The Effect of the Number of Blades on the Efficiency of A Wind Turbine

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Abstract. In this paper, we examine existing literature on the way that the number of blades of a wind turbine affects its efficiency and power generation. A wind turbine blade is an important component of a clean energy system because of its ability to capture energy from the wind. The power that a wind turbine extracts from the wind is directly proportional to the swept area of the blades; consequently, the blades have a direct effect on power generation. The number and configuration of the blades is very important because it affects the speed and efficiency of turbine. Unfortunately, as the number of blades increases, so does the slipstream effect. Too few a number of blades results in poor efficiency and thus inadequate performance. Too large a number of blades increases weight and production cost. The correct number of blades is important to fit the generator performance curve to optimize overall turbine performance and efficiency.

1. Introduction

Wind turbines extract energy from the wind and convert it into electricity [1]. A wind turbine blade is an important component of a clean energy system because of its ability to capture energy from the wind. The configuration of blades plays an important role in their efficiency [2]. Characteristics such as tip speed ratio, angle of attack, materials used in the manufacture of the wind turbine blade, and weight of the wind turbine blade play important roles in determining the efficiency of blade as well as that of the turbine. In real life, wind turbines cannot capture more than 59.3% of the energy from the wind, which is known as the Betz limit [3]. Blade characteristics determine the amount of energy that can be extracted from the wind. For this reason, improving the performance of a wind turbine blade directly increases the efficiency of the wind power plant [4]. Designers of most commercial wind turbines, which are mostly horizontal axis wind turbines and a few vertical axis wind turbines, have tried to design wind turbines that operate at efficiencies close to the Betz limit. However, there are limitations due to losses in the system from the mechanical assembly in the nacelle. Figure 1 compares the performance of different types of wind turbine to the Betz limit (0.593).
Subtracting the sum of the losses from 0.593 gives the maximum amount of energy that can be extracted. According to Siemens in 2007, modern three-blade wind turbines have combined intelligent blade design and a well-chosen rotational speed of up to 80% of the Betz limit. A two-blade turbine will be approximately 5% less efficient than a three-blade turbine, but will provide a higher return on investment due to lower costs [6]. The efficiency of three-blade turbines is approximately 51%, whereas it is reported to be 49% for two-blade turbines [7]. In this paper, we examine the literature to determine the effect of the number of blades on the efficiency of wind turbines and the power generated.

2. Literature review

The number of blades is very important because it affects the speed and efficiency of a turbine [8]. The power that a wind turbine extracts from the wind is directly proportional to the swept area of the blades; consequently, the blades have a direct effect on power generation. The more blades that a wind turbine has, the more torque it produces (force that produces rotation) [6], [7] and the slower the rotation speed (due to the increased drag caused by resistance to wind flow) [8]. Typically, turbines that are used to generate electricity must run at high speeds and, hence, do not require much torque. Thus, greater power generation results from a fewer smaller number of blades [9]. In general, most horizontal axis wind turbines have three blades. The decision to design three-blade turbines was a compromise. Due its reduced drag, a one-blade design is the optimal number for maximum efficiency. However, a single blade causes imbalance and, hence, is not practical [10]. A number of blades greater than three produces greater wind resistance, lower power generation and, therefore, is less efficient than three-blade turbines. For example, two-blade wind turbines face an unbalanced torsional force acting at the center (and supporting pole) of the blade. This unwanted twist can reflect to the blades, causing them to vibrate. If the rotating speed is equal to the natural vibration

![Figure 1](image_url). Comparison between the performances of different types of wind turbine. The Betz limit is 59.3%. [5]
frequency of the blades, catastrophic mechanical damage can result. With three or more blades, the mechanical behavior of the turbine is practically the same for every possible blade orientation. The maximum number of blades that will produce maximum power on a particular size turbine is four. Mechanical problems with two-blade turbines can be solved in a four-blade design, but ignoring the extra weight of the blade, economically four blades are more expensive than three blades. For these reasons, turbines manufactured with three blades represent an ideal compromise between high energy output, high stability, light weight, and turbine durability [9–11]. A fewer number of blades increases flow speed, while a larger number of blades results in higher torque. The highest power is between these two extremes. Figure 2 compares the coefficient of electricity with the speed of the tip of a wind two and three blades [7].

Figure 2. The power coefficient versus tip speed of a two bladed and three bladed wind turbine [7].

The correct number of blades is important to optimize overall performance and efficiency [12]. Therefore, the three-blade design is often the best compromise with the lowest cost between a simple and reliable design, high power and low weight [11]. The number of blades is believed to determine turbine speed characteristics, as well as aerodynamic performance, design and manufacturing costs [13]. Rachman et al., examined the effect of blade number on the rotational speed characteristics of a riverflow turbine with a horizontal axis by performing a parametric study using the blade element momentum theory. As a result, they found that a turbine with fewer blades has a high rotational speed characteristic, and a turbine with more blades has a low rotational speed characteristic. The very low angle of attack, which results in a low lift coefficient, is one of the factors that prevent turbines with many blades from operating at high speeds. The researchers recommended that for a large number of blades on the turbine, high gear ratios are required to endure high generator rotation [14].

Kurniawati et al., (2018) conducted a pilot study on the effect of the number of blades on the performance of cross-flow wind turbines (cross-flow wind turbines are a type of vertical axis wind turbines). The turbine design was 0.4 x 0.4 m² and was experimentally tested with three blade configurations (8, 16 and 20). The turbines were tested at low wind speeds of 2–5 m/s. The results showed excellent performance of 16 blades. They concluded that increasing the number of blades in a cross-flow wind turbine can increase the coefficient of performance ($C_p$) for a specific number of blades [15]. Junior et al., studied the effect of the number of blades on the design of propeller hydrokinetic turbines. Using simulations of blade element momentum theory and wind tunnel experiments, the $C_p$ of runners with different numbers of blades (two, three and four) is examined in a specific low-rotational-speed operating condition. The results showed a reduction in performance reduction in runners with two and three blades compared to runners with more blades [16].
A study of the effect of the number of blades on the mechanical power curve of wind turbines was performed by Predescu et al. The results showed a slower decrease in the $C_p$ of the rotor with 6 blades with blade tip angle than the $C_p$ of the rotor with 2 or 3 blades. Therefore, increasing the number of blades increased the margin to adjust the cut-in wind speed without significantly affecting the power coefficient [17]. Sunyoto et al investigated the effect of blade number on the performance of H-Darrius-type wind turbines. The number of blades affected the rotation of the wind turbine. The results showed that by using more blades in the wind turbine, the wind turbine is easier to rotate at lower wind speeds, but a greater number of blades causes lower performance and higher torque [18]. Comparing five-blade and three-blade wind turbines, five-blade wind turbines greatly improve annual performance in poor wind conditions in areas with an average wind speed of 5 m/s. Compared to the traditional three blade wind turbine, a five-blade turbine can increase annual performance by more than 60%. The speed of the blades of a five-blade turbine is 60% of the three-blade wind turbine. Five-blade wind turbines greatly reduce the chance of high-speed malfunction. Five-blade wind turbines greatly reduce the chance of over-speed control malfunction. This ensures operational reliability in the long run. The five-blade wind turbine has a lower blade speed, which reduces the sound of wind turbines, and five-blade wind turbines are more aesthetically pleasing than three-blade wind turbines [19]. Figure 3 shows how the number of blades affects the performance of wind turbines.

![Figure 3. Effect of number of blades on performance [20]](image)

Using analytical and statistical methods, Warjito et al investigated the effects of water kinetic energy on the energy conversion process in a waterwheel. Variable input speeds of 1 m/s, 3 m/s and 5 m/s and blade numbers of 6, 7, 8, 9 and 10 were tested. According to the results, the 8-blade waterwheel is the most efficient with 1 m/s (45.58% efficiency) and 5 m/s (13.84% efficiency) variable input speeds [21]. Similarly, Sritram and Suntyvarakorn built and tested water turbines with two to seven blades to find the most suitable number of blades experimentally. Their results showed that the five-blade turbine is most suitable because it produces the highest torque while increasing the system efficiency [22]. Ali et al studied the efficiency of mixed inflow turbine under steady conditions with the effect of the number of blades. Many simulations were performed on different rotors of different blade numbers (8 to 20) having the same geometrical shape. Results indicated that the 14-blade rotor is more efficient in approximately 84% of design conditions. Under design conditions, the fourteen-blade, mixed-inlet turbine performed...
better. The fourteen-blade rotor was a good compromise between good operational characteristics and reduced losses [23]. Baidar et al studied the optimal design for a micro hydropower site in Nepal. The turbine was designed using computational fluid dynamics analysis to assess the performance with three configurations: eleven, thirteen and seventeen blades. The turbine with thirteen blades showed better performance and manufacturability [24]. In another study by Payambarpour et al, a 4-inch diameter in-pipe, drag-based (Savonius turbine inspired) turbine was designed and the effect of increasing the number of turbine blades numerically was examined. The results showed that increasing the number of turbine blades up to five blades improves the efficiency. They found out that increasing the number of blades beyond five increased the hydraulic resistance of the turbine and reduced efficiency. They proposed that turbines with fewer than five blades are less efficient than optimal because they cannot harness the potential flow capacity [25]. Chakraborty and Pandey performed numerical studies on the characteristics of centrifugal pump using Ansys Fluent software. The model pump had an impeller with 4, 5, 6, 7, 8, 9, 10, or 12 blades and a rotation speed of 4000 rpm. Results showed that 10 blades gave optimum efficiency [26]. Unfortunately, as the number of blades increases, so does the torque, and thus the rotation of turbine is smoother. So, the choice of the number of turbine blades has a direct impact on efficiency and economy. Too few blades result in reduced efficiency and performance. Too many blades causes increased weight and production cost, among other issues [27].

3. Highlights

3.1 Performance and efficiency
Two-blade wind turbines are slightly less efficient than three-blade wind turbines and must rotate faster for maximum efficiency [7]. Similarly, two blades will produce more electricity than three blades, but have their own problems. Two-blade turbines are sensitive to gyroscopic precision, which results in wobbling. Naturally, this wobbling will cause stability problems for the entire turbine. This will also put pressure on the turbine’s components, reducing its efficiency and lifetime [10]. According to the latest research, a two-blade design for a wind turbine is 3% less efficient than a three-blade counterpart of the same diameter. Additional power can be obtained from the longer wind turbine blades, with the advantage of lower construction, material and maintenance costs [6]. Five-blade wind turbines greatly improve annual performance in poor wind conditions in areas.

3.2 Balance
A rotor with an even number of blades can cause stability problems in a rigid frame machine. The reason is that the moment from the upper blade is reflected back, and it achieves its maximum wind power and the lower blade passes through the wind shade in front of the tower [28]. Wind turbine's three-blade rotor has more consistent performance than two or four blades [18].

3.3 Cost
The economic benefit of two-blade wind turbines is associated with lower manufacturing and transportation costs. Research from a previous feasibility study reported that two-blade turbines cost 10–12% less than three-bladed units for offshore wind farms under certain operating conditions [29], [6].

3.4 Weight
Two blade wind turbine designs have reduced cost and weight as compared to a three-blade rotor [28]. Two-blade wind turbines are 30% lighter than three-blade wind turbines [6]. Lower weight is a particular advantage for offshore application, as are ease of handling, transportation and assembly [7].
3.5 Rotor vibration

Two-blade wind turbines withstand an unbalanced twisting force acting on the hub (and pole) at twice the speed of the blade. This unwanted deflection can return to the blade, causing them to vibrate [11]. A three-blade turbine on the other hand, has very little vibration. The reason for this is that when one blade is horizontal, its two resistances are balanced by the other two blades. So, a three-blade turbine is the best combination of high rotational speed and minimum stress [9]. The hub mechanism and/or post itself may need to be made stronger or more rigid to resist these unwanted torsion forces [11]. In addition, it is expected that load reduction techniques to reduce the effect of load imbalance on the two-blade rotor, such as teetered hub, reduce the high natural vibration of the two-blade rotor by reducing the energy performance of the asymmetric configuration will make it better [29].

3.6 Noise

Two blade wind turbines must rotate faster for maximum efficiency. This is a disadvantage for onshore wind turbines, because the noise increases due the increase in tip speed [7], [28], whereas increases in the number of blades lowers blade speed, which reduces the sound of wind turbines.

3.7 Wake effect

The turbulent intensity, however, indicates a high variability for the two-blade rotors. The intensity of the turbulence is particularly high in the tip area, due to the strong vortices generated. This higher level of turbulence in the wake supports higher wake recovery rates in two-blade rotors than three bladed rotors, especially behind the turbine [30].

3.8 Aesthetics

Another factor influencing the number of blades is aesthetics. It is generally accepted that a three-blade turbine is more satisfying to the eye than one- or two blade-turbines [31]. Although, it is worth noting that five-blade wind turbines are more visually appealing than three-blade turbines [19].

3.9 Storm resilience

The main disadvantage of areas with frequent strong winds is that they can turn into regular violent storms and hurricanes. Most wind turbines cannot withstand high wind speeds in stormy conditions. Two-blade wind turbines can be easily erected into position and then laid back down on the ground with one crane instead of two [6] if necessary in preparation for a storm. However, five-blade wind turbines greatly reduce the chance of malfunction, which ensures operational reliability in the long run [19].

4. Conclusion

The effect of having more than one number of blades on a wind turbine has been examined using a cost benefit perspective. Currently, three-blade designs are used for horizontal axis wind turbines because it provides the ideal compromise between high energy yield, greater stability, low weight, and durability. Future forecasts suggest that two-blade wind turbines will begin to penetrate the market due to lower energy costs, greater energy yield, lower weight, ease of handling, transportation and assembly, greater storm resilience and better use for onshore applications. Although two-blade wind turbines have efficiencies only 3% lower than its three-blade counterpart with the same diameter, increased electrical output can be obtained from longer turbine blades on two blade turbines, while still benefiting from lower construction, material and maintenance costs. Stability and reduced rotor vibrations in two blade wind turbines can be obtained by implementing load reduction techniques such as a teetering hub and the stronger designs of the rotor hub. In the case of cross-flow wind turbines, 8-blade rotors seem optimum and for waterwheels. Blade numbers between eight and fourteen appear optimum for a balance between efficiency, speed, torque and manufacturability under most design conditions. Ultimately, a fewer number of blades increases the flow speed, while a greater number of blades results in a higher torque. The optimal power is produced by designs in between the two extremes. Efficiency, wind turbine cost with respect to the number of blades, blade weight, and physical, geometric, and aerodynamic blade
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Acknowledgements
The authors give special thanks to the African Centre of Excellence, Energy for Sustainable Development, University of Rwanda, Kigali, Rwanda through the ACE II World Bank program for their sponsorship. The views expressed in this paper does not necessarily reflect the view of the World Bank.