop.

Appendix P: Economic Analysis

This appendix presents our initial economic analysis which we used to evaluate the commercial feasibility of our selected VAWT concept prior to mass production.

Appendix P: Economic Analysis

Introduction

VAWT Ventures performed an initial Economic Analysis to determine the feasibility of the selected VAWT concept in the commercial market, assuming it has not reached the mass-production scale. In our analysis, we looked at the cost of fullscale prototype production, the

Selected VAWT Construction and Bill of Materials

To perform an initial economic analysis for our selected VAWT, we needed to understand how the VAWT would be constructed and what materials would be needed to construct it.

Construction

In determining how the VAWT would be constructed, the team considered the structural stability of the VAWT, the cost to produce the VAWT, and the strength of the material connections between the VAWT. A visual of our final construction concept is shown in Fig. P1 below and a table describing the materials used in this final construction concept are shown in Table P1 below.



Fig. P1. CAD of final construction concept, including generator, flange mounts, pole and 3D printed blades and attachment to center.

Table P1
Bill of materials

Material	Cost Estimate
Generator [P1]	\$900
3D Plastic Printing	\$10,000
1 Central Aluminum Rod [P2]	\$600
3 Flange Mounts [P3]	\$300
Nuts, Bolts, Caulking / Hardware	\$200
Total Cost	\$12,000

McConnell Case Study

Before analyzing the performance of the turbine on McConnell Hall, we needed to estimate the power production of our VAWT under these conditions.

To determine power production on the roof of McConnell, we used Equation (P1) shown below. Equation (P1) produces the mechanical power produced by a VAWT from the amount of power available in the wind multiplied by an efficiency coefficient (the coefficient of power).

$$P_T = C_p \left(\frac{1}{2} \rho S U^3 \right) \quad (P1)$$

where P_T is the mechanical power produced, C_p is the coefficient of power, ρ is density, S is swept area, and U is wind velocity.

We estimated C_p at 0.19 from the results of our CFD analysis. The x-component of the velocity, U , was calculated from the 2025 wind data from the anemometers located ~ 7 ft above the roof of McConnell. In our calculations, we used the average from each day to get an average power estimate for that day and then added up those estimates to get the power production in the full year. The swept area was calculated to be 5.058m² based on the geometry of our fullscale VAWT which has a diameter of 7 ft and a height of 7.78 ft.

From these parameters, we calculated an estimated power production of $P_T = 9.85 \text{ kWh/yr}$.

This is not very much power and is only equivalent to saving 16.7 miles driven by car annually in greenhouse gas emissions. With a cost and power production estimate, we were able to perform an initial economic analysis using Rate of Return on investment (ROI) to understand whether the VAWT is commercially viable.

For a customer to breakeven, or make the money they spent on the product back in energy production, the ROI will equal zero. In Fig. P2 below, we set ROI equal to zero to calculate how long it will take for the consumer to breakeven.

I =	\$	12,000.00					
National \$/Kwh	\$	0.21					
E =		9.85	kwh	annually			
Life =		20	Years				
Time =		5802	Years				
		9.85	kWh				
	x	\$	0.21				
Annual Savings =	\$	2.07					
Net Savings =	\$	12,000.00					
ROI =	net gain	x100 =	\$	(0.0) x100	=	0	
	cost		\$	12,000.00			

Fig. P2. ROI set to zero to determine the amount of time it will take to break even

For ROI to equal zero the net savings must be equal to the initial investment (I) in the product (Fig. P3).

I =	\$	12,000.00					
National \$/Kwh	\$	0.21					
E =		9.85	kwh	annually			
Life =		20	Years				
Time =		5802	Years				
		9.85	kWh				
	x	\$	0.21				
Annual Savings =	\$	2.07					
Net Savings =	\$	12,000.00					
ROI =	net gain	x100 =	\$	(0.0) x100	=	0	
	cost		\$	12,000.00			

Fig. P3. The initial investment and net savings are equivalent.

The net savings are calculated by multiplying the annual savings by time. Fig. P4 shows that 5,802 years would be necessary for the VAWT to breakeven. The lifetime of a VAWT is generally between 20 and 30 years, so a 5,000 year breakeven is clearly unviable.

I =	\$	12,000.00				
National \$/Kwh	\$	0.21				
E =		9.85 kwh	annually			
Life =		20 Years				
Time =		5802 Years				
		9.85 kWh				
	x \$	0.21				
Annual Savings =	\$	2.07				
Net Savings =	\$	12,000.00				
ROI =	net gain	x100 =	\$ (0.0) x100	=		0
	cost		\$ 12,000.00			

Fig. P4. The time it will take for the VAWT to breakeven at its current power production and cost estimates is over 5,800 years.

Next, we estimated how much the VAWT would need to cost to breakeven in a more viable timeframe of 10 years. Over 10 years on McConnell, the VAWT will save \$20.68 on energy. With this level of energy savings, the VAWT would need to cost \$20.68 to break even in 10 years. This calculation can be seen in Fig. P5 below. Although in mass production, a product's cost will decrease, a decrease to \$20.68 is unreasonable, as the selected generator alone costs \$900.

I =	\$	12,000.00				
National \$/Kwh	\$	0.21				
E =		9.85 kwh	annually			
Life =		20 Years				
Time =		10 Years				
		9.85 kWh				
	x \$	0.21				
Annual Savings =	\$	2.07				
Net Savings =	\$	20.68				
ROI =	net gain	x100 =	\$ (11,979.3) x100	=		-99.82763
	cost		\$ 12,000.00			

Fig. P5. Net savings of \$20.68 from VAWT over 10 years.

9 m/s Rated Case Study

Since the VAWT was unable to produce a reasonable amount of power on the roof of McConnell, we decided to perform an additional economic analysis for an area with higher wind speeds. We tested multiple rated wind speeds in Equation (P1) above and selected 9 m/s because it provides

a roughly 0.5 kW rated power production, while still being a relatively low wind speed (Fig. P6). A rated power production of 0.5 kW also matches realistic ratings offered in commercial technology.

9 m/s					
TSR	0.8		Swept Area	5.06	m^2
Cp	0.19		ρ	1.225	kg/m^3
Diameter	7	ft	Rated Wind	9	m/s
Diameter	2.13	m			
Height	7.78	ft			
Height	2.37	m			
Power Production					
429	W				
0.43	kW				

Fig. P6. Rated power production of 0.43 kW at 9 m/s using Equation (P1).

We then used Equation (P2) below to calculate a realistic power output for the VAWT, where P_T is power output, CF is capacity factor, and CN is nominal power.

$$P_T = CF * CN * \text{hours/year} \quad (P2)$$

In our calculations for total power of the VAWT in 9 m/s wind conditions, we used a Capacity Factor estimate of 0.09, meaning we are assuming the VAWT is operating at its rated wind speed 9% of the time. This capacitor factor is based on a study by V. Kouloumpis, R.A Sobelowski, and X. Yan entitled “Performance and life cycle assessment of a small scale vertical axis wind turbine” [P4]. Since VAWTs are often not performing at their rated power, this additional factor is necessary to make a more accurate estimate of power generated. An estimate of power production using equation (P2) is shown in Fig. P7 below.

Conclusion

The turbine is not economically viable for our given wind conditions on McConnell and its estimated power generation. Wind speeds have the largest impact on power generation, as wind speed is increased, the power generation of our turbine will increase. Although operating at 9 m/s 9% of the time the turbine is still not economically viable, as this rated wind speed increases and/or the VAWT is moved to locations with more consistent higher speed wind, the VAWT will produce more power and therefore become more economical.

References

- [P1] 50W to 100kW Rated Power Motors Providing Higher Reliability and Robust Construction Suitable for Heavy Duty Industrial,” Permanent Magnet Alternator. [Online]. Available: <https://www.permanent-magnetalternator.com/sale-54947129-50w-to-100kw-rated-power-motors-providing-higher-reliability-and-robust-construction-suitable-for-he.html> [Accessed: April 20th, 2026].
- [P2] Metalsdepot® - Buy Steel Round Bar Online! (no date) MetalsDepot. Available: <https://www.metalsdepot.com/steel-products/steel-round-bar> (Accessed: 02 April 2026).
- [P3] *Configurable components: Distributor & manufacturer - buy online* (no date) MISUMI. Available: <https://us.misumi-ec.com/vona2/detail/110300011750/?HissuCode=STHCNL12-MB&seriesCode=110300011750&tab=drawingAndSpecifications&Page=1> (Accessed: 02 April 2026).
- [P4] V. Kouloumpis, R. A. Sobolewski, and X. Yan, “Performance and life cycle assessment of a small scale vertical axis wind turbine,” *Journal of Cleaner Production*, vol. 247, p. 119520, Feb. 2020. doi:10.1016/j.jclepro.2019.119520 [Accessed: October 17th, 2025]

Appendix Q: Power Electronics

This appendix outlines our approach to selecting and integrating off-the-shelf power electronics, with a focus on how generator choice supports the performance of our design.

Appendix Q: Power Electronics

In our work understanding wind turbines, we quickly learned that power electronics are an important component that impacts the power generation of the turbine. Power electronics encompass the electronic components of the turbine that convert mechanical energy into electrical power. There are ways for an engineer to design custom power electronics for specific turbines, but for our phase of the project, we decided to focus on optimizing the turbine aerodynamics and select an off the shelf generator that aligns with our needs for the VAWT. In this appendix, we detail some of the research that went into selecting a generator and specifications of the generator itself.

To select a generator, we looked into the types of generators currently used in wind turbines. Our priorities for a generator were mainly low-torque and low working wind speeds, since our turbine needs to function in low and variable wind speed environments. One paper provides clear tables of information summarizing literature on where different wind turbine generators are used, shown in Tables Q1 and Q2 below [Q1].

Table Q1
Comparison of turbine generators based on wind velocity [Q1]

Manufacturers - Reference	Type	Rated Wind Speed (m/s)	Working wind speed (m/s)	Power (kW)
Aircon 10	PMSG	11	2.5–25	10
Ampair ph	PMSG	12.6	3–25	0.1–0.3
ASW.6.4	PMSG	10	2.5–25	5
Eclectic Energy SG D400	PMSG	16	2.5–25	0.4
Eoltec	PMSG	12	2.7–25	6–250
ACSA A27/225	Asynchronus	13.5	3.5–20	225
Fuhrländer	Asynchronus	12	2.5–20	30–2700
Gaia-Wind A/S	Induction Generator	10	2.5–25	11
ACSA A20/100	Induction Generator	12	3–25	1000
Acowind A-63	Induction Generator	12	4.5–25	90
WS-WT 300W	SCIG	12	1.5–20	0.3
Aeritalia AIT 02	SCIG	10.1	4.2–20	225
Gazelle Wind Turbines	DFIG	13	4–20	20
AMSC wt1650df	DFIG	12	2.5–20	1650
Acciona AW-125/3000	DFIG	12	3.5–25	3000
2-B Energy 2B6	DFIG	13	3-25	6000

Table Q2
Comparison of wind turbine generators for HAWTs [Q1]

Generator Type	Horizontal-Axis Wind Turbines (HAWT)	Vertical-Axis Wind Turbines (VAWT)
Synchronous Generator	Commonly used in large-scale HAWTs due to its high efficiency and grid compatibility. The generator is directly connected to the grid, and its rotational speed must be synchronized with the grid frequency.	Less commonly used in VAWTs as synchronization with the grid is challenging. If used, it requires additional power electronics for grid connection.
Induction Generator	Widely used in medium to large HAWTs as it is relatively simple and does not require rotor excitation. Works well with variable wind speeds and grid connection.	Rarely used in VAWTs due to the difficulty of controlling the slip, which affects grid compatibility. Not ideal for variable wind speeds.
Permanent Magnet Generator	Increasingly popular in both HAWTs and VAWTs due to its high efficiency, compact size, and low maintenance. Provides better partial load efficiency.	Also gaining popularity in VAWTs as it offers advantages of high efficiency and low maintenance. Suitable for variable wind speeds.
Direct Drive Generator	Becoming more common in large HAWTs as it eliminates the gearbox, reducing maintenance and improving efficiency.	Occasionally used in VAWTs, especially smaller ones, to simplify the design and reduce maintenance.
Hybrid Generator	Used in certain HAWTs to combine different generator types for better performance under varying wind conditions.	Not commonly used in VAWTs due to the complexity of combining generator types.

From the available off-the shelf generator types, we determined that the permanent magnet generator would work well for our application. We chose this type because it is capable of generating electricity at low and variable wind speeds and has high power conversion efficiency. The specific generator we selected is the Greef low torque coreless permanent magnet generator rated at 0.5 kW, with a low starting torque of <0.1 Nm, and a low rated RPM of 200 rev/min, shown in Fig. Q1 below [Q2].



Fig. Q1. Images of selected Permanent Magnet Generator: 3 Phase Coreless 0.5 kW low torque Generator by Greef [Q3].

RPM Comparison

To understand how the selected generator will work with our turbine, we calculated the RPM range for our turbine on McConnell roof as well as the idealized 9 m/s case and compared these values to the reported RPM range for the generator shown in Fig. Q2 below.

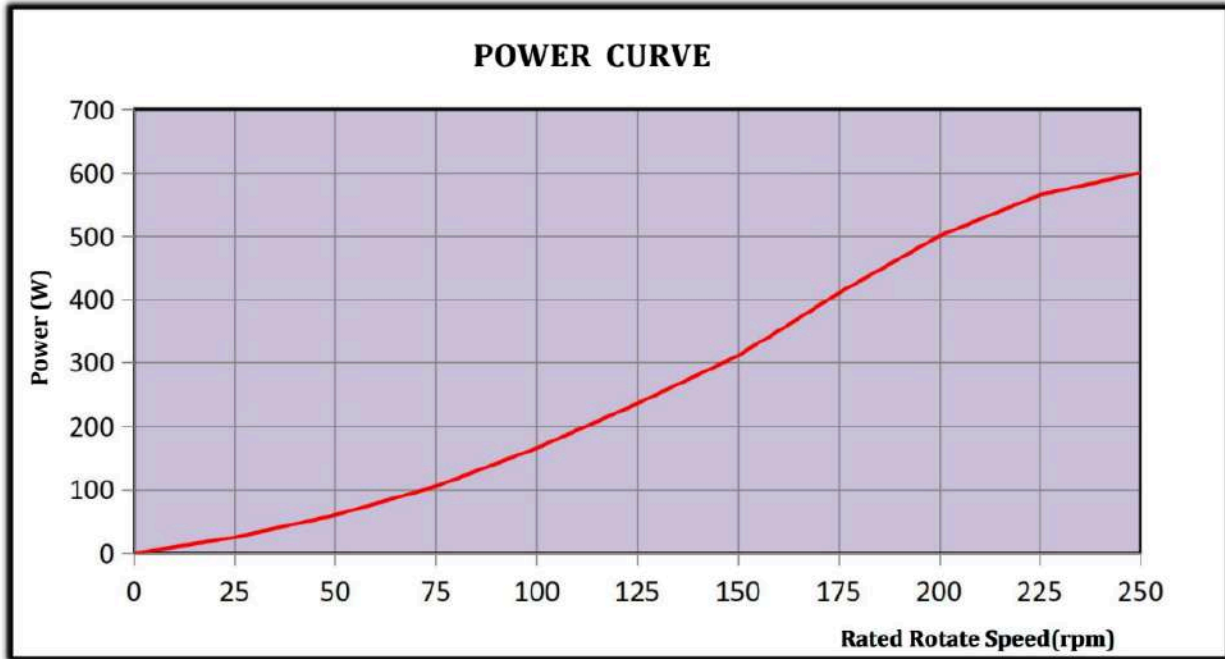


Fig. Q2. Power curve for 0.5kW three phase coreless low torque generator [Q3].

To calculate RPM, we used Equation (Q1), where ω is angular velocity, U is the velocity of the wind, and R is the radius of the turbine.

$$RPM = \omega * \frac{60}{2\pi} = \frac{TSR * U}{R} * \frac{60}{2\pi} \quad (Q1)$$

From this equation, we calculated the RPM for the average conditions on McConnell at 2 m/s, with an estimated TSR of 1 due to the low wind speeds. We then calculated the RPM for the same turbine under 9 m/s wind conditions with TSR varying between 1 and 3, since a hybrid is capable of a higher TSR range in higher wind conditions [Q4].

Under the conditions on the roof of McConnell, at 2 m/s, the RPM will be much lower. We calculated the RPM to be 14.1 rev/min at a TSR of 0.8 (estimated due to the low wind conditions) with a power output of 6.2 W. Although the generator is not operating at maximum efficiency at the 2 m/s RPM, it is still presented as capable of producing power and the power output of the generator and turbine align relatively well since the turbine is also incapable of producing much power at low wind speeds.

For the 9 m/s case, we calculate the rated RPM of our turbine to be 93 rev/min at a TSR of 1, 185 rev/min at a TSR of 2, and 278 rev/min at a TSR of 3. The TSR of our turbine at 9 m/s is something that needs to be analyzed further to understand it in ideal conditions. Ideally, its maximum condition would match well with the rated 200 rev/min, but this is not something we can say definitively without knowing the TSR of the turbine at higher wind speeds.

Conclusion

In summary, the type of generator was selected to align with the turbine based on its low starting torque, low rated rotations per minute, and its ability to work under variable wind conditions. Greef's Phase Coreless Low Torque Generator and our designed turbine are well aligned in their power production capabilities and potentially in their rotations per minute depending on what TSR the wind turbine has at the rated wind speed of 9 m/s.

References

- [Q1] A. Mansouri, A. El Magri, R. Lajouad, I. El Myasse, E. K. Younes, and F. Giri, “Wind energy based conversion topologies and maximum power point tracking: A comprehensive review and analysis,” *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 6, 2023, Art. no. 100351, doi: 10.1016/j.prime.2023.100351.[Accessed: April 20th, 2026]
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Appendix R: Construction of VAWT

This appendix outlines construction considerations and design-for-construction principles to guide future teams in developing a full-scale VAWT prototype.

Appendix R: Construction of VAWT

Introduction

The process of constructing a full scale VAWT prototype would be up to a future phase team. Although they may not be constructing our selected VAWT, the principles of our construction and design for construction may be helpful to the next phase teams in understanding how they could approach this process. In this appendix, we detail our thinking of how the VAWT would be constructed, what materials and parts are necessary to construct the VAWT, and 3D printing specifications.

Construction

In determining how the VAWT would be constructed, the team considered the structural stability of the VAWT, the cost to produce the VAWT at low-scale production, and the strength of the material connections between the VAWT. The full VAWT construction CAD is shown in Fig. R1 below.



Fig. R1. CAD of final construction concept, including generator (at bottom), flange mounts, pole and 3D printed blades and attachment to center.

We selected to 3D print the majority of the design because plastic to plastic connections will be stronger than metal to plastic connections, so we wanted to limit the number of metal to plastic connections we included. The cheapest option in large scale 3D printing is Fusion Deposition

Modeling, which we recommend for this reason. We investigated alternative kinds of printing as well, which included Carbon DLS, HP Multijet Fusion, and Stereolithography [R1]. After reaching out to a few different sources, including Mack Prototype (a prototyping company out of Gardner, MA), UMass Amherst's Additive Manufacturing Lab, and MIT's Large Scale Additive Manufacturing Lab we determined FDM would be the most cost effective option and learned about the necessity of splitting the design into multiple pieces for print and removing unnecessarily complex geometric features. Fig. R2 below shows the portion of the final design to be 3D printed alone.



Fig. R2. CAD of 3D printed blades and 3D printed attachment to center.

Future Work

More work needs to be done by the next phase team to break up this design into sections for printing and include threaded holes for nuts and bolts that attach the plastic to the metal flange mounts and the internal Savonius to the pole. These threaded holes will be located in the triangle attachments to center and through the cylinder printed in the center of the Savonius to ensure a strong connection there.

References

[R1] 3D Printing / Additive Manufacturing,” *Mack Prototype, Inc.* [Online]. Available: <https://www.mackprototype.com/3d-printing-additive-manufacturing/>. [Accessed: May 1, 2026].

Appendix S: Structural Evaluation

This appendix outlines recommended approaches for structural analysis, suggested modeling strategies, and relevant sources that may help guide a future phase's work.

Appendix S: Structural Evaluation

Introduction

Our team developed the conceptual design and preliminary digital validation methods of a hybrid vertical axis wind turbine (VAWT) consisting of an internal helical Savonius rotor and three external helical Darrieus blades. Due to project time constraints, we did not complete structural analysis and finite element analysis (FEA) during Phase 1. These analyses will be critical for ensuring that the turbine design can be effectively manufactured and safely operated on a rooftop.

This appendix outlines recommended approaches for structural analysis, suggested modeling strategies, and relevant sources that may help guide a future phase's work.

Suggested FEA Workflow

FEA can be performed using the Simulation workspace in Fusion [S1].

Recommended process:

1. Perform analytical stress calculations to estimate initial dimensions
2. Build a simplified CAD model of structural components
3. Run static stress analysis to validate stresses and deflections
4. Conduct modal analysis to evaluate vibration behavior
5. Refine geometry or materials based on simulation results

FEA should be used primarily to validate analytical calculations, rather than as the sole method of determining design parameters.

Recommended Structural Analysis Areas

1. Blade Structural Analysis

The turbine blades will experience several loading conditions during operation and must be designed to withstand both aerodynamic and rotational forces.

Key considerations:

- Bending stresses from aerodynamic lift and drag forces
- Centripetal forces due to blade rotation
- Potential torsional stresses from uneven loading
- Optimal blade thickness and internal structure

Recommendations:

- Determine blade stresses using basic solid mechanics equations before performing FEA
- Consider hollow blade structures to reduce weight while maintaining stiffness
 - The current small-scale VAWT models use solid blades, so the blade geometry may need to be modified when scaling the design in Fusion

Relevant precedent:

A capstone project at Memorial University designed an H-rotor Darrieus turbine and used:

- Analytical bending and torsion calculations
- Composite laminate analysis
- FEA validation of blade stresses

Their methodology provides a useful example workflow for validating turbine blade structural performance [S2].

2. Shaft and Rotor Support Analysis

The central shaft transfers loads from the rotor to the generator and support structure.

Key considerations:

- Bending stresses caused by aerodynamic loads
- Torsional stress from transmitted torque
- Shaft deflection under loading
- Interaction between the shaft and blade support struts

Recommendations:

- Estimate loads using aerodynamic forces obtained from CFD simulations
- Use bending stress equations to determine preliminary shaft diameter
- Perform FEA to verify shaft stresses and deflection

3. Blade-Strut Attachment

The structural connections between the blades and the shaft must transfer loads efficiently.

Key considerations:

- Bending stresses in the struts
- Load transfer between blade, strut, and shaft

Recommendations:

- Conduct simplified beam calculations before validating designs with FEA

4. Vibration and Resonance Analysis

Wind turbines operate under cyclic loading, making vibration analysis critical.

Key considerations:

- Natural frequency of blades, shaft, and support structure
- Potential resonance with operating rotor speeds
- Structural stability of rotating components

Recommended approach:

1. Determine expected turbine operating speed
2. Calculate the frequency at which aerodynamic and centripetal loads vary during blade rotation
3. Perform modal analysis using FEA to determine natural frequencies
4. Compare natural frequencies with operating frequencies to ensure resonance is avoided

5. Critical Speed of the Drive Shaft

Rotating shafts may experience instability at certain speeds due to imbalance or eccentricity.

Key considerations:

- Critical shaft speed
- Shaft deflection and dynamic stability
- Generator coupling effects

Recommendations:

- Determine the expected operational rotational speed
- Calculate the shaft's critical speed and ensure it remains well above operational speed

Research and Validation Recommendations

Structural analysis should be supported by existing literature and validated modeling methods.

Recommended research areas include:

- Structural design of Darrieus and Savonius turbines
- Composite turbine blade structures
- Vibration behavior of rotating shafts
- Rooftop wind turbine structural considerations

Validation of results can be achieved through:

- Comparison with published turbine designs
- Sensitivity analyses on material properties and loads
- Experimental testing of prototype components

Conclusion

The next phase team should approach structural analysis through a combination of analytical calculations, FEA validation, and comparison with existing turbine research. This multi-step process will help ensure the turbine is structurally feasible before prototype construction.

References

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