Available Online at www.jourcc.com

Journal homepage: www.JOURCC.com

Journal of Composites and Compounds

A mini review on thermoplastic composite inner blades for vertical-axis wind turbines (VAWT): Aerodynamic and mechanical insights

Younes Nasirinia [a], Seied Hossein Azizi [b], Mohammadreza Pourdizaji [c]*

[a] *Department of Mechanical Engineering, Shiraz University of Technology, P. O. Box: 71555-313, Shiraz, Iran*

[b] *Department of Mechanical Engineering, Bandar Lengeh Branch, Islamic Azad University, Bandar Lengeh, Iran*

[c] *Department of Mechanical Engineering, Yasouj University, P. O. Box: 75914–353, Yasouj, Iran*

A B S T R A C T

As global demand for more sustainable energy grows, wind energy has emerged as a key renewable energy source, especially when it pertains to the aerodynamic optimization of wind turbine blades for aerodynamic efficiency. When it comes to wind turbine blades, thermoplastic composites are gaining significant interest. This paper analyzes the impact thermoplastic composite inner blades will have on vertical axis wind turbine (VAWT) performance. Thermoplastic composite inner blades may enhance performance due to low weight and design flexibility to achieve improved start-up and increased aerodynamic efficiency along with toughness and cyclic load fatigue resistance for increased structural reliability of the blades. Advanced technologies for the manufacturing of thermoplastic composite blades will enable the use of precision manufacturing and easy or rapid repairs. Subsequently, an evaluation of the effectiveness of the various strategies are considered, including a thorough analysis of various performance enhancing strategies and successes on VAWT performance, and concludes with various effective strategies. Therefore, as an evaluation of issues and resolved issues related to VAWTs, the findings will assist future research efforts focusing on addressing aerodynamics and mechanically optimizing VAWTs more effectively.

A R T I C L E   I N F O R M A T I O N

Article History:
Received 05 January 2024
Received in revised form 19 March 2024
Accepted 26 March 2024

Keywords:
Aerodynamic optimization
Thermoplastic composite
Wind turbine blades
Vertical-axis wind turbines
Renewable energy

Table of Contents

1. Introduction

Recent years due to environmental pollution, demand for energy increases, and finite resources for fossil fuel, the researcher will give increasing emphasis on Alternative Energy Resources in recent years. Alternative Energy Resources are solar, geothermal, wind, biomass, and hydroelectric [1, 2]. Wind energy is rapidly becoming a significant sustainable energy source with considerable economic potential, and it has been utilized in numerous global markets. The fast-paced global installation of wind power is putting substantial pressure on the wind power supply chain [3].Wind turbines are classified most frequently according to their axis of orientation: Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT) (Fig. 1) [4]. The strength and aerodynamics of VAWTs are heavily influenced by material selection and blade configuration. Over the past few years, progress on thermoplastic composites have created the opportunity to further optimize the performance of blades for

* *Corresponding author: Seied Hossein Azizi, E-mail: s.hossein.azizi@gmail.com*

https://doi.org/10.61882/jcc.6.1.7

VAWTs based on their aerodynamics and mechanical properties [5, 6]. Thermoplastic composites, especially those strengthened with carbon fiber, are advantageous for wind turbine blades due to their stiffness and strength-to-weight ratio. Several studies show that the pultrusion process of pulling the fibers and extrusion can achieve high fiber volume fractions (up to 70%), leading to superior mechanical properties of composite materials [7].This improvement is very important for blades that have to handle different wind loads and changing conditions that come with running a wind turbine. It helps the turbine use less energy overall. Studies on optimization show that these materials can be carefully designed to improve blade performance, and that multi-objective approaches can be used to fine-tune structural parameters [8]. By means of smart blade design, wind turbine engineers may be able to increase the aerodynamic performance of VAWT significantly. There are many differences between VAWT and HAWT in terms of operation. One of the main differences is that angle of attack changes during rotation of the rotor, while the direction of rotation is fixed. This means the blades of VAWTs must be designed with maximized lift and minimized drag in mind. Most of the studies show that the aerodynamics of the blade of VAWTs, which are typically made with symmetrical airfoils, is not nearly as effective as using airfoils that are specifically designed to be cambered, which have the ability to create a substantially higher lift-to-drag ratio than the symmetrical airfoils [9, 10]. Novel techniques to improve aerodynamic performance via the use of circulation control technology with tangential air jets has been described as a method to increase the lift produced by VAWT during the operation [9].

More empirical studies indicate that enhancements to performance can be achieved by optimizing blade tips. Moreover, Jiang et al. [11] demonstrate that improved aerodynamics can occur via nontraditional means of eliminating flow separation and providing better lift using advanced blade tip designs. These advances in aerodynamics are especially important when considering the highly variable wind conditions that exist within Cities (urban areas). Another benefit of using thermoplastic composite materials in the design of VAWT blades is the mechanical performance they provide, as well as their increased resistance to degradation from environmental elements. Thermoplastic composites have been shown to be less susceptible to moisture absorption than traditional epoxy-based composite materials; therefore, longevity and durability are achieved in the most challenging applications [12].

In addition, by limiting the effects of environmental erosion, mechanical properties of leading edge protection systems indicate that thermal plastic coatings will enhance blade life [13]. The developments in the area of thermoplastic composite inner blades for VAWTs and the interaction between the composite materials and the airflow represents a unique contribution to current research on aerodynamics and design and will provide the basis to increase performance, longevity and sustainability of composite inner blades.

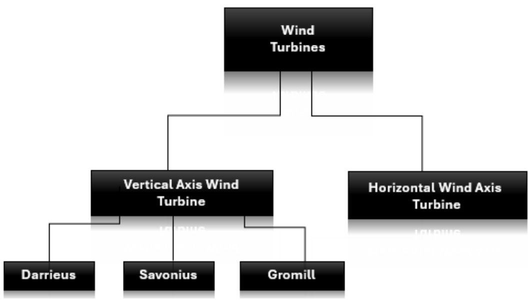


Fig. 1. Classification of wind turbines.

2. Material advantages of thermoplastic composites

Thermoplastic composites are gaining recognition for their substantial benefits in diverse applications, such as wind turbine blades. Their material features boost performance, durability, and sustainability, rendering them a viable alternative to conventional materials [14]. Fig. 2 presents a comprehensive overview of thermoplastic composite blade technology employed in wind turbines.

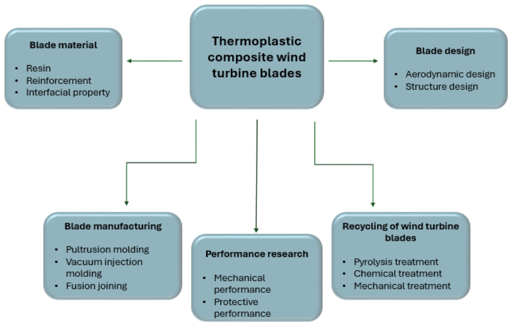


Fig. 2. Overview of thermoplastic composite wind turbine blades.

The mechanical properties of thermoplastic composites are among the most important advantages of these materials as determined by scientific research. These composites exhibit very high tensile strength, impact resistance, and fatigue-tolerance relative to other materials, allowing them to be used in challenging environments, such as that experienced by wind turbines. Liu et al. [15] showed that thermoplastic composites, including those with carbon fiber reinforcement, are more resistant to damage. Because of this, structures can stay strong even when they are under cyclic loading, which is common for wind turbines. Thermoplastic materials are also easier to work with than thermosetting resins. Thermoplastic composites are usually made with less energy because they don't need to be cured at high temperatures. Murray et al. [16] demonstrated that new thermoplastic resin systems can polymerize at room temperature. Room-temperature polymerization cuts down on the time and energy needed to make things by a lot, which lowers costs, makes production programmable, and makes recycling easier. As a result, it may become more important for wind energy applications to be sustainable. Thermoplastic composites are also easier to recycle and fix than thermosetting composites [17]. Also, they can be thermally welded or remolded, which makes them more environmentally friendly because it lets you fix broken parts without making new ones [16]. This feature is especially useful for wind turbine blades, which have to deal with harsh weather and often wear down over time. Additionally, the performance of thermoplastic composites can be improved even more by optimizing their interfacial properties. Research indicates that modifying the interface between the fiber and matrix can significantly improve the mechanical properties of composite materials, leading to innovative solutions for applications in wind energy [18]. In a study by Koki Matsumoto et al, [19] integrating nanofillers such as carbon nanotubes into the thermoplastic matrix, researchers have demonstrated marked improvements in adhesion and toughness, which translates to enhanced durability in wind turbine blades.

3. Aerodynamic performance considerations

The issue facing wind turbine blade manufacturers is optimized blade structural designs related to material selection and cost-effective manufacturing. Rotor blades must be stiff to achieve aerodynamic performance, lightweight to reduce the effects of gravity, and have long fatigue life to reduce material degradation [20]. VAWTs are less efficient aerodynamically than HAWT. This is due primarily to the lack of a thorough understanding of the VAWT aerodynamic phenomenon. In addition, the construction of high-power wind turbine industrial installations using a simplified approach omits the latest achievements of blade aerodynamics in dynamic stall and is based on a priori empirical hypotheses about the flow around VAWT rotors.

Four main levels of mathematical modelling are used to describe the aerodynamics of wind turbines [21]:

i. Engineering and empirical methods;
ii. Inviscid flow models based on the potential and Euler equations;
iii. Viscous flow models using turbulence-averaged formulations such as the rans equations; and
iv. Viscous flow models that resolve unsteady turbulent structures, including DES, LES, and DNS approaches.

At present, wind turbine design mainly depends on the first two modelling levels. Aerodynamic, dynamic, and power characteristics of turbine rotors are typically determined using techniques grounded in experimental data [22], impulse and vortex theories [23], and numerical solutions of the potential/Euler equations. These approaches usually assume quasi-steady flow and neglect viscous inviscid interactions. The accurate prediction of dynamic stall during unsteady flow around turbine blades remains a major difficulty [24]. Up to now, simplified models have often yielded aerodynamic predictions with limited accuracy, especially under dynamic stall conditions. Moving to the third modelling level, simulations based on the RANS equations are increasingly adopted in industrial applications. For instance, Sun et al. [25] analysed operating behaviour of a Darrieus VAWT using RANS, while Gonzalez Madina et al. [26] applied similar methods to a Savonius VAWT. The fourth level involves high-fidelity CFD methods like LES and DNS, which are computationally expensive. Nevertheless, some researchers such as Abkar and Dabiri [27], and Nguyen et al. [28] have already applied these advanced methods to analyses VAWT flow and wake behaviour. Mahmoodi et al. [29] introduced a simple wake–induction interaction model validated with field data from a utility-scale turbine equipped with a four-beam nacelle-mounted LiDAR. The model reasonably estimated wake induction effects between two turbines using the Direction-to-Hub (Dh) parameter, though it could not fully capture the asymmetric wake profile observed within the limited angular range of the measurements (up to 245°). Even so, Dh proved highly sensitive for model evaluation and useful for horizontal alignment of nacelle-mounted LiDARs. Model accuracy could be improved by including wake-expansion corrections, testing alternative wake or induction formulations, and applying correction functions to reduce outlier predictions (Fig. 3).

4. Mechanical integrity

The operational conditions and parameters influencing wind turbine blades need the optimization of three material properties: density, stiffness, and fatigue life [30].

Maintaining optimal aerodynamic performance requires high material stiffness, low density to reduce self-loading and gravity forces, and long fatigue life to reduce material failure and deterioration [31]. A combination Savonius wind turbine has demonstrated a maximum power coefficient of 0.4, necessitating a start-up torque exceeding 0.1 Nm at low wind speeds of 2 m/s [32]. The performance of Darrieus-Savonius blades is influenced by configuration, airflow parameters, geometry and the quantity of blades, which also impacts power efficiency [33]. The wind turbine blade is an essential element constructed from polymeric composites.

These composites may consist of carbon fiber, glass fiber, nylon, and stainless titanium, as they are both robust and lightweight. Currently, up to 50% of European wind blade manufacturers utilize epoxy resins owing to its superior characteristics, including lightweight, strong adhesion, high modulus, fatigue resistance, minimal creep, adequate higher temperature performance, and absence of shrinkage post-cooling. Nevertheless, they are fragile and prone to failure upon impact [31, 34, 35]. Inorganic glass particles have been included into the epoxy resin to enhance its hardness [36]. The incorporation of elastomers and thermoplastics has been examined, revealing that the mechanical properties are contingent upon the rubber content in the mixture [37]. In research by K. Brown et al. [38] constructed a sandwich construction blade with commingled woven E-glass fiber/polypropylene thermoplastic composite skins and a polyethylene terephthalate foam core.

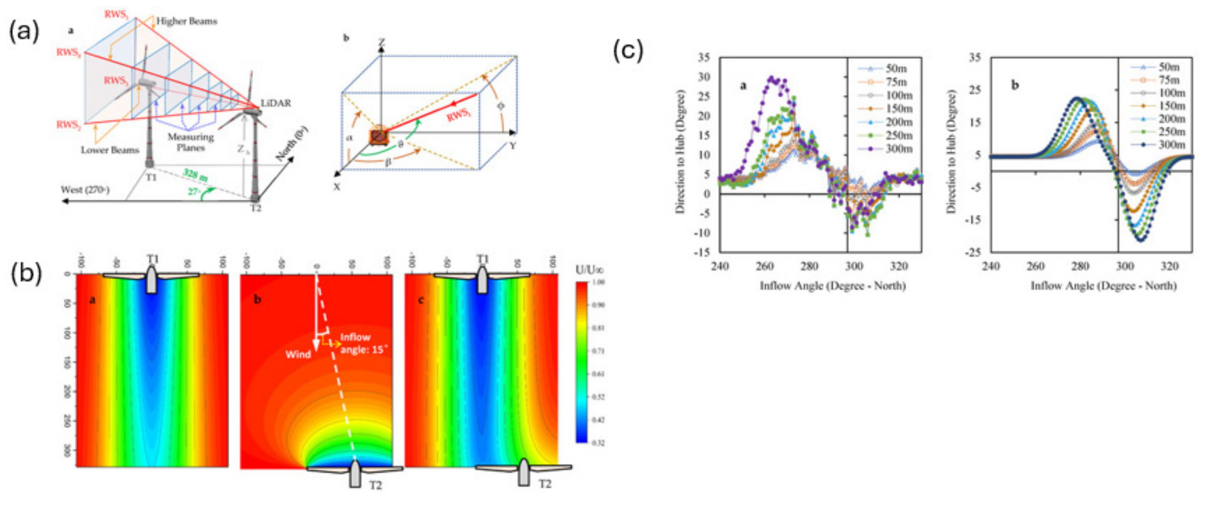


Fig. 3. Schematic of the nacelle-mounted LiDAR setup and measurement geometry (a), simulated wake and induction fields for different inflow conditions (b), and comparison between measured and model-predicted Direction-to-Hub (Dh) values at multiple downstream distances (c). Panel (c-a) shows asymmetric wake behavior captured by LiDAR measurements, while panel (c-b) presents the corresponding predictions from the simplified wake–induction interaction model. Together, these figures illustrate the methodology for assessing wake–induction interactions and evaluating model performance using field LiDAR data [29].

They utilized finite element modeling to forecast blade natural frequency and structural performance, corroborating models via vibration and static bending testing. The research together demonstrates that thermoplastic composite blades provide improved design flexibility, reduced weight, and possible cost benefits for vertical axis wind turbine applications [38]. Another study demonstrated the mechanical properties of a natural-fiber composite VAWT blade composed of fique and epoxy. The fique-epoxy composite exhibits sufficient mechanical properties to replace traditional synthetic fiber-reinforced polymers (SFRPs) for bearing aerodynamic pressure loads. The findings indicate that the most crucial region of the blade is the bonded interface between composite layers, where the inner edges of the airfoil profile generate stress concentrations. A smooth geometric transition, facilitated by rounded corners and an additional stiffener, significantly decreases surface stress, decreasing it from 97.64 MPa to 2.51 MPa. This strengthening is crucial for guaranteeing the structural integrity of the VAWT blade. The utilization of continuous natural-fiber-reinforced polymers (NFRPs) facilitates the creation of a biodegradable, eco-friendly composite material that can substitute fiberglass in the manufacturing of VAWT blades [39].

Mechanical property research by Chainuson Kasagepongsan and Sunisa Suchat [31] found that 5% ENR 50 and 3% nanosilica loading in epoxy resin increased nanocomposite impact strength. The nanocomposites' mechanical characteristics were assessed before and during UVB-accelerated weathering in a weathering chamber. Treatment increased tensile strength by 35% after 168 h. These nanocomposites are weather-resistant enough for outdoor application as Savonius-Darrieus blades for low-speed wind turbines at 2 m/s. High fatigue strength, low density to reduce inertial forces and weight, and delayed deterioration during outdoor use characterize these nanocomposites. Low wind speed might initiate turbine operation. The maximum wind speed was 4 m/s, generating 5000 Watts. The unique stacking of Savonius-Darrieus models in turbines employing lightweight nanocomposite materials could boost low-speed vertical axis wind turbines.

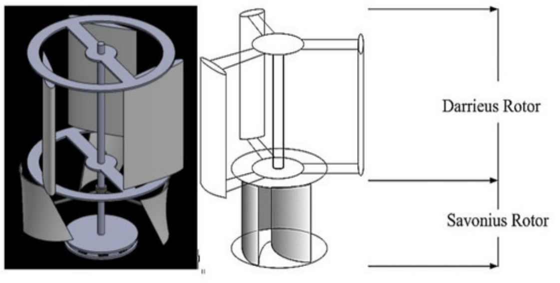
Mohamed M. Z. Ahmed et al. [40] examined the mechanical properties of 20-year-old GFRP from a 100 kW wind turbine blade. The fiber weight percentage was 0.55–0.60, and the number of fiber layers declined with blade length, with the highest fiber density in the length direction and the lowest in the transverse direction. Good fiber wetting, resin under-penetration, and porosity were found microstructurally. Tensile tests showed the blade length direction had the highest strength and modulus, with temperature having no effect. Transverse compressive strength was maximum and blade length was lowest, decreasing with temperature. Fiber orientation greatly affected bending properties, with blade length having the highest values and transverse having the lowest.

5. Manufacturing of thermoplastic composite inner blades for VAWT

There are a variety of different techniques used to make blades, with two groups of methods being used based on the size of the blade as determined by its physical dimensions. Small and Medium-sized blades are generally manufactured using manual (human operated) techniques, while larger blades are generally manufactured using mechanical (machine operated) techniques. The primary manual technique employed is hand lay-up (either wet lay-up or prepreg lay-up), which involves the manual placement of materials onto molds, followed by curing at ambient temperature or in an autoclave or oven. Two shells are fabricated and bonded together with stiffeners using adhesive by manual methods. Mechanical methods include resin infusion, filament winding, and tape winding, all of which necessitate the use of various types of molds [41, 42]. Resin infusion involves pouring resin into a mold with reinforcement, and curing it at room temperature or in an oven.

The process of filament winding involves impregnating fibers on a spinning mold, similar to a mandrel, then curing the material in an oven. While all procedures have pros and cons, the lay-up approach is the most cost-effective if curing is done in air or an oven, as autoclaves are costly. Researchers often combine computational and experimental investigations to enhance turbine performance [43, 44]. One approach to ensure a higher energy production the objective is to create a counter-rotating vertical axis wind turbine (CR-VAWT) [45]. Counter-rotating wind turbines signify a dual-rotor system wherein the rotors revolve in opposing directions, with one rotor turning clockwise and the other in counter-clockwise direction. Furthermore, it was noted that symmetric airfoils yield superior performance. performs superior than nonsymmetrical ones [46]. The interest in composite materials for wind turbines production has risen not solely due to their technical capabilities, but also because now various methods exist for their recycling.

In the reported study, VAWT blades were fabricated using a simple hand lay-up process in which glass-fiber mats were layered with a nanocomposite resin system and cured at room temperature. The resulting design a Savonius–Darrieus hybrid blade with twisted buckets (Fig. 4) demonstrated how fiber–matrix stacking and nanocomposite modification can enhance the aerodynamic and mechanical response of inner blades [31].



(a) Forming the Darrieus-Savonius rotors of a vertical wind turbine blade

Fig. 4. A vertical wind turbine blade section [31].

Filament winding is a common way to make thermoplastic composite blades because it lets you control where the fibers go very precisely. In this method, the thermoplastic matrix is melted and put on a rotating mandrel with fiber reinforcements in a continuous process [47]. Vacuum-assisted resin infusion is another form of manufacturing which involves placing dry fiber reinforcement into a vacuum-formed cavity, and applying pressure to force thermoplastic resin into the dry fiber reinforcement. The curing process can occur much more quickly due to the fact that thermal cycles are shorter, so production costs are much lower when compared to the conventional method of thermo-setting resins [35].

6. Challenges and future perspectives

Techniques for blade manufacture, as well as the selection of materials, are one of the research directions that are being explored for wind turbines. The challenges, process optimization and material durability associated with thermoplastic composite inner blades for VAWTs are revealed in contemporary studies, which indicate some of the many factors that will shape the design and research into the future of these blades [48]. One significant challenge pertains to the fatigue resistance of composite materials employed in VAWT blades.

Ghoneam et al. [49] elucidate the determinants influencing the fatigue life of these blades, emphasizing the significance of variables such as stress levels and fiber type in assessing performance. Their research utilizes modal analysis to generate stress-life curves specifically for glass/carbon-polyester composite configurations, underscoring the critical necessity for accurate engineering designs capable of enduring operational requirements. These result, when combined with multi-response optimization techniques, show how important computational analysis is for making blades work better.

It is difficult to accurately forecast the potential for damage to composite blades in localized areas. As discussed by Brown and Brooks, forecasting localized damage and the potential for failure in thermoplastic composite blades presents considerable challenge. The authors utilize finite element analysis and designed a 5 kW VAWT representative blade from a glass-reinforced thermoplastic composite material in a sandwich construction. The outcomes of this research reflect that there remains a significant need for improved predictive capabilities of composite blade design. Further research into localized modes of failure will provide information to support increasing the structural strength of blades throughout their service lives [20].

Advancements in numerical simulations also support our understanding of how composite blades behave structurally. Sharma et al. [50] showed that composite materials have greater strength than traditional aluminum alloys when applied to a 2 MW VAWT's. They also suggested that new materials could improve structural performance under extreme environmental conditions and therefore support their proposal for increased use of composites when designing VAWTs.

The overall implications of these results suggest that there are ample opportunities to continue to innovate with respect to the development of composite materials. Further development of manufacturing methods, including the advent of thermoplastic composites and hybrid designs will lead to maximized efficiency for the performance of VAWTs. Researchers also state that experimental validation and numerical modelling of new composite designs must be performed in order to demonstrate how they can improve the performance of savonius VAWTs that have been optimized for efficiency [51]. Further research can be done in order to develop blades that use state-of-the-art materials as well as being optimally designed utilizing advanced computational techniques.

7. Conclusion

The design of lightweight, transportable, recyclable wind turbine blades is predicated on using environmentally friendly or "green" design principles during all phases of the blade's design and manufacture. Currently, thermoplastic composite materials being used to build wind turbine blades are being developed with larger sizes, greater power output, and environmentally friendly lightweight designs.

As global markets transition to renewable energy, there is an increasing demand and opportunity for manufacturers to produce thermoplastic composite wind turbine blades. These blades represent the next generation of wind turbines, combining easy production, recyclability, excellent aerodynamic and mechanical properties, fatigue resistance, and impact resistance. By combining these properties, manufacturers will create wind turbine blades with better energy capture, increased life-span, and decreased negative impact. Therefore, manufacturers' designs will meet both industrial and environmental objectives.

Author contributions

Younes Nasirinia: Investigation, Writing – original draft, Writing – review & editing; **Seied Hossein Azizi:** Conceptualization, Writing – original draft, Writing – review & editing; **Mohammadreza Pourdizaji:** Writing – original draft, Writing – review & editing.

Funding

No funding was received for this study.

Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

REFERENCES

[1] M.M. Aslam Bhutta, N. Hayat, A.U. Farooq, Z. Ali, S.R. Jamil, Z. Hussain, Vertical axis wind turbine – A review of various configurations and design techniques, Renewable and Sustainable Energy Reviews 16(4) (2012) 1926–1939.
[2] J.L. Holechek, H.M.E. Geli, M.N. Sawalhah, R. Valdez, A Global Assessment: Can Renewable Energy Replace Fossil Fuels by 2050?, Sustainability, 2022, p. 4792.
[3] J. Zhang, J. Lu, J. Pan, Y. Tan, X. Cheng, Y. Li, Implications of the development and evolution of global wind power industry for China—An empirical analysis is based on public policy, Energy Reports 8 (2022) 205–219.
[4] M.B.A. Bashir, Principle Parameters and Environmental Impacts that Affect the Performance of Wind Turbine: An Overview, Arab J Sci Eng 47(7) (2022) 7891–7909.
[5] Y. Wang, X. Sun, X. Dong, B. Zhu, D. Huang, Z. Zheng, Numerical investigation on aerodynamic performance of a novel vertical axis wind turbine with adaptive blades, Energy Conversion and Management 108 (2016) 275–286.
[6] M. Ahmad, A. Shahzad, M.N.M. Qadri, An overview of aerodynamic performance analysis of vertical axis wind turbines, Energy & Environment 34(7) (2022) 2815–2857.
[7] D. Mamalis, T. Flanagan, C.M. Ó Brádaigh, Effect of fibre straightness and sizing in carbon fibre reinforced powder epoxy composites, Composites Part A: Applied Science and Manufacturing 110 (2018) 93–105.
[8] J. Svorcan, Z. Trivković, T. Ivanov, M. Baltić, O. Peković, Multi-objective Constrained Optimizations of VAWT Composite Blades Based on FEM and PSO, FME Transactions 47(4) (2019).
[9] A. Shires, V. Kourkoulis, Application of Circulation Controlled Blades for Vertical Axis Wind Turbines, Energies, 2013, pp. 3744–3763.
[10] M. Ahmad, I. Rehman, Investigating aerodynamic performance of vertical axis wind turbines using computational techniques, Journal of Power Generation Technology 1(1) (2023) 20–41.
[11] Y. Jiang, C. He, P. Zhao, T. Sun, Investigation of Blade Tip Shape for Improving VAWT Performance, Journal of Marine Science and Engineering, 2020, p. 225.
[12] A. Dorigato, Recycling of thermosetting composites for wind blade application, Advanced Industrial and Engineering Polymer Research 4(2) (2021) 116–132.
[13] I. Katsivalis, A. Chanteli, W. Finnegan, T.M. Young, Mechanical and interfacial characterisation of leading-edge protection materials for wind turbine blade applications, Wind Energy 25(10) (2022) 1758–1774.
[14] Z. Arwood, D.S. Cousins, S. Young, A.P. Stebner, D. Penumadu, Infusible thermoplastic composites for wind turbine blade manufacturing: Static characterization of thermoplastic laminates under ambient conditions, Composites Part C: Open Access 11 (2023) 100365.
[15] L. Han, Y. Song, H. Qi, J.-S. Yang, S. Li, P.-A. Liu, A Comparative Study on the Mechanical Properties of Open-Hole Carbon Fiber-Reinforced Thermoplastic and Thermosetting Composite Materials, Polymers, 2023, p. 4468.
[16] R. Murray, D.R. Snowberg, D.S. Berry, R. Beach, S.A. Rooney, D. Swan, Manufacturing a 9-meter thermoplastic composite wind turbine blade, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2017.

[17] J.P. Reis, M. de Moura, S. Samborski, Thermoplastic Composites and Their Promising Applications in Joining and Repair Composites Structures: A Review, Materials, 2020, p. 5832.
[18] W.Y. Li, H.T. Cheng, S.B. Zhang, Methods of Improving the Interfacial Compatibility of the Bamboo Fiber/Thermoplastic, Advanced Materials Research 602 (2013) 1130–1134.
[19] K. Matsumoto, T. Ishikawa, T. Tanaka, A novel joining method by using carbon nanotube-based thermoplastic film for injection over-molding process, Journal of Reinforced Plastics and Composites 38(13) (2019) 616–627.
[20] K. Brown, R. Brooks, Design and analysis of vertical axis thermoplastic composite wind turbine blade, Plastics, rubber and composites 39(3-5) (2010) 111–121.
[21] D. Redchyts, K. Portal-Porras, S. Tarasov, S. Moiseienko, U. Tuchyna, N. Starun, U. Fernandez-Gamiz, Aerodynamic Performance of Vertical-Axis Wind Turbines, Journal of Marine Science and Engineering, 2023, p. 1367.
[22] G. Brochier, P. Fraunie, C. Beguier, I. Paraschivoiu, Water channel experiments of dynamic stall on Darrieus wind turbine blades, Journal of Propulsion and Power 2(5) (1986) 445–449.
[23] J.H. Strickland, B. Webster, T. Nguyen, A vortex model of the Darrieus turbine: an analytical and experimental study, OSTI.GOV (1979).
[24] A.M. Biadgo, A. Simonovic, D. Komarov, S. Stupar, Numerical and analytical investigation of vertical axis wind turbine, FME transactions 41(1) (2013) 49–58.
[25] X. Sun, Y. Wang, Q. An, Y. Cao, G. Wu, D. Huang, Aerodynamic performance and characteristic of vortex structures for Darrieus wind turbine. II. The relationship between vortex structure and aerodynamic performance, Journal of Renewable and Sustainable Energy 6(4) (2014).
[26] F. González Madina, A. Gutiérrez, P. Galione, Computational fluid dynamics study of Savonius rotors using OpenFOAM, Wind Engineering 45(3) (2021) 630–647.
[27] M. Abkar, J.O. Dabiri, Self-similarity and flow characteristics of vertical-axis wind turbine wakes: an LES study, Journal of Turbulence 18(4) (2017) 373–389.
[28] V.-D. Nguyen, J. Jansson, A. Goude, J. Hoffman, Direct finite element simulation of the turbulent flow past a vertical axis wind turbine, Renewable energy 135 (2019) 238–247.
[29] E. Mahmoodi, M. Khezri, A. Ebrahimi, U. Ritschel, L.P. Chamorro, A. Khanjari, A Simple Model for Wake-Induced Aerodynamic Interaction of Wind Turbines, Energies, 2023, p. 5710.
[30] P. Brøndsted, H. Lilholt, A. Lystrup, Composite materials for wind power turbine blades, Annu. Rev. Mater. Res. 35(1) (2005) 505–538.
[31] C. Kasagepongsan, S. Suchat, Novel Engineered Materials: Epoxy Resin Nanocomposite Reinforced with Modified Epoxidized Natural Rubber and Fibers for Low Speed Wind Turbine Blades, Polymers, 2021, p. 2761.
[32] M. Tahani, A. Rabbani, A. Kasaeian, M. Mehrpooya, M. Mirhosseini, Design and numerical investigation of Savonius wind turbine with discharge flow directing capability, Energy 130 (2017) 327–338.
[33] A. Ramadan, K. Yousef, M. Said, M. Mohamed, Shape optimization and experimental validation of a drag vertical axis wind turbine, Energy 151 (2018) 839–853.
[34] S.P. Subadra, P. Griskevicius, Sustainability of polymer composites and its critical role in revolutionising wind power for green future, Sustainable technologies for green economy. 1(1) (2021) 1–7.
[35] R.E. Murray, R. Beach, D. Barnes, D. Snowberg, D. Berry, S. Rooney, M. Jenks, B. Gage, T. Boro, S. Wallen, Structural validation of a thermoplastic composite wind turbine blade with comparison to a thermoset composite blade, Renewable Energy 164 (2021) 1100–1107.
[36] L. Mishnaevsky, K. Branner, H.N. Petersen, J. Beauson, M. McGugan, B.F. Sørensen, Materials for Wind Turbine Blades: An Overview, Materials (Basel) 10(11) (2017).
[37] A. Lanna, M. Suklueng, C. Kasagepongsan, S. Suchat, Performance of novel engineered materials from epoxy resin with modified epoxidized natural rubber and nanocellulose or nanosilica, Advances in Polymer Technology 2020(1) (2020) 2123836.
[38] K.A. Brown, R. Brooks, Design and analysis of vertical axis thermoplastic composite wind turbine blade, Plastics, Rubber and Composites 39(3-5) (2010) 111–121.
[39] D. Castro, A. Pertuz, J. León-Becerra, Mechanical behavior analysis of a vertical axis wind turbine blade made with fique-epoxy composite using FEM, Procedia Computer Science 203 (2022) 310–317.
[40] M.M.Z. Ahmed, B. Alzahrani, N. Jouini, M.M. Hessien, S. Ataya, The Role of Orientation and Temperature on the Mechanical Properties of a 20 Years Old Wind Turbine Blade GFR Composite, Polymers, 2021, p. 1144.
[41] A. Bej, I. Bordeasu, T. Milos, R. Badarau, Considerations concerning the mechanical strength of wind turbine blades made of fiberglass reinforced polyester, Mat. Plast 49 (2012) 212.
[42] N.R. Council, D.o. Engineering, P. Sciences, C.o. Engineering, T. Systems, C.o.A.o.R.N.f.W.T.R.M. Technology, Assessment of research needs for wind turbine rotor materials technology, National Academies Press 1991.
[43] A. Alaimo, A. Esposito, A. Messineo, C. Orlando, D. Tumino, 3D CFD analysis of a vertical axis wind turbine, Energies 8(4) (2015) 3013–3033.
[44] Y. Jiang, C. He, P. Zhao, T. Sun, Investigation of blade tip shape for improving VAWT performance, Journal of Marine Science and Engineering 8(3) (2020) 225.
[45] I. Shchur, V. Klymko, S. Xie, D. Schmidt, Design Features and Numerical Investigation of Counter-Rotating VAWT with Co-Axial Rotors Displaced from Each Other along the Axis of Rotation, Energies, 2023, p. 4493.
[46] I. Hashem, M. Mohamed, Aerodynamic performance enhancements of H-rotor Darrieus wind turbine, Energy 142 (2018) 531–545.
[47] A. Yousefpour, M.N. Ghasemi Nejhad, Experimental and computational study of APC-2/AS4 thermoplastic composite C-rings, Journal of thermoplastic composite materials 14(2) (2001) 129–145.
[48] D.P.R. Thirumalai, Future Perspectives and Challenges of Thermoplastic Wind Blades, Indo-Danish Workshop On Future Composites Technologies for Wind Turbine Blades, 2012, pp. 7–8.
[49] S.M. Ghoneam, A.A. Hamada, T.S. Sherif, Fatigue-life estimation of vertical-axis wind turbine composite blades using modal analysis, Journal of Energy Resources Technology 146(3) (2024) 031301.
[50] A. Sharma, L. Zhang, J. Qu, S. Panthi, J.K. Tharu, Blade Structure Analysis of 2 MW V-Shaped Vertical Axis Wind Turbine Using Numerical Simulation, Kathford Journal of Engineering and Management 3(1) (2023) 149–171.
[51] K.A.H. Al-Gburi, F.B.I. Alnaimi, B.A.J. Al-quraishi, E.S. Tan, A.K. Kareem, Enhancing savonius vertical axis wind turbine performance: A comprehensive approach with numerical analysis and experimental investigations, Energies 16(10) (2023) 4204.