Research article

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# Design, construction, and scaling of a direct drive MAGLEV vertical-axis wind turbine


## Abstract

Magnetic Levitation (MAGLEV) systems are becoming increasingly popular in vertical-axis wind turbines due to their ability to reduce friction and wear. The present research investigates the design, construction and efficiency of a direct drive magnetically levitating Savonius vertical-axis wind turbine. In fabricating the prototypes of these wind turbines, three variations were developed and tested. The three variations of cup blade diameter size were tested with solidities of 0.545 (0.076 m diameter), 0.367 (0.05 m diameter), and 0.285 (0.038 m diameter cups). Tests were performed to determine the most effective approach for medium to high wind applications with and without MAGLEV. It was found that the MAGLEV system, with a solidity of 0.545, achieved the best efficiency and tip speed ratio of 0.56. In scaling the turbine, the research shows a promising design for manufacturing and further testing of these prototypes.


**Keywords:** magnetic levitation, vertical axis wind turbines, design, construction, efficiency, MAGLEV, solidity

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Caleb Polillio,[1] Nuggehalli M. Ravindra[2]

[1]Department of Mechanical & Industrial Engineering, New Jersey Institute of Technology, USA
[2]Department of Physics, New Jersey Institute of Technology, USA

**Correspondence:** Nuggehalli M Ravindra, Department of Physics, New Jersey Institute of Technology, Newark, New Jersey 07102, USA, Tel (973) 5963278, Fax 9735965794
Email nmravindra@gmail.com, ravindra@njit.edu

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**Abbreviations:** $C_p$, coefficient of power; HAWT, horizontal-axis wind turbine; VAWT, vertical-axis wind turbine; MAGLEV, magnetic levitation; m/s, meters per second; TSR, tip speed ratio; σ, solidity; RPM, rotations per minute; W, Watt; V, Volt; kWh, Kilowatt-hour

## Introduction

Renewable energy is becoming increasingly prevalent in recent years, enabling the world to produce clean and reliable sources of energy. These renewable energy sources include wind, solar, hydro, tidal, geothermal, and biomass. Wind being the most favored, dates back to the beginning of time. As early as 5000 B.C., wind energy was used to drive boats down the Nile River.[1] From then on, wind energy evolved into a very serviceable natural resource. It began to be used as an agent to produce grain, timber, oil, tobacco, and pumping water. It was not until 1887 that James Blyth invented the first electricity-producing wind turbine. He was able to simulate the conversion from kinetic energy (wind flowing) to mechanical energy (rotating a wind turbine) and subsequently to electrical energy (using a generator) to light his home. While James Blyth was one of the pioneers in wind-electric generation, he was not alone. Other notable inventors, Charles de Goyan and Charles Brush, were also involved in the field, growing the possibility of this clean energy source to new heights.[2] With the use of wind energy on the rise, more research started to be performed on all the components involved in the turbine.

### Efficiency

A significant discovery was made by Albert Betz in the theoretical aspect of turbines, who found that only 59% of the kinetic energy from wind can be converted to mechanical energy.[3] The company "Vernier Science Education" explains this well, "For a wind turbine to be 100% efficient, all of the energy available in the wind would need to be converted into electricity. In other words, all the energy in the wind would be transformed and the air would stop moving. This is not possible in practice because a rotor only spins if the wind passes over the blades" (Figure 1).[4]

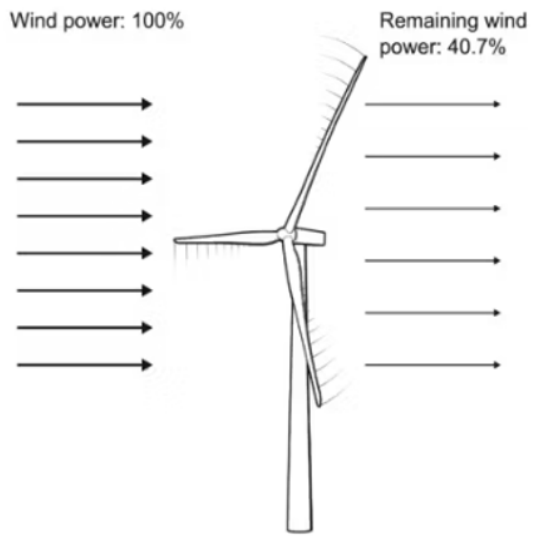


**Figure 1** Schematic of a traditional horizontal axis windmill.[4]

This is where the Coefficient of Power ($C_p$) comes into play. $C_p$ measures the efficiency of the wind turbine via equation (1). It is determined by calculating the ratio of the measured total electricity produced by the wind turbine to the maximum amount of energy in the wind at that speed.[5]

$$C_p = P \;/\left[1/2\left(\rho\, U^3 A\right)\right] \qquad (1)$$

where, $P$ = Electrical Power, $\rho$ = density of air, $U$ = wind velocity, $A$ = swept area of the blades.

### Horizontal-axis versus vertical-axis wind turbines

While there are many types of wind turbines, they can be classified into two categories, Horizontal-Axis (HAWT) and Vertical-Axis (VAWT). While HAWTs can harness more energy, they are both used in entirely different applications. Horizontal-axis wind turbines are applied in vast open areas where the wind is at high volume. They are much larger than VAWTs, ranging from 91.44 m tall onshore to around 152.4 m tall offshore. With the large rotor blades, the turbine can catch wind from the full rotation of the rotor in consistent airflow conditions.[6] A single HAWT can run at around 50% efficiency and can produce 26.1 MW in one day ≈ around 6000 MWh of electricity a year. Since HAWTs normally are in farms with around 50 units, that means a farm could produce 300,000 MWh a year, powering millions of homes.[7]

VAWTs are, at a smaller scale, applied in urban areas where wind direction can be variable. The major advantage of a VAWT is its ability to accept wind from any direction allowing manufacturing to be simpler. They can range anywhere from 0.914 to 21.336 m and have an efficiency between 15-40% based on the layout and orientation. The VAWT design method is categorized into two types based on the driven forces, Savonius and Darrieus. This is illustrated in Figure 2. Savonius wind turbines are propelled by the aerodynamic force of "drag". Drag is the force from the wind that acts in a direction parallel to the wind. While this force usually resists aircrafts, it drives the Savonius VAWT. The positive aspect of a drag-driven turbine is that it needs very little wind speed to start. The drawback is that since drag is driving only one blade at a time, there is resisting force on the other blades to rotate, so it can only perform at around 15-20% efficiency.

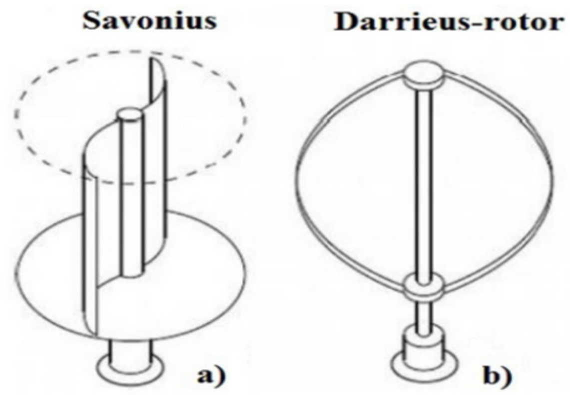


**Figure 2** Savonius vs Darrieus rotor blades.[8]

Darrieus wind turbines are propelled by the aerodynamic force of "lift". Unlike drag, lift force acts perpendicular to the wind direction. With this, the rotor blades are oriented in a way where the wind comes in contact with the blades, the lift force acts in the forward direction causing positive torque and rotation. The Darrieus type wind turbine runs at around 40% efficiency and can be a very good option for capturing electricity. The major drawback of the lift-driven approach is that it has a difficult time to self-start. Since the drag force is minimal, it is very hard to pick up the wind at a resting position. Self-starting capabilities have been implemented in the Darrieus system to help the turbine to start.[8]

Considering the size, efficiency, and design, the turbine can produce around 80-4,100 MWh of energy per year.[7]

VAWTs and HAWTs are complementary to each other because they both excel in the disadvantages of the other. In HAWTs, being able to catch wind throughout the entire rotation makes them exempt from a major drawback in VAWTs which is the backtracking effect.[6] The backtracking effect is what makes a VAWT less efficient than a HAWT. Since VAWTs are omnidirectional, they are very good at picking up variable wind, but it is also a drawback. Since they are rotating around a vertical axis, while one of the blades is picking up wind and rotating the shaft, the other blade is resisting the wind causing it to slow down. Especially with a cup-shaped Savonius type being drag-driven, the opposing cup is resisting much more than a Darrieus lift type.

Even though a VAWT, that is omnidirectional, can have a resistance as its drawback, it is a huge advantage. Since the HAWT can only accept wind from one direction, a yaw system has been implemented. Yaw systems are rotational mechanisms that track the direction of the wind. When the wind is flowing in a different direction, the yaw system aligns the turbine in the direction of the wind allowing it to capture as much wind as possible.[9] While this is an improvement for HAWTs, it is a complex system and adds more difficulty in construction, maintenance and cost.

## Magnetic levitation (MAGLEV) technology

In the constant and rapid development of wind turbines, a new technology has been immersed in VAWTs. Magnetic Levitation (MAGLEV) is a technique for holding a weight without support from outside structures.[10] The idea behind it involves having two magnets with like poles facing each other. With the magnetic like poles facing each other, it allows the wind turbine to function with reduced force on the generator. With this reduced force on the generator, the wind turbine can run smoother and with less friction. Furthermore, with no weight on a generator, it can have an extended shelf life, improving sustainability and maintenance costs. Figure 3 illustrates this well.[11]

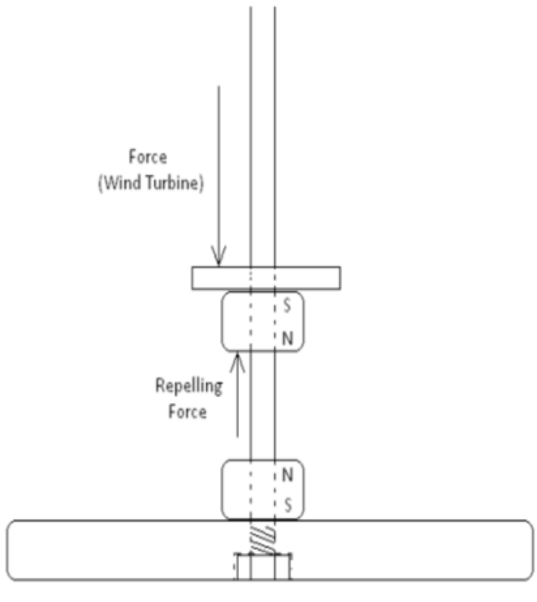


**Figure 3** Demonstration of MAGLEV technology.[11]

## Direct drive versus gearbox

Another aspect of wind turbine technology is to utilize gearboxes or direct drive mechanisms. Most Turbines today use a gearbox to increase the power output and torque proportionally using a gear ratio.[12] For example, if a wind turbine rotor is running at 100 rpm, a 10:1 gear ratio can be implemented, so as the rotor spins at 100 rpm, the generator spins at 1000 rpm. This can be very effective in maximizing the power output of the wind turbine. On the contrary, the gearbox produces a significant amount of friction, slowing down the turbine. Additionally, a gearbox can cause malfunctions in the system and increase the amount of maintenance needed on the wind turbine. In order to eliminate the constant maintenance and reduce frictional losses, a direct drive system has been implemented in wind turbines.

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The rotor is directly connected to the generator; so as the rotor blades rotate, the generator rotates at the same angular velocity. While this could make a turbine produce less power, it reduces the cost of maintenance and increases its reliability & sustainability (Figure 4).[13]

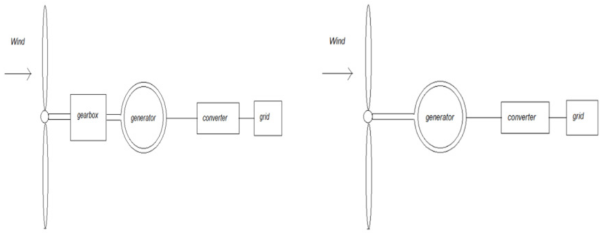


**Figure 4** Direct drive compared to a gearbox turbine.[13]

## Review and comparison of literature

In the paper "An experimental study on the performance of Savonius wind turbines related with the number of blades"[14] by Wenehenubuna et. al., the authors study the quantity of blades on a VAWT and its influence on performance. They fabricated a Savonius VAWT and tested it in a wind tunnel. Testing 2, 3, and 4 blades, they studied the Tip-Speed Ratio (TSR) of each wind turbine from 1-10 m/s wind speed. During wind speed of 1-6 m/s, the TSR increases significantly. After that, from 7-10 m/s, the TSR plateaus. Our studies show similar finding, demonstrating that the wind speed of 6-14 m/s keeps a similar TSR throughout. The authors also found that the 3-blade configuration was the best performing, showing a TSR of 0.56 at 7 m/s, confirming the results of the 3-blade design.

In "Design, Analysis & Fabrication of Maglev Vertical Axis Wind Turbine",[15] Patel et. al. aimed to harness power efficiently by reducing friction. They started by researching the field and selecting materials that were optimally fit for a wind turbine. After that, they fabricated their model. They were able to show the effectiveness of MAGLEV at low wind speeds providing a promising outlook for the future of Magnetic Levitation.

In "Design and Fabrication of Vertical Axis Wind Turbine with Magnetic Repulsion",[16] Nandurkar et. al. studied the MAGLEV system in a wind turbine to apply in very low wind speeds of around 1 m/s. Their goal was to achieve a very low self-starting capability and allow the turbine to run continuously even at very low speeds. They were able to get a self-start speed of 1.08 m/s which is low. While they were able to achieve a low self-start, the TSR was not high. It was not until the wind speed picked up that the TSR improved.

In the study "Designing and Manufacturing of Miniature Savonius Wind Turbine"[17] by Zein and Omar, the authors proposed a miniature Savonius wind turbine to mount on a bike. They planned to fabricate a wind turbine that could be mounted to a bike that would be able to charge low-power devices such as smartphones. They created a 0.108 m tall turbine with a 0.101 rotor diameter. They used 3D printing technology to physically demonstrate the prototype. The authors tested the windmill at wind speeds in the range of 4-12 m/s. They were able to produce high RPM (500-600 RPM) with the design but could only get a maximum efficiency of 3.5%. This was due to an increase in friction.

## Experimental methods

### Prototyping

In this study, throughout the research, prototyping and design became an integral part of the learning and analysis process. The goal of the prototype is to simulate the proposed method along with the different technologies involved, i.e., MAGLEV and direct drive, and to demonstrate its effectiveness to then scale up to manufacture. The project goal was to be able to design, fabricate and test a wind turbine with very minimal friction; thus, implementing the MAGLEV and direct drive were the best options.

In choosing the magnets for use to make the MAGLEV most effective, the hysteresis loop or (B-H curve) was the basis. The B-H curve represents the strength in magnetic properties of a material (Figure 5) and illustrates the relationship between the magnetic flux density B and the magnetizing field strength H.[18] In a MAGLEV wind turbine application, the second quadrant is very important because it represents demagnetization. Since the magnets are always opposing in MAGLEV, it can convey the maximum air gap allowed between the two magnets and the operating strengths at different positions that are away from each other.[19] The space between the magnets needed to be constant to reduce its vertical movement so that the stresses on the system were kept to a minimum. With that, it was found that the Ne-Fe-B (Neodymium-Iron-Boron) was the best option for MAGLEV due to its resistance to demagnetization and strong magnetic properties at room temperature.

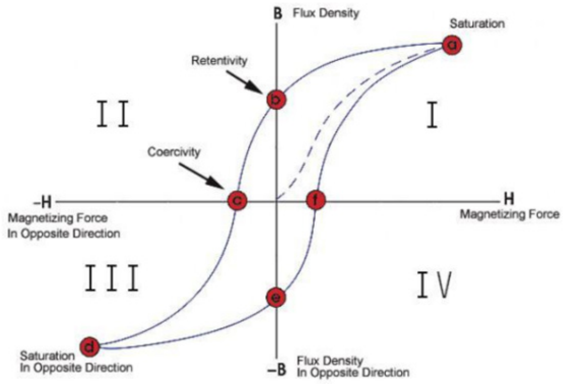


**Figure 5** General B-H Curve.[18]

In the construction of the prototype Direct Drive MAGLEV VAWT, 3D printing technology and other related machines were utilized. In striving for the best possible results, precision was key. 3D printing technology helps immensely with precision due to the accuracy and reliability of the machines. Using this technology, components for the wind turbine were printed. The components included the rotor bracket that holds the three rotor blades exactly 120 degrees apart. The software, Creo Parametric 9.0, was used to model the parts online and subsequently print using PLA (Polylactic Acid) filaments on a Cura Ultimaker 3D printer. PLA filaments helped to ensure the structural integrity and lightweight properties. A lathe, band saw, and drill press were pertinent machines needed to get the prototype correct. The lathe was used to make concentric holes that were needed for the connections between the various components. The band saw helped to get repeatable cuts on components such as the rotor blade supports. The drill press was used to create non-deviated holes for connections.

A strong, well-made generator is required to maximize the power output. Many generators were tested throughout the development process. With a limited budget and scaling opportunities, a brushless generator rated at 460 Kv was selected for the prototype. A brushless generator's rating is determined by its Kv, which is the ratio of the motor's unloaded revolutions per minute (rpm) to the peak voltage applied to the motor's coils. Achieving a low Kv depends on the coil wire size and number of turns. To reach low Kv, thin copper wire is needed at a higher number of turns of the coil. With that, it can achieve higher voltage at lower amperes producing a higher torque.[20]

The rotor blades were a difficult part of the process for picking up wind. We initially strived to make a Darrieus-type VAWT, but upon receiving non promising test results, we decided to switch to Savonius-type rotor blades. The Savonius rotor blades were made by cutting PVC (Polyvinyl Chloride) pipes to a height of 0.15 m, and then in half to make the shape of a cup. Keeping the rotor diameter (0.305 m) and height constant, we explored variable cup diameter. The following cup diameters were tested: 0.076 m, 0.05 m, 0.038 m. While we investigated various approaches to the design of the wind turbine (Figures 6a & 6b), only the results of the best-performing blades (Figure 6c) are presented here. See Table 1.

**Table 1** Specifications of overall VAWT prototype

| | |
|---|---|
| Height (overall) | 0.241 m |
| Blade height | 0.152 m |
| Rotor diameter | 0.305 m |
| Swept area | 0.046 $m^2$ |
| Support height | 0.102 m |
| MAGLEV distance apart | 0.019 m |
| Number of blades | 3 |
| Blade thickness | 0.006 m |

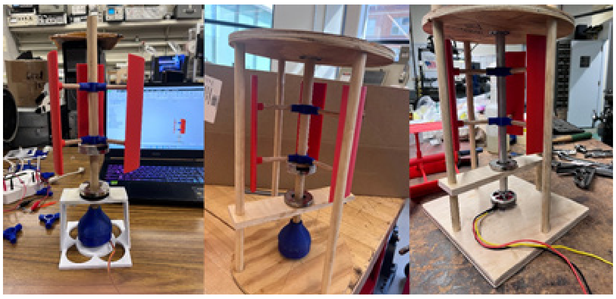

**Figure 6a** First prototypes. Added support to make it sturdier.

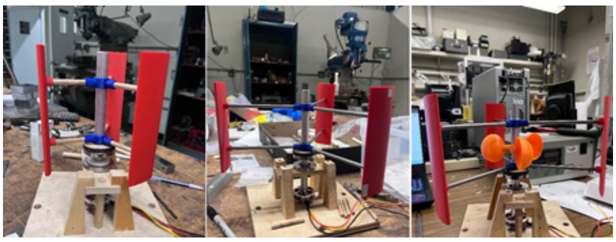

**Figure 6b** Change in support design to make it more secure and to fit into the wind tunnel. Increase in rotor diameter from 0.152 m to 0.305 m to increase the moment of inertia and torque. Hybrid design to allow better self-starting and more catch-on.

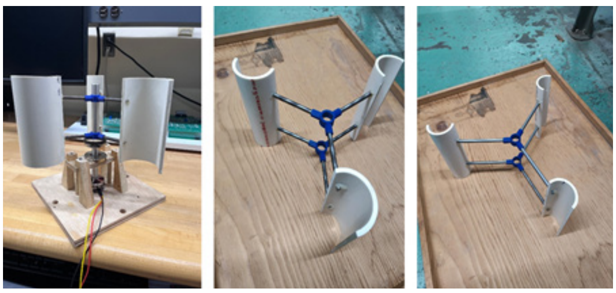

**Figure 6c** Final design with 0.076 m diameter cup, 0.051 m diameter cup, and 0.038 m diameter cup.

## Results and discussion

### Testing

After many iterations of prototypes, we followed the Savonius cup shape method to begin testing. In these tests, the performance of different cup diameters, at measured wind speeds with and without MAGLEV technology, are compared. We were able to utilize a wind tunnel (Figure 7) to test and obtain the most accurate results possible. The wind tunnel is effective in producing accurate results because of the enclosed space and the constant laminar flow it produces. Unfortunately, the lowest wind speed value in the tunnel was 6 m/s; so we had to test medium to high wind speed ranging from 6-14 m/s. Since the wind tunnel has a confined test space of 0.610 m x 0.305 m x 0.254 m, we had to optimize our wind turbine prototype to fit in the space available in the wind tunnel.


**Figure 7** Wind tunnel utilized in testing.

In testing the effectiveness of a VAWT, three variables were tested. The Coefficient of Power ($C_p$), the TSR, and the solidity (σ). $C_p$, as stated before, measures the efficiency of the wind turbine. For this approach, a $C_p$ of 0.15-0.2 or (15-20% efficiency) is desired. The TSR measures how fast the wind turbine is rotating with respect to the wind speed and can be calculated using Equation (2). TSR is a very important measurement because it shows how the blades are performing. The optimal TSR for a Savonius-type wind turbine ranges from 0-1.2.[21]

Solidity (σ) measures the amount of surface the cups are taking up compared to the empty space on the rotor, described by Equation (3). A lower solidity can lead to a faster rotational speed but experience a lower torque. With higher solidity, the rotational speed is slower, but it has higher torque.[22] The optimal range of solidity for a VAWT is 0.2-1.28.[23] The solidities for the 0.076 m, 0.051 m and 0.038 m are as follows: 0.545, 0.367, 0.285.

$$\mathrm{TSR} = \omega * r/v \quad (2)$$

Tip-Speed Ratio equation: $\omega$ = angular velocity of the wind turbine (rad/s). r = radius (m) v = wind speed (m/s).

$$\sigma = Nc / \pi R \quad (3)$$

Solidity equation: N = number of blades, c = chord length (m), R = radius of rotor (m).

### Results

Figure 8a shows the variation in the power coefficient as the wind speed increases. As the wind speed increases, the coefficient of power

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decreases. This result is generally acceptable since VAWTs are much more effective at lower wind speeds. The turbine is the most efficient at 6 m/s for all cup shapes with the 0.076 m diameter cup being the best, resulting in a $C_p$ of 0.066 or 6.6% efficient. The 0.051 m cup was only able to achieve 0.03, and for the 0.038 m, it was 0.013. The major decrease in $C_p$ from the 0.076 m diameter cup to the 0.051 m and 0.038 m explains the importance of considering solidity when modeling vertical axis windmills. With higher solidity, the turbine performed much better. This can be attributed to the amount of wind the turbine can pick up in rotation with larger blades.

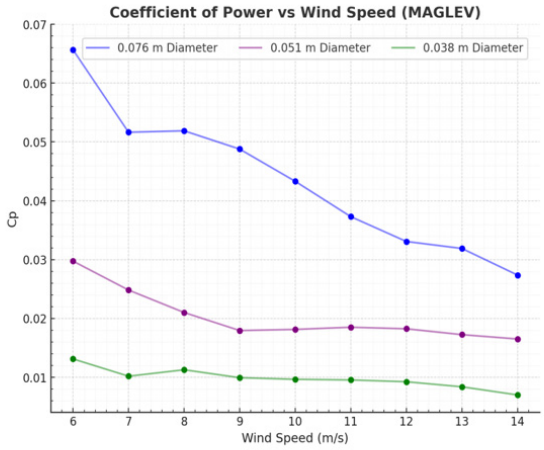


**Figure 8a** Coefficient of Power at different wind speeds with MAGLEV.

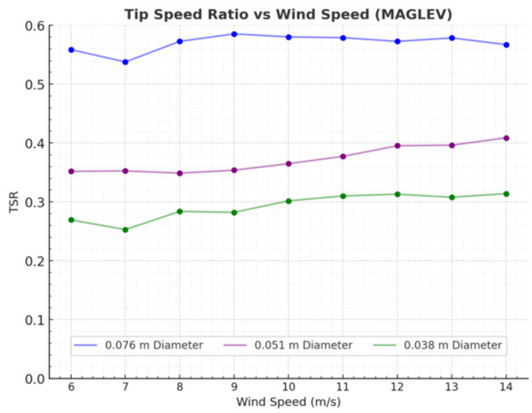


**Figure 8b** Tip-Speed Ratio at different wind speeds with MAGLEV.

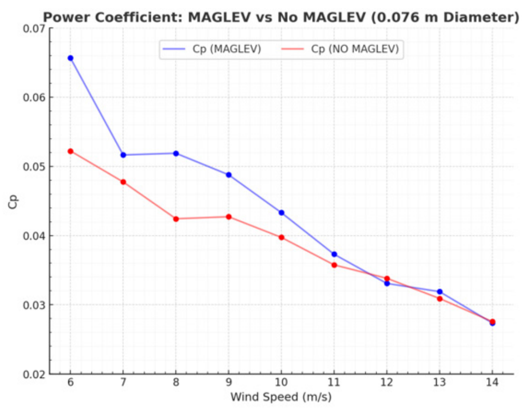


**Figure 8c** Power Coefficient at different wind speeds with and without MAGLEV.

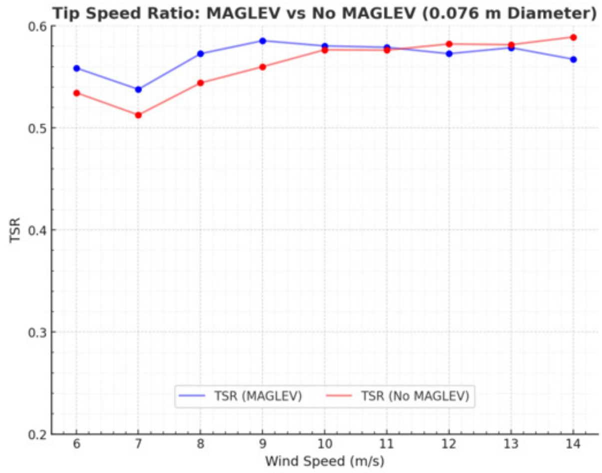


**Figure 8d** Tip Speed Ratio at different wind speeds with and without MAGLEV.

In Figure 8b, a graph is shown comparing the TSR at different wind speeds. It is seen that the 0.076 m diameter blades are performing significantly better than the 0.051 m and 0.038 m diameter blades. At first glance, it would not make sense for a heavier blade to be rotating faster than a lighter blade. After taking Figure 8a into account, one can see that a larger surface area cup can catch a notable amount of wind, allowing more torque and causing faster rotation.

In Figure 8c and Figure 8d, the comparison between the presence and absence of MAGLEV implementation is shown with the 0.076 m blades. It can be seen that the MAGLEV system provided higher efficiency along with a higher TSR. At the best performing wind speed of 6 m/s, MAGLEV shows a power coefficient of 0.066, while the non-MAGLEV system shows a 0.052 power coefficient. The MAGLEV was effectively able to increase efficiency by 26.92%. At the other points of the graph, the difference between power coefficient decreases. This can also show that the Savonius wind turbine is better at running at lower wind speeds. However, the behavior of the TSR graph is very similar. The biggest difference is at the 6 m/s wind speed with the MAGLEV running at 0.56 TSR while the non-MAGLEV is running at 0.53 TSR. It can be diagnosed that the MAGLEV system is not affecting the rotation of the turbine itself but the power generation. As seen in Figure 8b, the blade area had a more significant effect on the TSR and changed it remarkably.

After all the testing and diagnosis, it is observed that the 0.076 m diameter cup ($\sigma$ = 0.545) with MAGLEV performed the best. At the optimal wind speed of 6 m/s, the turbine demonstrated a power coefficient of 0.066 (6.6% efficiency) and a TSR of 0.56. The measured $C_p$ = 0.066 for the Savonius wind turbine is significantly lower than the expected range ($C_p$ = 0.15−0.20). This discrepancy is attributed to the generator's mismatch with the turbine's operational characteristics. Specifically, the generator requires a higher RPM to produce significant electrical power, while the turbine operates at low RPM with high torque. These factors collectively explain the observed low power coefficient, despite the turbine achieving an appropriate TSR of 0.56. With the budget being limited, we tried our best to get the most suited generator within the scope of the project.

## Scaling

In order to increase the power output of the wind turbine, scaling up the physical model is necessary. Several factors need to be

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considered in the construction of a larger version of the wind turbine including stresses, location, parts/materials, connecting to grid, etc. The parts and materials will be discussed briefly in this paper. In choosing the right parts for the turbine, materials have a significant impact on the performance of the wind turbine. Starting with the base, in a large turbine application, the wind turbine is most secure when it is drilled to the ground. It needs to have a strong concrete foundation around it. With the design considered in this study, a smaller size turbine of around 10 feet will work best to ensure stability. The overall dimensions of this wind turbine are summarized in Table 2.

**Table 2** Dimensions of VAWT scaled up

| | |
|---|---|
| Height (overall) | 3.048 m |
| Blade height | 1.83 m |
| Swept area | 5.57 $m^2$ |
| Rotor diameter | 3.66 m |
| MAGLEV distance apart | Inside 0.305 m |
| Number of blades | 3 |

Choosing the right material is critical for making the turbine effective. The rotor would be made of thick aluminum to ensure a sturdy structure without interfering with the magnetic field of the MAGLEV. With other metals such as steel, their magnetic properties could affect the performance of MAGLEV. The magnets for MAGLEV would be ring magnets. The distance apart from each other is variable based on the field strengths of the magnets. The magnets should be strong enough to hold the rotor up and not too strong to repel over 0.305 m. This would cause more instability with MAGLEV farther apart. The blades could be made of aluminum. Aluminum would be a suitable material because it is very strong and lightweight compared to other heavier metals. We would be able to use thin sheets of aluminum and form them to the desired shape of the cup. The solidity for the blades should be above 0.5 to allow for a good amount of surface area for wind to catch. In choosing a generator for a larger wind turbine, we would like to maximize the voltage and power output. With this, choosing a low rpm high voltage generator would ensure that the turbine runs efficiently at low and high wind speeds. While sourcing parts, a generator that is rated 220V and 12000W at 500 rpm was found. We could use this generator and with previous numbers of the wind turbine running at 200 rpm, we could get 110V and 6000W. With a wind turbine, it cannot operate the whole day because of wind variability. On an average, VAWTS run for around 6-18 hours a day. With these numbers, the proposed wind turbine would capture around 36-108 kWh per day. If that is multiplied by a whole year, that turbine can produce from 13,140-39,420 kWh per year. To put this into perspective, a house on average uses 10,800 kWh a year;[24] so producing that much energy is enough to power 1-3 houses. On this scale and taking into account that no gearbox is used, this turbine is very effective in producing energy. While these estimated numbers are generally accurate, there can be deviations. With the change in materials and larger size of the turbine, all the structural dynamics differ. Different material properties also affect the wind turbine. With that, it is difficult to determine the power coefficient. In simplified cases, using the scaling factor directly to estimate the change in power output can make sense, but it is important to understand the context and limitations of this approach. In this case, scaling cannot be done due to the change in materials which significantly affects the aerodynamic properties and structural dynamics.

In the industry, Darrieus turbines have been favored because of their high power coefficient and ability to produce power with lower RPM. While the Darrieus-type has been favored, many unique designs are in use and all of them are used differently depending on location and size. Figure 9 illustrates many variations of VAWTs.

**Figure 9** Variation of VAWTs.[25]

## Conclusion

In summary, through fabrication of a small scale Savonius wind turbine, we found an effective way to incorporate MAGLEV and direct drive technology into a vertical-axis wind turbine. In utilizing the 3-blade design with various solidities, we showed how the difference in cup diameter changed the effectiveness of the wind turbine. With our best design using a solidity of 0.545, we achieved a tip speed ratio of 0.56 and a power coefficient of 0.066. Similar studies validate the method and testing involved in our research. Using our best prototype, we found an application in scaling the wind turbine to power multiple homes, achieving cleaner energy. We see in this study that MAGLEV technology offers promise for achieving lower self-starting speeds in VAWTs.[25]

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## Conflict of interest

Authors declare that there are no conflicts of interest.

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