

Micro-Wind Marvels: A Comprehensive Review of Small-Scale Wind Turbines for Sustainability

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Abstract—This study examines the integration of renewable energy systems, including photovoltaic (PV) panels, wind turbines, and battery storage, in maritime transportation. The tool used for analysis is HOMER software, applied for the evaluation of different configurations in terms of technical and economic feasibility. Among the systems evaluated, the wind-battery-PV configuration is the least expensive, with minimal net present cost and breakeven energy cost, while satisfying design load demands. The results indicate that renewable energy solutions can be used to solve energy crises and environmental challenges in maritime applications. The study also emphasizes the advantages and disadvantages of wind energy, battery storage, and system efficiency. The study is recommending change towards sustainable and greener forms of maritime power systems, from the combination of developments in renewable technology with practical insights into their implementation.

Index Terms—Commercial Wind Turbine, Sustainable Energy, Optimization, Portable

I. INTRODUCTION

According to a report, wind energy has some of the most impressive growth rates and is poised to reach an annual rate of 14% in the next decade. Furthermore, it has outgrown the hydro power resources of the US and Europe by over 35%, making it the new leader in highest-capacity renewable energy resources. It's terribly far above the sun at this moment, and will soon dominate fossil fuels as well. Its cost of release decreased to a beneficial level of 69% over a span of ten years, followed by a further drop. The workload of the turbine also increased, which is currently at a range of 25% to 45%. In the past five years, offshore wind energy has increased at a speedy rate of 25%. Currently, wind energy's contribution stands at over six percent when

compared to other types of energy, while solar energy accounts for around 3%. Moreover, Europe, the United States and China are the new leaders of wind energy production at 70%. Wind energy also significantly reduces the emissions of carbon dioxide, saving around 2.2 Giga tonnes annually. This is equivalent to taking 47 million cars off the road. Experts at the World Wind Energy Council predict that wind energy will account for 20% of the world's electricity by 2030.

II. LITERATURE SURVEY

A. Rashid Iqbal, Yancheng Liu, Muhammad Arslan, Qinjin Zhang, Muhammad Yaseen, YujiZeng[1].

This paper presents how wind turbines play a crucial role in renewable energy systems by converting the kinetic energy of the wind into electrical energy. This renders them particularly useful for electric grids for ships, enabling cleaner and more ecological energy management. The main types of a wind turbine are rotor blades, shaft, generator and tower. Rotor blades capture wind power, which is converted into mechanical power and then transformed by the generator into electricity. The incorporation of wind turbines in the ship micro grid can dramatically lower consumption of fossil fuel, raise energy efficiency and produce greener maritime operations. In a techno-economic evaluation, wind turbine performance, economic viability, energy yield, and eco-environmental benefits are measured and provided as an input for estimating wind turbines' suitability for maritime applications. Wind energy is ample, renewable, and has little impact on the environment, but its turbines come with a drawback, such as variation in wind speed, an issue of no energy storage solution, and very high capital expenditure. Cases regarding the use of wind turbines in ship

micro grids revealed both the practical advantages and practicality of wind power for ships, where a bright future is foreseen with continued technological advancements, as well as integration with other renewable energy sources in offering sustainable and eco-friendly power to the shipping industry.

B. Wan Mohammad Amirul Bin Mohd Adnan, Shah Alam, Lilysuriazna Binti Raya [2].

In the vast majority of cases, the generation (production) of wind energy is the dominant renewable generation technology. This falls under the classification of the wind hybrid system list, which starts with a solar and other source hybrid system. In this work, to design a sample wind power generation configuration which stress the generation designs with significant difference between them, such that modulation is possible through the electricity storage using charge controller, another example of specialization has been implemented. At this stage, the appliance's voltage/current level is significantly different from the inverter which feeds the whole electrical power of the DC side to the AC side. Electric power is therefore generated from the power produced by registered appliances alone. Simple to its operation, with regard to the efficiency of all other elements of the turbine, the wind speed, and the height of the tower, wind energy from the wind power installation will have 11 blades who charge a 12V battery over 2 hours at a wind speed of 4.4 m/s. A smartphone application incorporating ESP32 Wifi with blink will be employed for the monitoring of AC voltage, current, and power consumption done by the appliances. At this stage of the work, this research investigates several technologies with a beginning right up to how winds might produce or evolve energy from it. The system will assist in the analysis of blade design effects on energy generation and even help to understand its role in a dynamic way of power application of the power in variable generation. More specifically, the paper will enter a pioneering work on a highly detailed information on the energy conversion efficiency in the systems management and thus, its potential applications in other fields for the utilization of these small components, such as charging and thus powering of a small domestic device. Certainly, it asks us to consider the design of the entire wind speed system and of the blades in the context of power systems (i.e. Basically, the idea of a

maximum power which the wind power plant can deliver seems to be possible number of turbine blades, wind speed, and distance. The output of the system, e.g., AC voltage, current, and appliance power, is possible to track remotely on a smartphone by means of the Blynk application that is incorporated in the ESP32 Wi-Fi module. The present project considers aspects of wind energy such as the fundamental energy generation from wind, the role of turbine blade geometry on energy output, and the need for energy storage to handle wind speed variation. The energy conversion efficiency of the system is also calculated, and the practicality of the system is illustrated by battery charging and powering microelectronics. Moreover, it takes into account the relation between wind speed, turbine blade shape, and energy production, so this research is also very useful for the optimization of small-scale wind power systems.

C. Razzaqul Ahshan, Abdullah Al-Badi, Nasser Hosseinzadeh, Mohammed Shafiq [3]

This paper states an upward trend in the use of micro wind energy systems. These are in part driven by technological advancements in relation to wind turbines, which have rapidly made wind energy less expensive. The research examines the potential use of mini wind turbines that cover a rotor swept area below 200 m² and/or a rated power up to 100 kW for tapping the wind power in the Sultanate of Oman. The site-specific wind data, annual energy collection, effective wind speed cumulation, and turbine capacity factors are analyzed. Five turbine models were compared in three different locations that took into account the influence of the pressure and temperature variations of air density on the annual energy production (AEP) and capacity factor (CF). The analysis uses the Weibull distribution function to fit wind speed distribution and give detailed attention to site-specific variations on the basis of wind data. The outcome demonstrates the high potential of small wind turbines to serve a variety of use cases, including residential, school, campus, community, greenhouse, irrigation, and small business application in Oman. The paper also presents main characteristics of operation, such as cut-in, rated and cut-out speeds, rotor diameters that are of great technical importance to turbine performance optimization. In addition, modeling the effects of air

density, pressure, and temperature on power output will be critical for calibrating turbines to different environments, such as potentially marine use.

D. Keita Shimizu, Hiroyuki Abo, Masaki Sato, Hisao Yaguchi [4],

This paper is about the increasing interest in wind power generation as part of the efforts toward sustainability, which has garnered much attention for offshore large wind turbines within Japan's decarbonization initiatives. Even so, implementation of large propeller turbine type units is still greatly restricted in inland areas because of installation and maintenance costs, noise pollution and visual impact. In the pursuit of higher efficiency

for such wind turbines, this work is directed at vertical-axis small wind turbines that are more affordable and less obtrusive, to find out the potential of the "Wind Lens"—a brimstone diffuser—to improve the performance of such turbines. Wind Lens technology speeds up incoming air momentum onto the turbine rotor and gives an unprecedented enhancement to rotational speed (particularly lift-type vertical-axis turbines, Darrieus type in particular) even at low wind speed. In the test of a Wind Lens-equip prototype, a wind tunnel test was employed; the device achieved higher rotational speeds, lower wind speed startup, and passive yaw stability. That guaranteed the smooth and constant functioning without dependence on wind directions. Additionally, robustness is guaranteed up to 20 m/s in wind speed, rendering the system practically feasible. This performance enables the vertical-axis small wind turbines to become an option for the inland regions, minimizing the environmental and economic challenges linked to the conventional large-scale turbines and enabling as much energy capture as possible under variable wind regimes.

E. Dr Pétér Kádá [5]

Two urban areas, provided by Óbuda University, and an unobstructed zone at Budapest Airport. The analysis included various turbine models including AIR X 400, Sollight 1 kW, and Windpower 600, representing both HAWTs and VAWTs. Wind speed measurements showed an average of 1.5 m/s in the urban environment and more than 3 m/s at the airport, with energy production being highly dependent on-site conditions. Urban locations had

lower energy yields as a result of lower hub heights and weaker wind speeds. Battery lifetime was a less direct challenge from the memory storage point of view, with limited lifetime of batteries, overcharged and undercharged batteries and self-consuming energy loss of batteries. Wind climate mapping revealed a diversity of points on a building where wind speeds varied to choose the best location for the turbines. Though the turbine generator characteristics matched the expected power curves, peak power was not maintained over long periods. According to the study, small-scale WT perform poorly in the city because low energy and battery management problem makes them more appropriate for the rural area or the high-altitude layout.

F. Dongran Song, Qing Chang, Songyue Zheng, Sheng Yang, Jian Yang, Young Hoon Joo [6],

This paper is set to indicate how kinetic energy in wind is converted into electrical energy by wind turbines; it employs rotating blades attached to a generator. The main components of a wind turbine are the rotor-blades, a nacelle containing the generator and gearbox, a tower and a control system. Advanced variable speed turbines control the rotor speed to match wind ranges for maximum energy capture, thus raising efficiency. The yaw system/system rotates the nacelle along the wind axis in order to reduce energy loss caused by misalignment. Model Predictive Control (MPC) type of advanced control strategies is employed for improving performance of the yaw system. This predicts future wind conditions for improved efficiency. Adaptive MPC advances the idea by adaptively refining control parameters to optimize performance for continuously changing wind conditions. The use of such an approach has been found to exhibit superior overall performance than fixed control horizon-based MPC as evidenced by simulation analysis of real wind data. Advancements like adaptive MPC are making wind turbines more efficient and reliable, supporting greater integration into power grids by maximizing energy capture while minimizing mechanical wear.

G. XiangHuanga[7]

The following paper figures the role tomlbering of ships to carry passengers and goods and marine resource lookshipping, the marine examination of

marine ecology, and marine resources for biological activities. Due to the navigation in this great sea, stable power supply is a key problem, and wind generation technology has accounted for more attention as a solution. Wind power generation transforms wind energy into mechanical energy and finally into electrical energy via wind turbines. This is widely used on ships. Earthing and power generation for independent operation of small coastal vessels is typically based on electricity obtained from a small wind turbine and stocked in batteries to fuel backup or standby power. Hybrid modes of operation integrate wind power with additional (e.g., solar, diesel) sources for remote navigation, which provides a more stable energy supply. Grid-connected operation modes are employed for large ships to make use of wind driven electricity into the ship's own power grid to provide continuous power. The wind-solar hybrid system is particularly suitable for using solar energy in great amounts daylong and wind energy at night to provide a steady power during prolonged voyages. These systems require special equipment, like low-speed generators for changing wind speeds and resilient solar panels which can stand against salty sea environments. By utilizing a combination of wind and solar power, ship operations are made more flexible, reliable, and environmentally sustainable, and dependence on conventional fuels is reduced.

II. COMPARATIVE ANALYSIS OF LITERATURE REVIEWS

A. Renewable Energy Based Microgrid Scheme for Greener Ship: Evaluation through Techno- Economic Performance Analysis Parameters

Rashid Iqbal, Yancheng Liu, Muhammad Arslan, Qinjin Zhang, Muhammad Yaseen, Yuji Zeng

This paper evaluates the feasibility of renewable energy micro grids for ships, integrating wind, solar, and battery systems. Using homer software, it identifies the wind/battery/pv system as the most optimal, offering lower costs and high energy efficiency. While bat/pv systems generate excess energy, the study concludes that hybrid renewable configurations are promising for sustainable maritime power, addressing energy crises and environmental pollution challenges effectively for greener transportation.

B. Feasibility Study of Wind Power Generation System Using Small Scale Wind Turbines

Wan Mohammad Amirul bin Mohd Adnan, Shah Alam, Lilysuriazna Binti Raya

The study investigates small- scale wind turbines for electricity generation, emphasizing the impact of blade design, wind speed, and IoT integration for energy monitoring. A prototype system utilizing an ESP32 module and the Blynk application is developed, showcasing efficient energy conversion and remote monitoring capabilities. It highlights that wind speed and blade count are crucial factors, with the system charging a 12V battery in two hours under specific wind conditions.

C. Small Wind Turbine Systems for Application in Oman

Razzaqul Ahshan, Abdullah Al-Badi, Nasser Hosseinzadeh, Mohammed Shafiq

This paper explores the application of small wind turbines in Oman, analyzing site-specific wind conditions and turbine performance. Using Weibull distribution and capacity factor calculations, it evaluates energy output under varying pressures and temperatures. The results show that small turbines are viable for residential, agricultural, and remote applications, particularly in areas with sufficient wind resources. The study emphasizes technological advancements in reducing costs and improving turbine efficiency for localized energy needs.

D. Experiment with a Prototype of Vertical-axis Small Wind Turbine with a Wind Lens

Keita Shimizu, Hiroyuki Abo, Masaki Sato, Hisao Yaguchi

Focusing on vertical-axis small wind turbines, this study examines the use of a wind lens to enhance turbine efficiency. Wind tunnel experiments reveal that the lens significantly amplifies rotational speed, improves start- up performance, and ensures stability in varying wind conditions. Designed for inland regions with low wind speeds, this technology offers a practical solution for affordable, sustainable energy generation while addressing issues of noise, maintenance costs, and environmental disruption.

E. Experiences with Small Scale Wind Turbines

Dr. Pétér Kádár

This paper explores wind power generation technology in ships, focusing on standalone, hybrid, and grid-connected systems. It highlights the advantages of combining wind and solar energy for

continuous power supply during long voyages. The study details independent operation for smaller ships and hybrid systems for larger ones, emphasizing sustainability, operational flexibility, and reduced reliance on fossil fuels. Wind-solar systems are identified as ideal solutions for ensuring stable marine power.

This paper summarizes experiences with small-scale wind turbines tested in urban and rural environments, including airports and cities. The findings highlight lower energy production in urban areas due to limited wind speeds and battery performance issues. However, in rural or high-altitude areas, turbines perform better. The study discusses the challenges of battery lifespan, wind climate mapping, and generator efficiency, recommending improvements for small turbine systems in suitable environments.

F. Adaptive Model Predictive Control for Yaw System of Variable- speed Wind Turbines

Dongran Song, Qing Chang, Songyue Zheng, Sheng Yang, Jian Yang, Young Hoon Joo

The study proposes an adaptive model predictive control (MPC) system for optimizing the yaw mechanism of variable-speed wind turbines. Simulations using real wind data demonstrate that adaptive MPC outperforms traditional control systems by dynamically adjusting parameters to improve efficiency and reduce energy losses. The advanced control system ensures better turbine alignment with wind direction, enhancing energy capture while minimizing mechanical wear, with potential applications in real-world windfarms.

G. Application of Wind Power Generation Technology In ship

Xiang Huanga

III. CONCLUSION

The review brings to light important progress in the technology of using wind energy and its ability to solve the problems of energy efficiency and sustainability in multiple uses. Wind energy, along with design and hybridization, is a source of power that is dependable and renewable. This technology is flexible and can be used in various settings. Other important changes: improved turbine effectiveness, Internet of Things (IoT) assisted supervision, and modernized control systems suggest the feasibility of increasing power availability while decreasing

expenses. These technologies have broadened the application of wind energy starting from small-scale uses to large-scale uses like integration into complicated systems, including marine power grid systems. Research and development are still stimulated by these challenges such as: the variability of wind resources, energy storage, and operational efficiency. The results underline the need for advanced technologies paired with local optimizations to make the most of wind energy, help in reaching the global goals of sustainability, and lessen the dependence on fossil fuels.

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