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An overview of comprehensive review of wind turbine technology: types, advantages, disadvantages and applications

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ABSTRACT
Wind turbines, as one of the key technologies in renewable energy production, play an important role in reducing dependence on fossil fuels andmitigating climate change. This paper provides a comprehensive review of different types of wind turbines, including horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT), focusing on the Darrieus and Savonius sub-types, as well as hybrid turbines. The advantages and disadvantages of each turbine type are analyzed from aerodynamic, structural, economic and environmental aspects, and the optimal applications of each technology in different operational scenarios are identified. The results show that although HAWTs have higher efficiency, VAWTs show significant advantages in low wind conditions, urban environments and floating marine applications. Hybrid Savonius-Darius turbines have been able to overcome the limitations of both types by taking advantage of the self-starting capability of Savonius and the high efficiency of Darrieus.

Keywords: **Wind turbine, horizontal axis, vertical axis, Darius, Savonius, power factor, aerodynamics, renewable energy**

1. INTRODUCTION
Wind turbines are divided into two main categories based on the direction of the axis of rotation: horizontal axis turbines (Horizontal Axis Wind Turbine (HAWT) whose axis of rotation is parallel to the direction of the wind flow, and Vertical Axis Wind Turbine (VAWT) whose axis of rotation is perpendicular to the wind direction [3]. Each of these categories has several subgroups, each of which exhibits unique aerodynamic, structural, and functional characteristics. Darius and Savonius wind turbines, which are considered vertical axis wind turbines, have attracted the attention of researchers due to their simple design and independence from wind direction. Despite their higher efficiency than Savonius, the Darius turbine has a fundamental problem Way Throwing AutomaticFacing ST. Based on the long-term goals set

in the National Strategy Document and Roadmap for the Development of Iran's Wind Industry, it is necessary to increase the share of wind power plants to at least 24.5 GW by 1404. Also, based on the short-term goals of the same document, at least 2,000 MW of wind turbines must be produced, localized, and installed.D[1] Given that the current installed wind power in the country is 0.162 GW, achieving the set goals requires large investments in the development of the country's wind turbine industry [1]. Achieving these goals requires that wind turbine manufacturing be localized in the country and that all the needs of this sector be met from the domestic market. In this regard, the Niro Research Institute has begun the design and construction of the first megawatt wind turbine since 2010, which has begun after completing the design phase, the construction and testing phase of this turbine. Installing a national megawatt wind turbine and conducting its standard tests requires choosing a suitable location, which is the main subject of this article. In this study, various wind turbine testing centers in the world have been examined and the necessary requirements and criteria for establishing this test center have been established.

The purpose of this article is to provide a comprehensive and comparative analysis of wind turbine types, examine the advantages and disadvantages of each, identify optimal applications, and present scientific perspectives based on recent research findings.

which are a non-isothermal steady-state coupled with non-steady-state three-dimensional thermo-mechanical process.

2- HORIZONTAL AXIS TURBINES (HAWT), STRUCTURE AND PRINCIPLES OF OPERATION

Horizontal axis turbines are the most common type of wind turbine in large-scale wind farms. They typically have two or three blades with an airfoil cross-section that produce lift (They use lift and drag to produce rotational torque [4]. The main components of a HAWT include the tower, nacelle (a housing containing the gearbox, generator, and control system), hub, and blades (**Figure 1**,**2**)

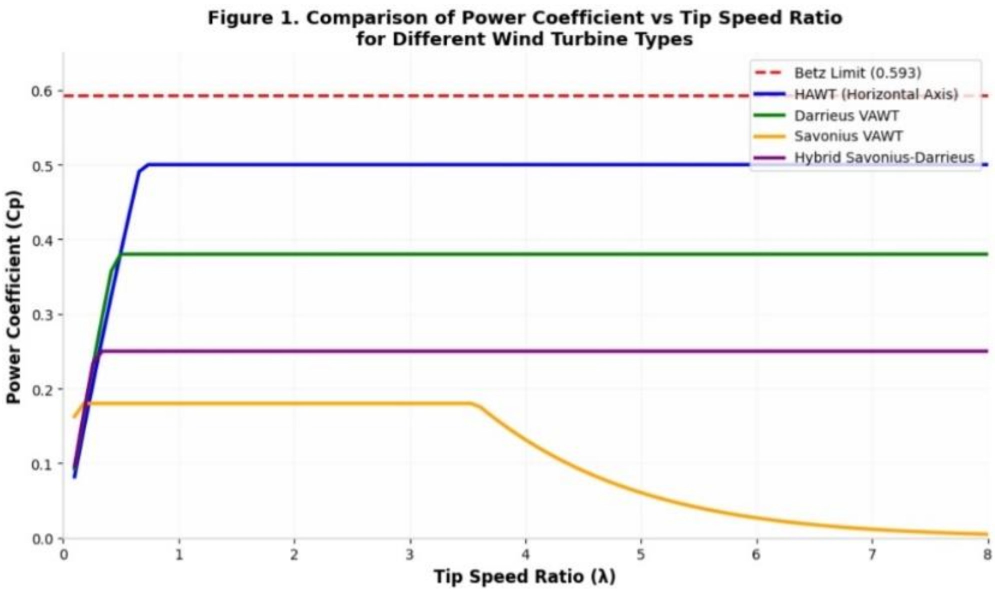

Figure 1. Comparison of power factor versus tip speed ratio for turbine types [5, 8, 10]

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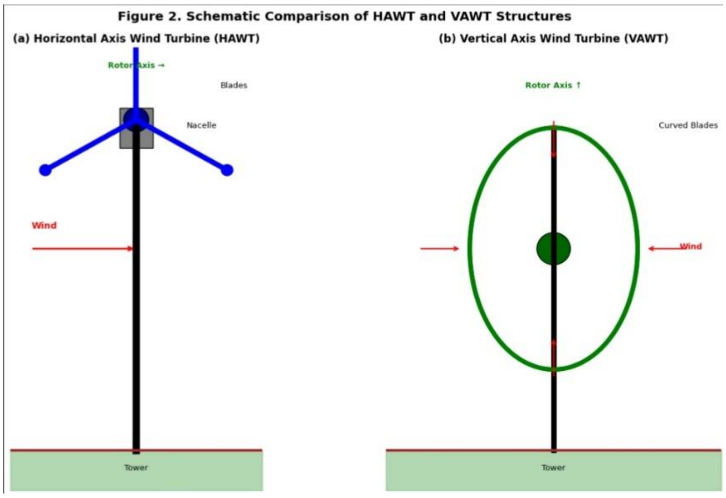

Fig. 2. Schematic comparison of the structureHAWT and VAWT [4]
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Shape 2.Comparison Schematic Structure(a)Turbine Axis Horizontal(HAWT)and(b)Turbine Axis Vertical(VAWT) [4]

3- WIND TURBINES INVESTIGATION

Wind turbines use the natural force of the wind to drive a generator to produce electricity. Wind is a clean, sustainable fuel source that has no emissions and will never run out because it is constantly renewed by solar energy.In many ways, wind turbines are a natural evolution of traditional windmills. But they now typically have three blades that rotate around a central horizontal ring that is connected to an electronic power supply located in a motor house at the top of a steel tower. Most wind turbines start generating electricity when the wind speed is about 2–5 m/s, and produce a maximum power of about 13 m/s, and stop and stop at 23 m/s or more to prevent damage from storms. [2] The wind passes through the blades, creating a rotating force. The rotating blades turn a propeller inside a motor that goes to a gearbox. The gearbox increases the speed of rotation for a generator. The generator uses a magnetic field to convert the rotational energy into electrical energy. The output power is fed to a transformer. The transformer converts the energy from the generator, which is about 711 volts, to a voltage suitable for the distribution system, which is usually 55111 volts (55 kilovolts). Regional power distribution networks or the national grid transmit electricity throughout the country. The other two parts are the measurement sensors, which include two speed and direction sensors, and the way-metsys (way-metsys) that positions the blades in the direction of the wind.

Table 1. Comprehensive comparison of wind turbine types (taken from scientific sources)

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Table 1. Comprehensive comparison of wind turbine types (taken from scientific sources [3, 5, 6, 8, 10, 12])

Table 1. Comprehensive Comparison of Wind Turbine Types
(Adapted from scientific literature)

Parameter	HAWT	Darrieus VAWT	Savonius VAWT	Hybrid S-D
Maximum Power Coefficient (Cp)	0.45 – 0.50	0.30 – 0.40	0.15 – 0.20	0.20 – 0.30
Optimal Tip Speed Ratio (λ)	4 – 8	2 – 5	0.5 – 1.5	1 – 3
Self-Starting Capability	Excellent	Poor	Excellent	Good
Wind Direction Requirement	Yaw mechanism needed	Omnidirectional	Omnidirectional	Omnidirectional
Generator Location	Nacelle (top)	Ground level	Ground level	Ground level
Maintenance Accessibility	Difficult (high)	Easy (ground)	Easy (ground)	Easy (ground)
Noise Level (dB)	35 – 45	25 – 35	20 – 30	25 – 35
Cut-in Wind Speed (m/s)	2.5 – 3.5	3.0 – 4.0	1.5 – 2.5	2.0 – 3.0
Structural Complexity	High	Medium	Low	Medium
Suitable Applications	Large wind farms, offshore	Urban, small-scale	Low wind areas, pumping	Urban, hybrid systems
Scalability	Excellent (up to 15 MW)	Limited	Limited	Limited
Bird Safety	High risk	Low risk	Very low risk	Low risk
Manufacturing Cost	Moderate	Moderate	Low	Moderate

Note: Values are approximate and may vary based on specific design parameters and operating conditions.

4- REVIEW OF TYPES OF WIND TURBINE TESTS

The most important tests performed in a wind turbine test center are:Wind turbine power performance test The purpose of this test is to determine the performance characteristics of wind turbines. For this purpose, IEC 61400-12 is used. This standard includes the process of evaluating the performance characteristics of single wind turbine generator systems and its application to testing all wind turbines of any type and size that are connected to the grid [12].

In this test, the power performance characteristics are determined by the power curve and the amount of annual energy produced. The power curve is determined by simultaneously measuring the wind speed and output power at the test site over a specified period. The duration of the measurement period should be such that it covers a specified range of wind speeds and different wind conditions [12]. The annual energy production (APE) can be calculated using the measured power curve in terms of the frequency distribution of the reference wind speed and assuming 100% availability of the wind turbine [12]. 4.2 Mechanical load measurement test The IEC 61400-13 standard is used to perform a test to determine the mechanical loads of a wind turbine, especially large horizontal axis turbines used to generate electricity. Of course, the methods mentioned can also be used for other wind turbines [13]. The purpose of this test is to provide a methodology and related techniques for experimentally determining the mechanical loads applied to a wind turbine. These mechanical criteria are used as a guide for performing validation or direct calculations of structural loads [13]. The wind turbine acoustic emission measurement test The IEC 61400-11 standard is used to perform noise testing of wind turbines [14]. Noise The noise generated by wind turbines has mechanical and aerodynamic origins. In most cases, mechanical noise is generated from the rotating machinery in the nacelle - especially the gearbox and generator - and from parts such as cooling fans, auxiliary equipment - such as engines and compressors - and the yaw system [14].

Benefits

HAWTs have the highest power factor (Cp) of any wind turbine type, which can reach 0.45 to 0.50 under optimal conditions, close to the Betz Limit of 0.593 [5]. Other advantages include:

• Excellent self-starting capability
• Possibility of controlling the angle of attack (Pitch control to optimize power and limit load in high winds
• Excellent scalability up to powers above 15 MW
• Independent of wind direction
• No need for a control system or low rotational speed More to The operating medium of this turbine Lower blade tip speed ratio
• Less noise pollution
• Ability to withstand high winds, simple design More, lower construction and maintenance costs, and greater securityLEther for life Birds and bats canvas[12-6].

2-1-4. Disadvantages

LimitationsHAWTs include the need for a yaw system to orient against the wind, difficult access to nacelle components at high altitudes (60–120 m), sensitivity to turbulent wind conditions, and higher noise levels (35–45 dB) [6]. Also, large blades with high tip speeds (tip speed ratio 5–7) increase the risk of bird strikes [7].

5- VERTICAL AXIS TURBINES (VAWT)

Darius turbine (Darrieus)

The Darius turbine, patented by Georges Darius in 1931, uses curved blades with an airfoil cross-section to generate lift [8]. These turbines are capable of achieving power factors of 0.30 to 0.40.Useof vertical axis wind turbines due to the advantages they offer in comparison2 with

horizontal axis wind turbines, have become more common in the urban industry. So that, in order to achieve a higher power factor, researchers turned to optimizing a multi-blade Savinius wind turbine with blades based on circular arcs, and the results of their research showed that the power factor of 0.32 is improved with an aspect ratio of 1.5 and the power factor of 0.32 is improved with an aspect ratio of 2.5, and in a two-blade wind turbine, the performance of the wind turbine increases by 12% compared to its classic model [3]. The most important feature of vertical axis wind turbines is their independence from the wind direction and their acceptable performance in urban wind conditions with low wind speed and high turbulence levels. In addition, due to the limited space available in urban areas, the final turbine with suitable sizes for installation in urban environments is needed. In particular, micro-scale wind turbines have recently received more attention due to their good ability to adapt to any space, in large numbers and in different configurations [4], and the vertical axis turbine will eventually replace the horizontal turbine. The vertical axis turbine has several advantages, including the following: It is omnidirectional, unlike the horizontal axis turbine, which requires a deflection mechanism to adjust the direction of the flow. Its construction is so simple that it can be placed close together to produce more energy in each area and is suitable for environments with high surfaces.LaThe turbulence is suitable and relatively inexpensive [5]. Vertical axis turbine powered by airLaHowever, its self-starting capacity is moderate. When the turbine5 Darius arrives at a specific azimuth angle point with low flow velocity, the blade may The direction of the inlet flow has no effect on how a vertical axis wind turbine operates. However, there is little capacity for the turbine itself. It has a shape. There are different configurations for the blades of Darius turbines, including straight blade, complex spiral and Troposkin curve models. Also, the number of blades can be from one to five blades (depending on economic considerations). Darius turbines have the highest efficiency among vertical axis wind turbines, but their main problem is low torque at the moment of starting and lack of structural integrity.. Also, the pitch angle of the blades can be fixed or variable. Changing the pitch angle of the blades can help increase the starting torque. Fixed pitch blades have a simpler structure, but produce less torque[2]. Currently, large-scale vertical axis turbines are not economically attractive, but they are suitable for areas far from the main electricity grid and areas where horizontal axis turbines and large wind farms cannot be installed, which is why small-scale vertical axis turbines have become more common. The main problems of vertical axis turbines are low starting torque, blade lift, low efficiency, and their non-integrated structure.
Instead, the advantages of these turbines over the horizontal axis type are as follows:

1. They are not sensitive to wind direction.
2. Vertical axis blades have a longer lifespan because they are stable under the force of gravity and inertia.
3. They have lower manufacturing and production costs than the horizontal axis type.
4. They are less sensitive to turbulent and cross-flows and are mechanically capable of operating safely in high winds and storms.

Due to their lower rotational speed, they are quieter than horizontal axis turbines [1] and[3]. For the above reasons, small vertical axis turbines can be installed close to the ground, on rooftops in urban and rural environments, and wherever turbulence is more severe than at the wind farm site. Advances in vertical axis wind turbine technology require increased efficiency, better start-up capability, optimization of the aerodynamic characteristics of the airfoils used, and consideration of the effects of stiffness and pitch angle of the blades. [1]

Advantages:

• No need for a systemyaw (multidirectionality)
• Generator is located at ground level (easy access for maintenance)
• Lower loads on the tower due to equal force distribution above and below the axis

Disadvantages:

• Poor self-starting capability (requires external initial start)
• Cyclic torque fluctuations that can lead to fatigue wear
• Blades close to the ground do not benefit from stronger winds at higher altitudes [9].

2-2-2. Savonius turbine (Savonius)

Savonius turbine based on traction force (drag) and consists of two or three semicircular bowls [10]. These turbines have a lower power factor (0.15-0.20) but produce high starting torque.

Advantages:

• Excellent self-starting capability
• Simple structure and low cost
• Good performance at low wind speeds (cut-in wind speed 1.5-2.5 m/s)
• Very low sound levels (20-30 decibels)

Disadvantages:

• Low aerodynamic efficiency
• Limited tip speed ratio (0.5-1.5)
• Limited scalability [11]

2-2-3. Combined turbines (Hybrid Savonius-Darrieus)

Hybrid turbines attempt to combine the self-starting capability of Savonius with the high efficiency of Darius by integrating a Savonius rotor into the center of a Darius rotor. Recent research has shown that these turbines can achieve power factor at low tip speed ratios (λ=1.45) can improve up to 26.91% over pure Darius [12]. However, vortex interactions between the two rotors can lead to reduced efficiency at higher tip speed ratios [13].

2.4. Applications and adaptations

Table 2. Applicability types table2_application_matrix.png

Table 2. Applicability matrix of wind turbine types for different applications [1, 2, 9, 11, 14]

Table 2. Application Suitability Matrix for Different Wind Turbine Types
(★ = Low suitability, ★★★★★ = High suitability)

Application Area	HAWT	Darrieus VAWT	Savonius VAWT	Hybrid S-D	Key Considerations
Large-scale Onshore Wind Farms	★★★★★	★★☆☆☆	★☆☆☆☆	★★☆☆☆	High efficiency, scalability, grid integration
Offshore Wind Farms	★★★★★	★★★☆☆	★☆☆☆☆	★★☆☆☆	Corrosion resistance, maintenance access, foundation cost
Urban/Building-integrated	★☆☆☆☆	★★★★☆	★★★☆☆	★★★★☆	Low noise, aesthetics, turbulence handling
Remote/Isolated Areas	★★★☆☆	★★★★☆	★★★★★	★★★★☆	Self-starting, reliability, low maintenance
Water Pumping/Irrigation	★★★☆☆	★★☆☆☆	★★★★★	★★★☆☆	High starting torque, mechanical simplicity
Small-scale Residential	★★★☆☆	★★★★☆	★★★★☆	★★★★★	Cost, noise, visual impact, local regulations
Developing Countries/Rural	★★★☆☆	★★★☆☆	★★★★★	★★★★☆	Low cost, local manufacturing, durability
Hybrid Energy Systems	★★★★☆	★★★★☆	★★★☆☆	★★★★★	Complementary operation, storage integration
Floating Offshore Platforms	★★★★☆	★★★★★	★☆☆☆☆	★★★☆☆	Low center of gravity, platform stability, LCOE
Military/Disaster Relief	★★☆☆☆	★★★★☆	★★★★★	★★★★☆	Portability, rapid deployment, robustness

6- LARGE-SCALE ONSHORE AND OFFSHORE POWER PLANTS

HAWTs are the dominant choice for fixed-base onshore and offshore wind farms due to their high efficiency and excellent scalability. Today's offshore turbines have reached capacities of 15 MW with rotor diameters exceeding 220 m [2].

7- FLOATING MARINE APPLICATIONS (FLOATING OFFSHORE)

VAWTs offer significant advantages in floating marine applications. The lower center of gravity and lower center of traction force result in a 53% lower overturning moment than HAWTs, allowing for the use of lighter platforms and a 33% reduction in pitch response (RAO) [14]. These features can result in a 7% reduction in LCOE.

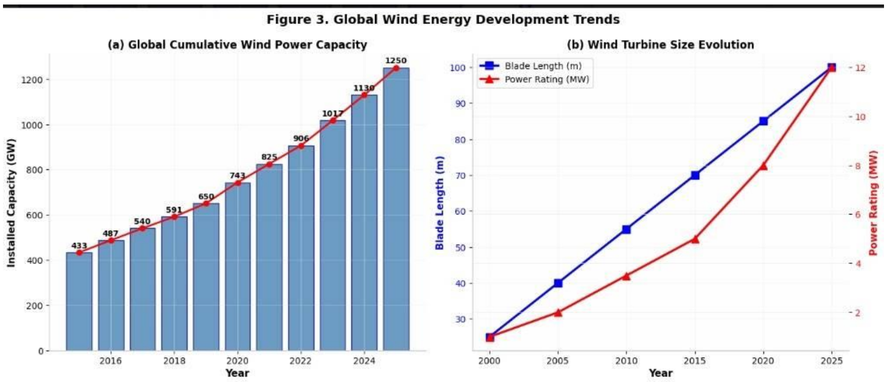

Figure 3. (a) Platform torsional motion response and (b) cost separation in floating offshore applications [14]

8- URBAN ENVIRONMENTS AND SMALL-SCALE APPLICATIONS

VAWTs are preferred due to lower sound levels and no need for a yaw system.,and better performance in urban turbulent wind conditions, they are more suitable for urban and building applications [6]. Savonius and hybrid turbines are optimal for remote areas and water pumping applications [11].

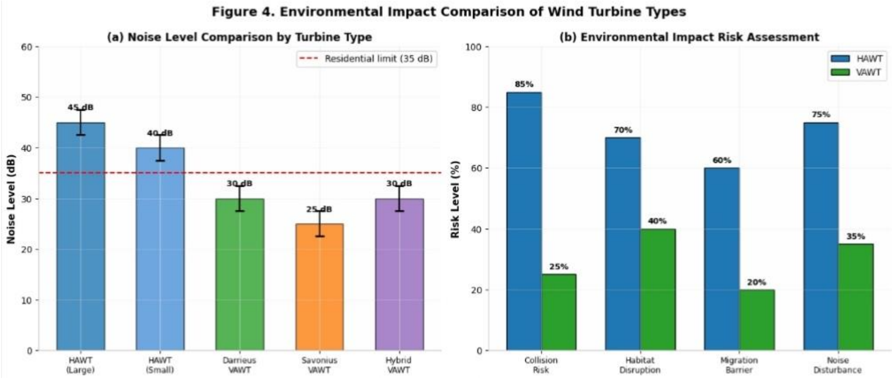

Figure 4. Comparison of environmental impacts of turbine types [7, 15]
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9- ENVIRONMENTAL ASPECTS

2.5.1 TurbinesHAWTs

TurbinesHAWTs with high tip speed ratios (5–7) produce aerodynamic sound levels of 35–45 dB, which can cause annoyance to nearby residents [6]. In contrast, VAWTs with lower tip speed ratios (1.5–2) are virtually silent and are more suitable for residential areas.

2.5.2. Bird safety

High blade tip speedHAWTs significantly increase the risk of bird strikes. Studies have shown that VAWTs pose a lower risk to birds due to their lower rotational speed and larger cross-sectional area [7].

10- BLADE MATERIALS AND FATIGUE

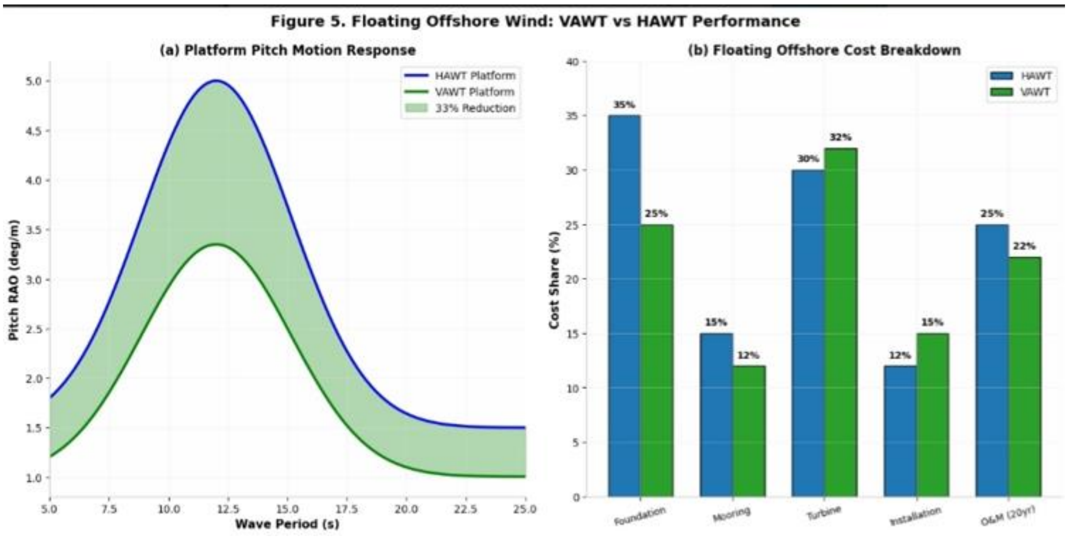

Figure 5. Fatigue properties of wind turbine blade materials [16, 17]

Figure 5. (a) SN curves for different blade materials and (b) damage mechanisms in composites [16, 17] /mnt/agents/output/figure6_blade_materials.png

Most modern blades are made of glass fiber reinforced polymer composites (GFRP) or carbon (CFRP). These materials have higher strength-to-weight ratios, superior corrosion resistance, and more favorable fatigue properties than metals [16]. However, challenges include fiber breakage (35%), matrix cracking (25%), delamination (20%), and environme
ntal degradation (8%) [17].

11- **RESULTS**

A comprehensive analysis of wind turbine types reveals the following key results:

1. Efficiency superiority**HAWT:**Horizontal axis turbines with a power factor of 0.45-0.50 remain the most efficient technology for large-scale applications.
2. Benefits**VAWT in specific applications:**Vertical axis turbines have significant competitive advantages in low wind conditions, urban environments, and floating marine applications.
3. Potential of hybrid turbines: Savonius-Darius integration can overcome the limitations of self-starting, although optimization of the spacing between the rotors is necessary.
4. Reducing environmental impacts**VAWT:**Lower sound levels and less risk to birds make VAWTs more suitable for sensitive areas.
5. Floating marine opportunities:VAWTs have the potential to reduce LCOE by 7% in floating offshore applications by reducing platform loads.

12- CONCLUSION

Selecting the right type of wind turbine requires a deep understanding of operating conditions, technical limitations, and economic and environmental considerations.HAWTs are optimal for large-scale fixed-base onshore and offshore wind farms. VAWTs have a unique position, especially in urban, remote, and floating offshore applications. Combining the strengths of both technologies, Savonius-Darius hybrid turbines offer a promising solution for medium- to low-wind applications. Future research should focus on aerodynamic optimization of hybrid turbines, development of more durable composite materials, and reduction of LCOE costs in novel applications.

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