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Sustainable Energy Solution: Improving Efficiency in Thermal System, Wind Turbine Blade Design & Hydrogen Fuel Cell Technology

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Abstract: *The climate changes that are becoming visible today are a challenge for the global research community. The stationary applications sector is one of the most important energy consumers. Harnessing the potential of renewable energy worldwide is currently being considered to find alternatives for obtaining energy by using technologies that offer maximum efficiency and minimum pollution. In this context, new energy generation technologies are needed to both generate low carbon emissions, as well as identifying, planning and implementing the directions for harnessing the potential of renewable energy sources. Hydrogen fuel cell technology represents one of the alternative solutions for future clean energy systems. This article reviews the specific characteristics of hydrogen energy, which recommends it as a clean energy to power stationary applications. The aim of review was to provide an overview of the sustainability elements and the potential of using hydrogen as an alternative energy source for stationary applications, and for identifying the possibilities of increasing the share of hydrogen energy in stationary applications, respectively. As a study method was applied a SWOT analysis, following which a series of strategies that could be adopted in order to increase the degree of use of hydrogen energy as an alternative to the classical energy for stationary applications were recommended. The SWOT analysis conducted in the present study highlights that the implementation of the hydrogen economy depends decisively on the following main factors: legislative framework, energy decision makers, information and interest from the end beneficiaries, potential investors, and existence of specialists in this field.*

Keywords: Alternative energy; Energy efficiency; Fuel cell; Hydrogen energy; Stationary application

I. INTRODUCTION

Unconventional energy sources have gained and will continue to gain an increasing share in energy systems around the world [1], due to both the research and political efforts [2–8] involved in their development, as well as due to the price increases of energy obtained by traditional methods [9]. The primary energy sources, generally called renewable, are those sources found in the natural environment, available in virtually unlimited quantities or regenerated through natural processes, at a faster rate than they are consumed. Officially recognized renewable energies originate from the Sun's rays, the internal temperature of the Earth or the gravitational interactions of the Sun and the Moon with the oceans. The processes and methods of producing or capturing these types of alternative energy are in the process of being improved, the lower costs of infrastructure investments and the improved efficiency of conversion processes have made renewable energy sources provide a small part of the energy needs on a planetary scale [10]. The more optimistic forecasts estimate that renewable energy production will enjoy a 30–50% share of the total energy market by around 2050, but this depends on reducing production costs and finding massive energy storage possibilities [11]. In addition, none of these forms of energy can also provide fuels in satisfactory quantities for use in various stationary, mobile or industrial applications [5].

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In this context, we are currently looking for alternatives for obtaining energy by using technologies that offer maximum efficiency, high reliability and minimum pollution. Such a technology, considered at the moment the cleanest, through which sustainable energy can be obtained, is based on fuel cells [12]. As fuel cells develop, hydrogen-based energy production has become a reality [13]. The future hydrogen-based economy presents hydrogen as an energy carrier within a secure and sustainable energy system [14]. Humanity is on the verge of a new era characterized by advanced technologies and new fuels. We will witness new and completely different ways of producing and using energy. The energy could be generated by sources with virtually zero pollution. Hydrogen can be considered as a synthetic fuel, carrying secondary energy in a future era after the fossil fuel economy In order to outline an overview of the sustainability elements, the potential of using hydrogen as an alternative energy source for stationary applications and for identifying the possibilities of increasing the share of hydrogen energy in stationary applications, in this paper, a SWOT analysis was performed.

Improving wind turbine blade design and overall performance is essential; as a result, this study offers a thorough analysis of recent developments in advanced materials and aerodynamic optimization techniques. The escalating global demand for sustainable power necessitates maximizing the efficiency and sustainability of wind energy. Despite progress, challenges remain in optimizing energy capture, ensuring the structural integrity of increasingly larger turbines, and addressing environmental concerns. This review critically examines the potential of highperformance composites (such as CFRPs and bio-based alternatives), smart materials (including SMAs and selfhealing polymers), and nanomaterials (for surface coatings) to improve blade performance, durability, and sustainability. Furthermore, it analyses the impact of innovative aerodynamic profiles (including bio-inspired designs), variable pitch and twist technologies, and load reduction strategies on energy efficiency. The study identifies key challenges and research gaps in the integrated application of advanced materials and aerodynamic design for next-generation wind turbines, emphasizing the need for cost-effective and scalable solutions alongside comprehensive Life Cycle Assessments (LCAs). By synthesizing current knowledge, this review highlights promising future research directions to achieve more efficient, sustainable, and economically viable wind energy solutions through the synergistic advancement of materials and design.

II. MATERIALS & METHODS

The documentation for carrying out the study is based on the specialized scientific literature, articles in journals, papers presented at conferences on the hydrogen applcation topic and on-line scientific databases and web pages, including Google Academic, Google Scholar, MDPI, Science Direct, Scopus and research platforms or topic-specific web pages. In addition, this paper utilizes and analyzes a large number of reports, informations regarding the hydrogen & fuel cell strategic research agenda and documents published by the European Union (EU), the United Nations Organization (ONU), the International Energy Agency (IEA) [19–21] and other important dates from research and development institutions that are relevant to hydrogen economy, including E4Tech [22,23], International Association for Hydrogen Energy (IAHE) [24], National Research and Development Institute for Cryogenic and Isotopic Technologies (ICSI) Râmnicu Vâlcea, Romania.

The instrument used in this paper in order to verify and analyze the overall position with respect to general acceptance status regarding the harnessing energy potential of hydrogen technology and its use as an alternative energy source for stationary applications is the SWOT analysis. SWOT analysis provides an overview of the characteristics specific to the objective/domain of analysis and the environment in which it will be implemented. The SWOT analysis functions as an x-ray of the concept of hydrogen energy implementation in stationary applications and at the same time evaluates the internal and external influence factors of the concept, as well as its position in the applicability environment in order to highlight the strengths and weaknesses of the concept, in relation to the opportunities and threats existing at the moment The steps to perform the SWOT analysis are shown schematically in the diagram in Figure 1 in order to identify the strengths, weaknesses, opportunities and threats characteristics of the concept of hydrogen energy for stationary applications.

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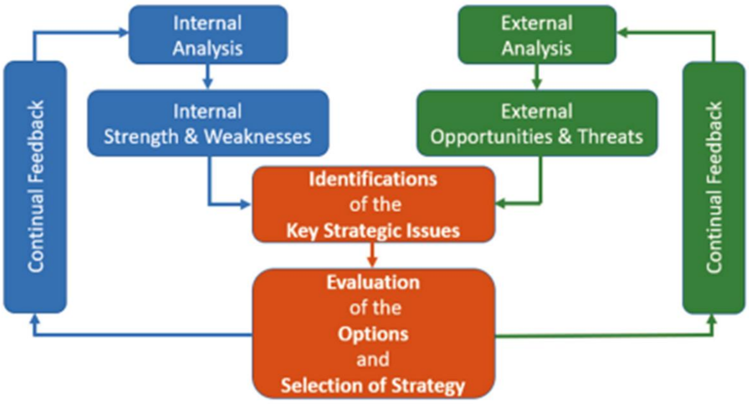

Fig. 1: The SWOT Process

As a rule, SWOT analysis allows investigators to improve the performance of current strategies by using new opportunities or by neutralizing potential threats [25]. Therefore, this analysis could be useful in helping decision makers and stakeholders to have a better overview of the concept of hydrogen energy used in stationary applications, facilitating the improvement of the current situation. As a result, SWOT analysis can be considered as an appropriate instrument for this research with scope to identify significant elements and advantages regarding the use of hydrogen energy in stationary applications, research/implementation/solutions/market status and possible changes, challenges, perspectives and improvements

III. OPTIMIZATION OF WIND TURBINE

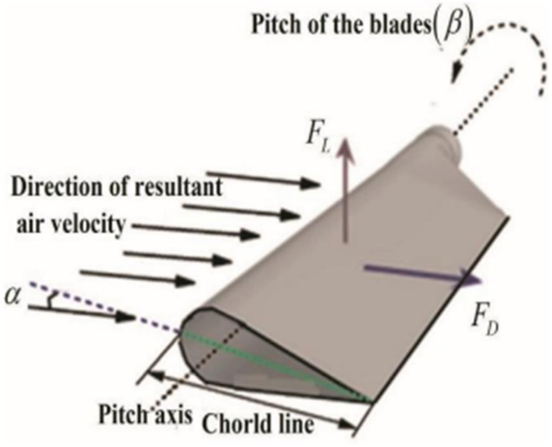

Fig. 2: Lift & Drag Force on Blads

The fundamental principles governing wind turbine performance are rooted in the conversion of kinetic energy from the wind into mechanical energy via the rotor blades and subsequently into electrical energy through a generator. The Betz limit, a crucial theoretical concept, dictates that a wind turbine can capture 59.3% of the wind's kinetic energy [13]. This limit is an inherent constraint on the efficiency of any wind turbine, regardless of material or design [13]. The power extracted by a wind turbine is fundamentally proportional to the cube of the wind speed, the swept area of the rotor blades, and the air density, further highlighting the critical role of blade design and operational environment [14]. The aerodynamic forces acting on the blades, primarily lift and drag, are essential for converting wind energy into rotational torque [15]. Optimizing the shape and orientation of the blades to maximize lift and minimize drag is a central tenet of wind turbine design [16]. The primary aerodynamic forces operating on the blade structures are drag and lift forces, which are shown in Fig. 1 as parallel and perpendicular to the direction of the incoming flow, respectively. The lift ðFLÞand the drag, and the lift ðFDÞ forces acting on each blade section basedð Þcland drag ðcdÞcoefficients are on the local resultant air velocity.

A. Blade Morphology Optimization

Bio-inspired blade geometries represent a fascinating avenue for aerodynamic enhancement. Nature offers numerous examples of efficient fluid dynamics, and researchers are increasingly exploring the potential of incorporating these principles into wind turbine blade design [33]. For instance, the tubercles found on the leading edges of humpback whale flippers have been shown to improve lift and delay stall in hydrodynamic applications [33]. Adapting such features to wind turbine blades could improve performance, particularly at higher angles of attack and under turbulent wind conditions [33]. Similarly, the aerodynamics of bird wings, with their complex shapes and ability to adapt during flight, inspire the development of more efficient and responsive blade designs. Computational Fluid Dynamics (CFD) modeling has become an indispensable tool in designing and optimizing wind turbine blade shapes [34]. CFD allows engineers to simulate the complex airflow around blade geometries, providing detailed insights into pressure distributions, flow separation, and vortex formation [35]. By iteratively modifying blade shapes and analyzing the resulting aerodynamic performance through CFD, optimized profiles can be developed to maximize lift and minimize drag for specific operating conditions [34]. This includes optimizing airfoil selection along the blade span, as different aerofoils may be more efficient at various radial positions due to varying Reynolds numbers and flow conditions [16]. Genetic algorithms and other optimization techniques are often coupled with CFD to explore a wide design space and identify non-intuitive but highly effective blade geometries.

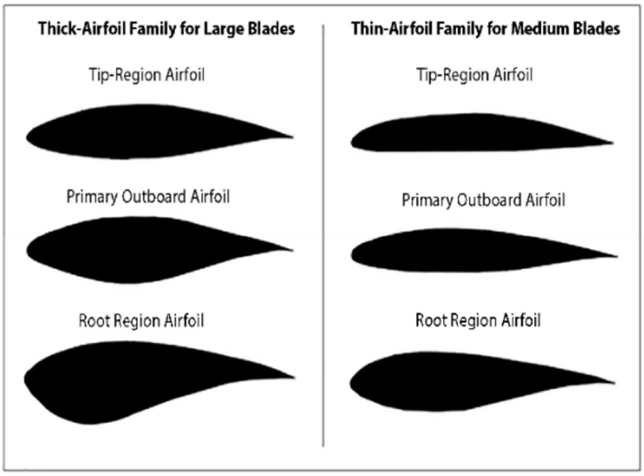

Fig. 3: Comparative airfoil profiles for wind turbine blades of different sizes

B. Load Reduction Strategies & Smart Control:

Managing the significant loads experienced by wind turbine blades is critical for their structural integrity and longevity. Distributed flow control devices, such as vortex generators and micro-tabs, can be strategically placed on the blade surface to modify the boundary layer and delay flow separation, thereby reducing drag and mitigating the impact of stall. Trailing-edge flaps, similar to those used in aircraft wings, offer the potential for active control of lift and drag. Adjusting the flap position in response to changing wind conditions makes reducing fluctuating loads and optimizing power capture possible. Artificial Intelligence (AI) integration is revolutionizing wind turbine control systems [37]. AI-based active pitch and yaw control systems can analyze real-time data from various sensors to proactively adjust blade pitch angles and nacelle yaw orientation [38]. This allows for optimized power extraction across a wider range of wind speeds and can also play a crucial role in reducing extreme loads during gusts or turbulent conditions [38]. Furthermore, AI algorithms can be used for predictive maintenance, identifying potential structural issues or performance degradation before they lead to costly failures.

C. Modular Scalable Design for Large Turbines:

As the quest for greater energy capture drives the development of increasingly larger wind turbines, logistical challenges related to the manufacturing, transportation, and assembly of massive blades become significant hurdles. Segmental blade designs offer a potential solution by dividing the blade into smaller, more manageable sections that can be transported and assembled on-site. This approach necessitates robust joining techniques that can maintain the complete blade's structural integrity and aerodynamic performance. The use of hybrid materials is also crucial for enabling the construction of these larger, more demanding structures [32]. Combining composite materials with complementary properties, such as high-stiffness carbon fibers in critical load-bearing areas and more cost-effective glass fibers elsewhere, achieves optimal structural reinforcement while managing weight and cost [32]. Integrating advanced adhesives and joining technologies is also essential for ensuring the long-term performance and reliability of hybrid material structures in large wind turbine blades. Additionally, the layers of sophisticated composite materials used to manufacture a wind turbine blade are depicted in Fig. 3. The spar, which is made of glass and carbon prepreg and serves as the main structural support, is an essential component of the design. Balsa and PET foam are core materials around the spar and other prepregs for the shell and web structures. Specialized epoxy and UV-protective gel coatings are applied to the surface to protect against external influences. The strength-to-weight ratio of the blade is optimized by this multi-material method, guaranteeing long service life and effective energy harvesting.

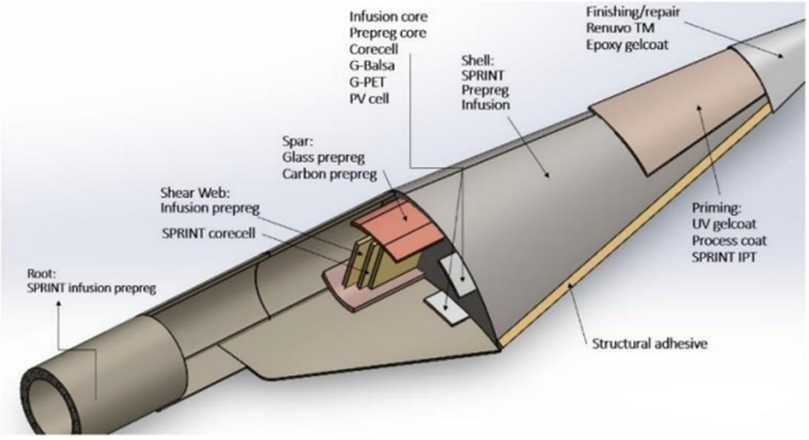

Fig. 5: Composite material layers in wind turbine blade construction

IV. CONCLUSION

This review highlights the significant role of advanced materials such as epoxy carbon, CFRP, and GFRP in enhancing wind turbine blade performance by improving strength, reducing weight, and enabling longer, more flexible designs [23]. Aerodynamic optimization techniques, leveraging CFD and increasing AI, are crucial for boosting energy efficiency through innovative profiles and design strategies [1], [38]. The development of VAWTs for urban environments also benefits from research into ultra-lightweight materials and advanced manufacturing like 3D Printing [56]. However, challenges persist in areas such as the scalability of advanced designs, material durability under harsh conditions, and the environmental impact of blade lifecycle.

In this work, the authors have performed a comparison between the steam methane reforming and steam methanol reforming technologies combined with HT-PEMFC and carbon capture systems for hydrogen-fueled ship applications. To find the most suitable technologies, an energy/exergy analysis, along with a space and fuel cost investigation, have been conducted. All the simulations have been conducted at a fixed Wnet, electrical (475 kW). It is shown that, at the base condition, the energy and exergy efficiencies of the methanol-based system are 7.99% and 1.89% higher than those of the methane-based system, respectively. The different efficiencies between systems mainly arises from the reforming temperature difference. For fuel and CO2 storage, the methanol-based system requires a space 1.1 times larger than that of the methane-based system for the total navigation time, although the methanol-based system has higher electrical efficiency. Accordingly, the methanol-based system has 2.2 times higher fuel cost than the methane-based system for 475 kW of net electricity generation during the total navigation time. In the parametric study, both systems show a similar trend, in which with increasing reforming temperature and S/C ratio, the electrical, exergy, and cogeneration efficiencies gradually decreased.

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REFERENCES

1. Firoozi, A. A., Hejazi, F., & Firoozi, A. A. (2024). Advancing wind energy efficiency: A systematic review of aerodynamic optimization in wind turbine blade design. Energies, 17(12), 1–31. https://doi.org/10.3390/en17122919
2. Tolasa, D. G., & Furi, A. T. (2025). The role of advanced materials in the optimization of wind energy systems: A physics based approach. Acceleron aerospace journal, 4(1), 847–857. https://doi.org/10.61359/11.2106-2504
3. Udorah, F. N., & Adeniran, A. O. (2025). A meta-study on smart coatings with carbon nanoparticles. Journal of environmental engineering and energy, 2(1), 44–63. https://doi.org/10.22105/jeee.v2i1.43
4. Familusi, O. B., Omoyeni, O. D., Samchuks, O. M., & Adeniran, A. O. (2024). Effect of renewable energy on co2 emission in Sub Saharan Africa. Systemic analytics, 2(2), 304–314. https://doi.org/10.31181/sa22202431
5. Ayoub, M. F. M. (2020). Reliability assessment of wind turbines. In Design optimization of wind energy conversion systems with applications. IntechOpen. https://B2n.ir/tm2441
6. Adeniran, A. A., Adeniran, A. O., Familusi, O. B., & Adedayo, O. (2024). The outlook of cyber security in african businesses: Issues and way-out. Management analytics and social insights, 1(2), 260–271. https://doi.org/10.22105/masi.v1i2.54
7. Dumitru, C. D., & Gligor, A. (2020). Optimal energy production planning in power systems with wind energy sources. In Design optimization of wind energy conversion systems with applications. IntechOpen. https://B2n.ir/zt5494
8. Chehouri, A., Younes, R., Ilinca, A., & Perron, J. (2016). Wind turbine design: Multi‐objective optimization. InTech. http://dx.doi.org/10.5772/63481
9. Animasaun, A. B., Adeniran, A. O., & Udorah, F. N. (2025). Mechanical properties of concrete by substituting sawdust with ground glass. Mechanical technology and engineering insights, 2(1), 1–9. https://mtei.reapress.com/journal/article/view/31
10. Karthikeyan, N., Anand, R. B., Suthakar, T., & Barhate, S. (2019). Materials, innovations and future research opportunities on wind turbine blades—Insight review. Environmental progress & sustainable energy, 38(3), e13046. https://doi.org/10.1002/ep.13046
11. Tong, C. (2018). Advanced materials enable renewable wind energy capture and generation. In Introduction to materials for advanced energy systems (pp. 379–444). Springer. https://doi.org/10.1007/978-3-319-98002-7_6