To what extent can the energy efficiency of wind turbines be improved?

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1. Introduction

The first automatic wind turbine was created in 1887 by the American scientist Charles F. Brush as a means to generate electricity.[1] However, it was not until nearly one hundred years later in 1980 when the first commercial wind farm was created.[2] This marked a substantial change in the purpose of wind turbines, changing from a scientific toy to an actual means of generating electricity. Today, turbines are produced in various sizes with various purposes, ranging from small domestic turbines to large commercial wind farms.[3]

Wind turbines have a very important place in our future. As humanity continues to develop and grow, the threat of climate change and global warming has never been more present. In the 2015 Paris Agreement, the countries of the world pledged to "limit the temperature increase to 1.5°C above pre-industrial levels".[4] This can be done by reducing the use of fossil fuels. As a result, there has been a growing interest in "renewable energy", energy derived from natural sources, such as wind.[5] This has become a particular focus in the United Kingdom (UK), as it has one of the best locations for wind in Europe,[6] allowing it to benefit greatly from wind energy. The UK government has committed to several targets regarding increasing renewable energy and it currently boasts the world's largest offshore wind farm, Hornsea 2.[7] It comprises 165 Siemens Gamesa 8MW turbines, and has a capacity of over 1.3GW allowing it to provide power to more than 1.4 million homes.[8] In 2022, almost 25% of the UK's electricity was generated by wind turbines,[9] making it one of the country's major power sources.

Wind power is often argued to be the most efficient and safe renewable energy source. Over the last few decades the technology behind wind turbines has advanced considerably, leading to lower costs. The turbines themselves don't contaminate local water supplies or emit toxic substances.[10] On top of this, wind turbines can be installed almost anywhere making them incredibly flexible.[11] It is for these reasons, wind turbines are perhaps one of the most important technologies to provide a sustainable and affordable source of energy. That is why, more than ever, the industry must ensure that wind turbines are as efficient as they can possibly be.

However, wind turbines aren't without their faults. A recent auction for the development of one of the UK's newest offshore wind farms, Norfolk Boreas, had no bids. The argument was that the "price set for electricity generated was too low to make offshore wind projects viable".[12] In addition to this, many onshore wind farms are objected to because of their unappealing visual impact, noise pollution, negative environmental impact and their contribution to reduced property values.[13] These concerns will limit the growth of wind power as a major source of energy. Therefore, it is important to consider how the number of wind turbines can be minimised, whilst the power output can be maximised. In order to do this turbines must be made more energy efficient.

It is clear that wind power is becoming more important and so we must consider how it can be improved in order to make it a better, more efficient energy resource.

2. Aims and Objectives

2.1 Overall Goal:

To explore if contemporary wind turbines can be made more energy efficient and if so, what changes can be made to increase their efficiency.

2.2 Aims:

1. To understand the functionality of wind turbines and the physics and engineering behind how wind turbines operate.
2. To learn what is meant by energy efficiency and how it is applied to a wind turbine.
3. To research and report on factors that have an impact on the energy efficiency of wind turbines.

2.3 Objectives:

1. To investigate how the current design and installation of wind turbines converts kinetic energy of air into electrical energy that can be used by a consumer.
2. To identify the variables which impact the power output of a wind turbine to determine the current range of energy efficiency for modern wind turbines.
3. To evaluate and make recommendations about the engineering techniques used to improve the energy efficiency of wind turbines.

3. Methodology

3.1 Search

A search was conducted through Google Scholar and Google on several search terms such as, "How a wind turbine works", "wind turbine", "energy efficiency", "onshore wind turbine", "offshore wind turbine", "direct-drive wind turbine" etc.

Other papers were identified because they were referenced by research found using the search terms or they were recommended by articles found online.

Some website articles were also identified.

3.2 Inclusion Criteria

The research was narrowed down to only include sources that met at least one of the following criteria:

- Whether the source came from a reputable source, such as a peer reviewed journal, or it was published on a reliable website

- The relevance of the source to the question. Those sources that didn't directly relate the research question or another part of the dissertation, were excluded. Some sources that weren't incredibly relevant were still used as they provided greater context about the research question.

- The source was referenced multiple times in various papers/websites. Sources that were considered more notable were given priority over those that weren't.

- The language of the source must be in English or an accurate, reviewed translation into English.

- Whether the source was accessible, for free, through websites such as Google Scholar or Research Gate. Access to some restricted articles was gained through the use of familial connections to Cardiff University.

- The source was published within the last 20 years. There were some exceptions to this (for example, Betz paper which was published in the early 20th century) if the research was very influential, no other research could be found or the currency of it did not impact the findings.

3.3 Analysis and collation of sources

The sources were then analysed using the CAARP (Currency, Authority, Accuracy, Relevance, Purpose) framework.[14]

The sources that met the inclusion criteria were presented in a table alongside their CAARP analysis. This can be found in Appendix A.

4. Main Findings

4.1 How the design and installation of wind turbines produces electrical energy

In order to understand how turbines can be made more efficient, it is important to understand the basics of how they work. Generally a wind turbine is composed of a tower, a rotor and a generator. Each component of a wind turbine has a function, the tower is a large pole-like structure that supports the upper part of the wind turbine; the rotor consists of propellor-like blades which are designed to spin; and the generator which generates electricity.[15]

In its least complex form, the concept of a wind turbine is fairly simple. The motion of the wind causes the blades to rotate. This captures the kinetic energy of the wind, converting it into a rotary motion that drives the generator. The kinetic energy is then converted into electrical energy by the generator that can be used by consumers on the national grid via a system of transformers and cables.[15,16]

In general, there tends to be two main types of wind turbine, the Horizontal Axis Wind Turbine (HAWT) and the Vertical Axis Wind Turbine (VAWT).

4.1.1 The Horizontal Axis Wind Turbine

The most commonly used wind turbine is the horizontal axis wind turbine (HAWT). It works by having rotor blades rotate around a horizontal axis (Figure 1).

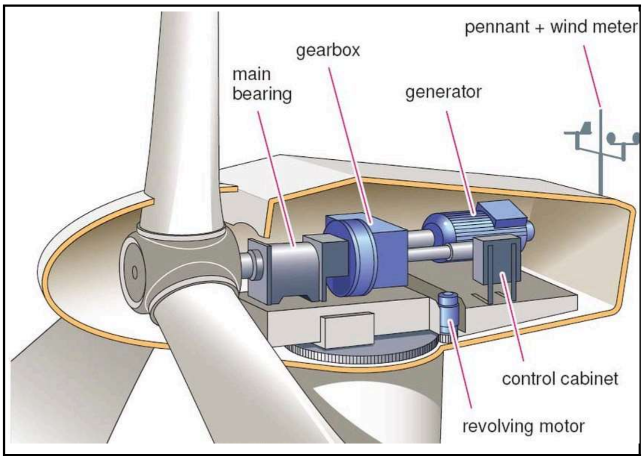
It tends to be favoured by the industry due to its capability of capturing more wind and thus being able to generate greater power.[16] HAWTs are composed of various components that work together to support the structure, maximise wind capture and generate electrical power.[15] These components are crucial in understanding how a turbine can be made more efficient.

Source: Alternative Energy Tutorials

Figure 1: A common HAWT

Perhaps the most important element of any wind turbine is its blades. In a HAWT these work similar to the airfoil of an aeroplane wing. As wind flows across the blade, there is a difference in air pressure between both sides of the blade, caused by a reduction in air pressure on one side.[15] On the side with greater pressure a lift force acts, which is perpendicular to the direction of wind motion. The lift force pushes the blades upwards and is translated into a rotational motion because the blades are attached to a “central rotational axis”.[16] Another force called drag acts in parallel to the direction of the motion. The drag force causes turbulence, which has a braking effect on the blade,[16] reducing the blade's motion. If the lift force is greater than the opposing drag force, then the blade will spin.[15]

Most HAWTs tend to have 3 blades, they are connected to a hub which together forms the wind turbine's rotor. The rotor is then connected to the wind turbine's main shaft, inside the nacelle (Figure 2). The nacelle is another important component of a wind turbine, it sits on top of the tower and is responsible for holding a lot of the important internal components, such as the generator, main shafts, yaw and pitch systems and gearbox.[15]



Source: E Al-Ahmar et al, University of Brest

Figure 2: A diagram showing the design and layout of the rotor and nacelle

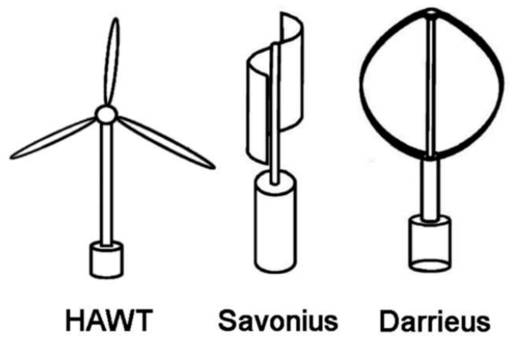
Most wind turbines have a drivetrain that uses a gearbox, however some newer turbines are moving away from this (something that will be looked at later).[15] The motion of the rotor drives the main shaft which is often connected to a gearbox, which is in turn connected to a generator. A gearbox allows the speed of the generator to better match the speed of the rotor.[15,17]

In order to convert the mechanical motion of the rotor into electricity a generator is used. The most commonly used alternating current (AC) generators for large wind turbines are the synchronous generator and the induction generator.[17] These generators take advantage of Faraday's law of induction, where a coil of wire cuts through a magnetic field causing a voltage to be induced in the wire. This then leads to the formation of an electrical current.[17] This can be achieved in two ways, either by using the mechanical force of the rotor to spin the magnet (while the coil remains stationary) or by spinning the coil (while the magnet remains stationary).[15,17] Both of these methods achieve the same outcome of producing an electrical current. Once electricity has been generated, it will be transmitted to a substation located nearby. The substation contains a step-up transformer that increases the voltage and decreases the current allowing the electricity to be transmitted over long distances throughout the national grid, with reduced power loss.[15]

The final key element is the wind turbine tower. The tower is often made from tubular steel and is about 40 m to 130 m tall.[15,18] As the force of the wind acts against the structure of the wind turbine, it creates a large moment (or turning effect) about the base of the tower.[18] In other words, the majority of the force of the wind is experienced by the tower's foundation and so it must be stable inorder to prevent the tower toppling. This is often done using either a spread foundation (a large plate/slab which spreads the force to the soil) or a pile foundation (groups of cylindrical beams driven deep into the ground).[18]

4.1.2 The Vertical Axis Wind Turbine

Another commonly used type of wind turbine is the vertical axis wind turbine (VAWT). In contrast to the HAWT, the blades of a VAWT rotate perpendicular to the ground and around the vertical axis.



Source: P Mehrpooya, Illinois Institute of Technology

Figure 3: Different designs of VAWTs

The two main designs, the Savonius and the Darrieus, are both omnidirectional and so can harvest the kinetic energy of wind from any direction (Figure 3). Which gives it an advantage over the HAWT as the biggest issue with HAWTs is that they must be pointed in the direction of the wind.[15,19] While this is usually fine, in areas with variable wind directions this can cause issues. VAWTs are often favoured in areas with low and/or variable wind speed. Additionally, the internal components (such as the gearbox) of a VAWT are located closer to the ground meaning.[19]

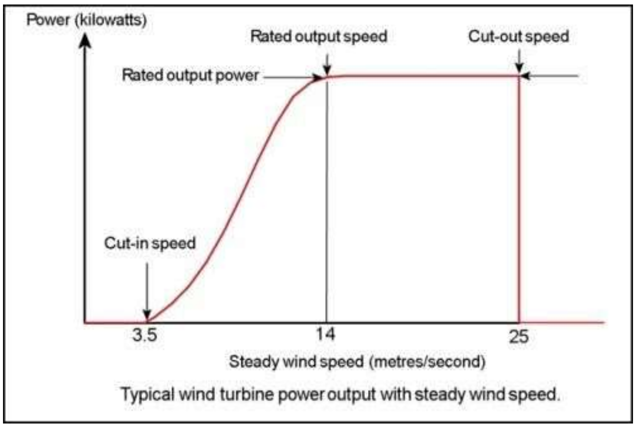
4.1.3 Onshore and Offshore Wind Turbines

Wind turbines are located either onshore or offshore. Onshore wind turbines are placed on land, often in rural areas where obstacles, such as buildings, don't interrupt the wind flow.[20] While onshore wind turbines are located closer to consumers and the national grid, they are often opposed due to their negative impacts. Most notably, their impact on people and nature such as noise pollution and damage to local habitats.[13,20] This leads to tighter planning regulations meaning it is difficult to locate onshore wind turbines in the most effective locations or use the most efficient turbine designs (if they are deemed too loud, bad for the environment, etc).[20]

Alternatively, offshore wind turbines utilise wind blowing across the sea. The capacity to produce electricity is much greater offshore. This is due to several reasons such as the fact there is significantly more wind available in the sea, some areas have up to twice as much wind as onshore locations.[20,21] Offshore wind turbines also tend to be greater in size, this is because a lot of the logistical issues associated with transporting turbine parts are reduced when placing them in the sea.[21] In turbines which are commonly installed around the UK, average onshore turbines produce around 2.5 - 3 MW compared to 3.6MW for offshore turbines.[20] Offshore wind turbines are usually supported with either fixed foundation (such as gravity or monopile), which can be harmful to local aquatic life, or floating foundations (which are still in development but may become favoured in the future).[18,21]

4.1.4 Power Curves

A wind power curve is a common way of graphing how much power a wind turbine produces at various wind speeds (Figure 4). It is made up of the cut-in speed; rated output power/speed; and the cut-out speed.[22]



Source: TheRoundup

Figure 4: A wind power curve

The cut-in speed is the wind speed required for the wind turbine to start rotating and producing electricity. At low wind speeds there isn't enough force (torque) to overcome the inertia of the blades and so it remains stationary until wind speeds increase. The cut-in speed for a turbine will vary based on design and size but is typically 3-4 ms^{-1}.[22] The rated output power is the maximum amount of power the generator can produce and the rated output speed is the lowest wind speed at which this is reached. At speeds above this, the turbine will produce no more than the rated power output.[22] At very fast high speeds there is a risk of damage to the wind turbine which can be costly and pose safety risks. This is why at high wind speeds the turbines generally tend to use a braking system to prevent the rotor moving and therefore reduce the risk of damage.[22]

4.2 Energy Efficiency of a Wind Turbine

When it comes to power generation, the terms "energy" and "power" are often, incorrectly, used interchangeably. Power is the rate of energy transfer. It can be seen as the amount of energy that can be transferred from the kinetic energy of the wind to the electrical energy of the generator, per second.[23,24]

There are two main metrics for how energy efficiency can be quantified, the Power Coefficient (C_p) and the Capacity Factor (CF). C_p is described as the ratio of power that is extracted by a wind turbine to the total power available in the wind. CF is the fraction of the actual generated power to the power that could potentially be generated by the turbine in ideal conditions.[23] The Power Coefficient can be expressed as a percentage and is the metric most commonly used when considering efficiency, it is the one that will be used in this paper.

The swept area of a wind turbine can be considered as a circle with radius, *r*. The volume of wind with velocity, *v*, going through this swept area can be considered as a cylinder with the same radius (Figure 5).

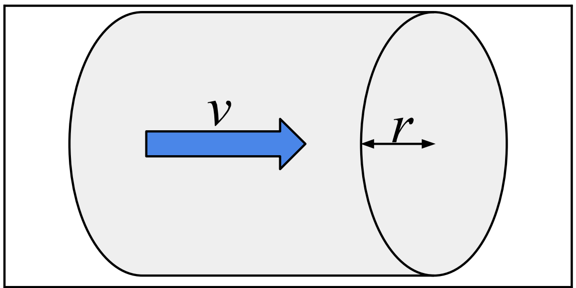


Figure 5: Deptics air flowing through the swept area of a wind turbine's blades

The formula to calculate the amount of power available from the kinetic energy of the wind flowing through the cylinder is shown below.[23]

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3$$

(1)

Where P is the power available from the wind, ρ is the density of air, A is the swept area. By substituting the formula for Area (Equation 2), the following formula (Equation 3) can be achieved:

$$A = \pi \cdot r^2$$

(2)

$$P = \frac{1}{2} \cdot \rho \cdot \pi \cdot r^2 \cdot v^3$$

(3)

Additionally, by assuming that the density of air will remain constant and then by combining all constant values into a new variable, K, the following formula can be obtained to give a value for available power.[24]

$$P = K \cdot r^2 \cdot v^3$$

(4)

This effectively means that the power available is directly proportional to the square of the radius multiplied by the cube of the velocity. Therefore, in order to increase power output, one would need to focus on improving the radius of the rotor (which is impacted by the length of the blades) and the velocity of the wind. A turbine with three times the radius will generate nine times the power and a turbine with double the velocity will produce eight times the power.[24,25] This means that some of the most effective ways of increasing power output is by making wind turbines larger and by finding a way of using faster wind speeds. However, this concerns power output, and not power efficiency.

By oversimplifying the physics, a wind turbine could theoretically be 100% efficient provided that all the kinetic energy from the wind is transferred to the mechanical energy of the rotor and then onto the electrical energy produced by the generator. However, in reality this is not possible for various reasons, most notably the law of conservation of energy.[24] This states that energy is conserved so when the kinetic energy of the wind is transferred to the rotor, the same value of energy is lost from the wind as is gained by the rotor (provided there are no energy losses). Therefore, when energy is harvested from the wind, it loses some of its kinetic energy. Given that the mass of air will remain constant, the wind will lose some velocity. If 100% of the wind's energy is harvested then the flow of air will stop (as the wind lacks energy to sustain motion), so no more wind will be able to flow through the rotor and therefore no more energy can be harvested.[23,24] This forms the basis of Betz Law.[23,24,25,26]

Betz Law states that irrespective of its design, a wind turbine can extract no more than 59.26% of energy in the wind.[24,26] This value is referred to as Betz Limit and is considered to be the maximum possible power coefficient of a wind turbine and is derived from the principles of the conservation of mass and momentum of air flowing through a volume.[26] However, Betz Law has been criticised by various authors for having made several "unneeded assumptions". For instance, Betz assumed that all of the wind that enters the front of the wind turbine will come out of the back. In reality, this isn't the case. Some wind will escape to the sides of the wind turbine which means that the actual theoretical maximum could be much greater, at approximately 67%.[27]

Regardless of which theoretical upper limit is correct, it is crucial to understand that no turbine can be 100% efficient. Even after considering an upper limit, the remainder of the power available can still not be fully harvested. Friction exists between almost all moving parts of a system, and is very difficult to fully remove. In a wind turbine, this exists in the generator, gearbox, rotor, etc.[25]

Therefore, even for the most efficient turbines currently available, it is difficult for them to operate at above 35% efficiency.[25]

4.3 Improving the Energy Efficiency of a Wind Turbine

There are several methods of improving the energy efficiency of wind turbines. For example:

- increasing the size of wind turbines by increasing the height of the tower which impacts the velocity of the wind,
- changing the number of blades which impacts the amount of energy that can be harvested,
- increasing the number of rotors and the development of dual rotor wind turbines,
- adjusting the design of blades,
- altering the design of the gearbox and generator.

These methods are not the only methods that can be used to improve the energy efficiency of a wind turbine, but they are some of the most impactful and/or common methods.

4.3.1 Increasing the Size of Wind Turbines

As mentioned in section 2, two of the most effective ways to increase the power output of a wind turbine is to increase the radius of the rotor and/or the velocity of the wind.[24,25] Despite this, increasing the rotor radius does not necessarily lead to an increase in energy efficiency. By increasing the rotor radius the input energy from the kinetic energy of wind will be increased as there is a greater swept area so more wind can flow, therefore more output energy will of course be produced. However, the proportion of this input energy to output energy (the power coefficient) will not necessarily increase. Therefore the energy efficiency of the wind turbine might remain the same, despite a greater output.[24] It can be argued that if a single wind turbine is capable of producing more power, less wind turbine units will be needed to achieve the same power output. Thereby making the system more efficient. While this may be true, this dissertation aims to identify ways the energy efficiency of a single wind turbine (quantified by its power coefficient and capacity factor) can be increased.

It is known that wind speeds tend to increase with altitude. This is because at greater altitudes there is less friction from obstacles, like trees and buildings, on the surface, which slow down the wind.[28,29] Consequently, in order to access the highest wind speeds, the height of wind turbines must be increased. In general, the most common method of doing this is increasing the height of the hub (which is connected to the rotor).[28] By increasing the hub height, a significant improvement in the capacity factor of the wind turbine can be observed.[29] Therefore by increasing the height of the wind turbine's hub, the energy efficiency of the wind turbine can be improved.

Unfortunately, simply increasing the height of wind turbines is not an easy task. The primary issue with increasing wind turbine height, regardless of the wind turbine's material, is the logistics behind transporting the structure. A large wind turbine design often requires the diameter of the tower to be large enough to support the structure.[30] However, the tower's diameter is limited by transportation barriers, for example the tower and the vehicle carrying it must be able to fit under bridges and tunnels, which limits the diameter to about 4.5m.[28,29,30] This can be overcome by making use of "hybrid towers" which are mainly constructed of tubular steel (like the vast majority of wind turbines), but have concrete bottom sections that can be constructed on-site.[29,30] Additionally, as the height of wind turbines increases it becomes increasingly harder to transport the entire tower as a single structure. Therefore the turbine must be assembled on site, making use of concrete to connect the structure.[30] However, these extra installation challenges come with added complexity and cost and so despite how increased hub heights lead to increased power output and energy efficiency, many companies are favouring smaller turbines as they are more economical.[29,30] Until new methods of transporting and assembling turbines (in a way that ensures the structure remains stable) are discovered, there appears to be a practical limit to wind turbine height.

The size of wind turbines does correlate with increased energy efficiency. Still, in an industry as complicated as the electric power industry, even the most energy efficient designs will struggle to be widely adopted unless they are economically better than their alternatives.

4.3.2 Number of Blades

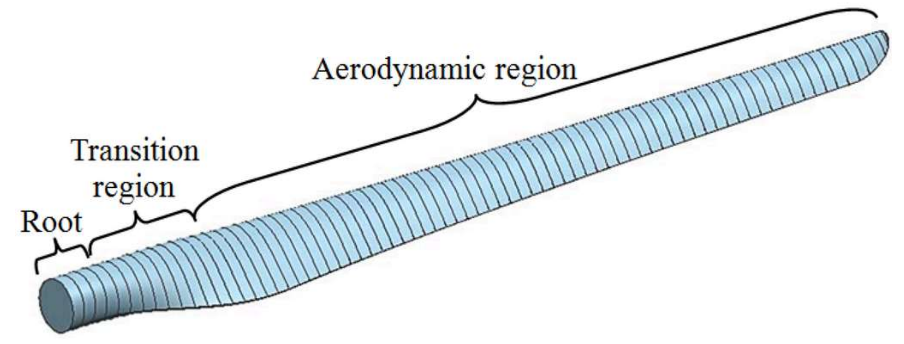
The number of blades attached to the hub of the wind turbine can also have an effect on the energy efficiency. A two-bladed wind turbine tends to be slightly less energy efficient than conventional three-bladed turbines, and they must rotate faster to reach maximum efficiency. However, when operating at maximum efficiency, as a result of higher wind speeds, they are capable of producing greater power outputs compared to three-bladed systems. Moreover, two-bladed systems can be beneficial in applications where transport and assembly are difficult (such as in offshore wind farms) due to their lower weight. This can also lead to reduced costs making them potentially more economical. Nevertheless, two-bladed systems have overall reduced efficiency; increased noise pollution; and stability problems. On top of this, there tends to be stability issues when an even number of blades are used. Wobbling may also lead to increased wear, reducing the turbine's lifespan. Stability problems can be overcome through load reduction techniques which strengthen the design of the hub but these can be expensive.[31]

When more than three-blades are used the energy efficiency of the turbine increases but not necessarily proportionally. The optimal number of blades for energy efficiency, speed, and manufacturability is between 8 and 14 blades. Clearly a larger number of blades leads to increased efficiency. More blades also produce greater power outputs at low wind speeds.[31] Although, more blades would lead to increased weight, cost and potentially balance/stability issues. However, for the purpose of this dissertation, a greater number of blades does contribute to a greater energy efficiency.

The optimal combination of blades that satisfy all critical factors (efficiency, power output, stability, cost, etc) lies somewhere between the two extremes.[31] While theoretically energy efficiency is at its highest with nearly five times the number of blades that are commonly used, the most practical design in terms of power output and economics is significantly lower.

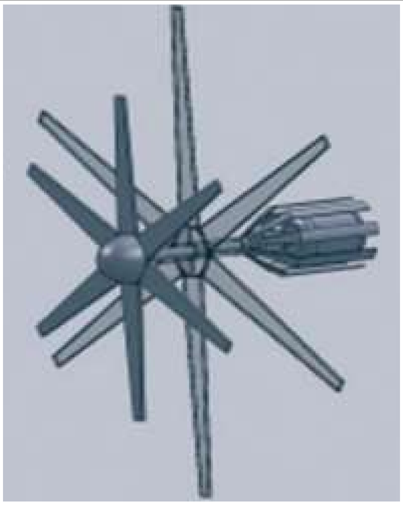
4.3.3 A Dual-Rotor Turbine

Conventional HAWTs have a single rotor (often referred to as Single Rotor Wind Turbines, or SRWTs). A lot of the energy efficiency lost by SRWTs comes down to aerodynamic losses caused by aerodynamically poor airfoils in the root region of the turbine.[32] Simply speaking, the design of a wind turbine blade is created in such a way that the bottom part of the blade, known as the “root region”, is designed to help the blade be structurally stable. This means that the root region is often a lot thicker and not designed to be aerodynamic compared to the rest of the blade. As a result, a lot of the kinetic energy from wind that flows through this root region cannot be harvested effectively, which reduces the energy efficiency of the turbine. Figure 6 shows the location of the root region on a wind turbine blade.



Source: J Zhe et al, Jiaxing University

Figure 6: The different regions of a wind turbine blade



Source: L Romański et al

Figure 7: The design of a 6-bladed dual rotor turbine, note that any number of blades could be used

One way to improve the energy efficiency of the wind turbine is to increase how much of the wind that flows through the root region can be harvested. One of the many suggested ways of doing this is by introducing a second, smaller rotor in front of the main rotor that can harvest the wind that flows in the root region (as shown in Figure 7).[32,33]

This design is known as a Dual Rotor Wind Turbine (DRWT). One of the proposed designs of such a system is that the two rotors are placed along the same axis before the generator. As there are multiple rotors, the structure of the wind turbine would have to be gearless and the generator's rotor and stator would each be driven by a different wind turbine rotor, in opposite directions. This would increase the amount of power the wind turbine can generate.[33] A series of simulations showed that the smaller rotor should be 25% of the size of the main rotor, and positioned 0.2 times the radius of the main rotor away from the main rotor.[32]

When a DRWT is used, there is a predicted 7% rise in the energy efficiency (quantified here by the power coefficient) of the turbine compared to a SRWT. There is also a net increase in power generation of about 5%.[32] Furthermore, the Betz limit is only applicable to SRWTs as the model used to calculate the limit was based on a single rotor. In addition to this, when a wind turbine is placed downwind of another wind turbine, it is still capable of extracting energy from the leftover wind of the other wind turbine. This shows that if two rotors are placed in the same stream of wind, as is the case for DRWTs, then more energy should be able to be extracted from the wind using a DRWT than Betz limit suggests.[27] In fact, when the model used to compute Betz limit was extended to a dual rotor turbine, a new maximum efficiency of 64% was achieved, slightly higher than the maximum for SRWTs.[32]

Evidently, DRWTs are proven to be slightly more energy efficient than SRWTs. Therefore, an effective way of improving the energy efficiency of wind turbines would be to attach an additional, smaller rotor to the front of the main rotor. It may also be possible to retrofit some already installed wind turbines with such a system, provided they do not have a gearbox.

4.3.4 Blade Design

The shape and material of a wind turbine blade can influence its aerodynamic efficiency which in turn has an impact on the energy efficiency of the wind turbine. The more rotational motion that occurs in the wind turbine rotor, the greater power is produced. This means if a turbine blade can more easily cut through the air (less air resistance acts on the blade so less energy is lost) then it can harvest more of the kinetic energy available in the wind and produce more power. Thereby increasing energy efficiency.

Current wind turbine blades are designed to maximise aerodynamic performance and power yield when operating below the rated cut-out speed and to withstand large forces from fast wind when operating above the cut-out speed. However, it can be difficult to satisfy both these criteria, as often the most aerodynamic designs aren't the most structurally stable. The energy efficiency of the turbine would be greatly improved if the design of a wind turbine blade allowed it to have an optimal aerodynamic design when operating below the rated cut-out yet a high level of structural stability when operating above the rated cut-out. One solution to this is an "aeroelastic adaptive blade" that takes advantage of the material of the blade's ability to twist in order to change the angle of blade at certain operating conditions. This means that the blade is capable of twisting at high wind speeds (above the rated cut-out speed) so that it is more structurally stable but less aerodynamic. When the wind speeds are less than the rated cut-out speed, the blades are not twisted so they are less structurally stable but more aerodynamic, thus more power can be produced (aided by the improved aerodynamic design). This improves the overall energy efficiency of the wind turbine as the blade can be made more aerodynamic, while still being safe, as to take advantage of the wind when the speed is below the cut-out speed.[34]

Another issue with the design of wind turbine blades is that they require a certain amount of energy from the wind to overcome inertia and actually begin moving. By lowering the cut-in speed of a wind turbine, it can begin to produce power at lower speeds. This is a particular problem for smaller wind turbines as there is often a lot of friction in the components of the turbine, such as the gearbox. This friction has little impact on large turbines but for small ones it means that a lot more force is required to overcome inertia than if the friction didn't exist. This can be overcome by adding more turbine blades, allowing the turbine to operate at lower cut-in speeds. However, adding more blades leads to increased cost weight. The aerodynamic design of the blades and the material it is made of can also be tweaked to reduce the value of the blades inertia. In one study, a 2-bladed wooden rotor was manufactured as it was much lighter and so had a lower value of inertia. A series of tests showed that the more specialised aerodynamic design had an efficiency nearly twice the value of the efficiency of a conventional 3-bladed rotor of the same size, operating at the same low wind speeds.[35]

Improving the aerodynamic design of blades can have a significant impact on the energy efficiency of the wind turbine. Finding ways to change the shape of blades at different wind speeds allows wind turbines to produce more power at safe wind speeds without having to worry about the structural stability until the wind speeds become dangerously high. Additionally, wind turbines are often idle when the wind speed is low so methods of lowering the cut-in speeds, allowing more power to be produced, could be crucial to improve the energy efficiency of wind turbines.

4.3.5 Bioinspired Blades

While still discussing the design of wind turbine blades, a new technology that is recently being developed is the use of “bioinspired blades”. In practice these blades have not yet actually been installed or tested outside of research. However, they have a lot of potential to help improve the aerodynamics of wind turbine blades. The blades are inspired from the wings of various insects which are naturally aerodynamic thanks to millions of years of evolution.[36, 37]

Source: T Segev et al, Massachusetts Institute of Technology

Figure 8: A model of a rotor made up of bioinspired blades, inspired by the wings of a bee, cicada and wasp

Similar to the aeroelastic blades that have already been looked at, bioinspired blades take inspiration from the elastic properties of insect wings, which have an ability to adapt to wind conditions leading to improved performance of the wind turbine.[36] Despite this, a major consideration of bio-inspired blades is whether the increased elasticity and use of veins (similar to that of the veins on an insect wing, shown in Figure 8) would reduce the strength of the blades.[37] Numerous tests were conducted on both the model shown in Figure 8 and blades with similar elastic properties to insect wings. It was found that bioinspired blades had a 35% rise in efficiency compared to conventional designs at the expense of overall strength of the structure.[36,37] However, if certain parameters were tweaked and the ideal combination was discovered then bioinspired blades could greatly improve energy efficiency with little impact on other areas of interest, such as strength.

4.3.6 Gearbox

The gearbox is a critical component in a wind turbine, responsible for multiplying the speed of the rotor so it can better match the speed of the generator, through a series of gears.[38] While the efficiency of gearboxes are already sufficient, there is still a small amount of friction that lowers the energy efficiency of the entire wind turbine. One way of reducing this friction is to use lubricating oils, experimentation has shown that adding certain gear oils to the components within the gearbox reduces the friction between gears, therefore reducing energy losses in the gearbox and the operating temperature of components. On top of this, having components be lubricated can significantly improve the lifespan of components which can reduce the cost of maintaining wind turbines. This reduction in energy loss increases the energy efficiency of the wind turbine.[38]

Another way of reducing the friction in a gearbox is to completely remove the gearbox all together. The most common way of getting around the need for a gearbox is by using a technology called direct-drive. Direct-drive wind turbines work by connecting the rotor directly to the generator in order to generate electricity. Installed generators use a large ring of permanent magnets that spin with the rotor, through stationary coils, removing the need for gears.[15] However, direct-drive turbines are often a lot bigger due to the large size of the permanent magnet ring. This tends to make them a lot more expensive and therefore, despite a much greater energy efficiency and power yield, they are yet to surpass the popularity of wind turbines with gearboxes.[39]

Conclusion

The energy efficiency of the most modern and high end conventional wind turbines currently sits at around 35%, as quantified by its power coefficient, one of the ways to measure the energy efficiency of a system. However, there exists a theoretical maximum efficiency at around 60%, known as Betz limit. This exists because it is not possible to remove all of the energy from wind without the wind coming to a complete stand still and preventing any more wind from fuelling the wind turbine. Although, Betz limit has long been criticised for making too many unneeded assumptions so the true maximum efficiency may be much greater. Either way, there is a significant margin for improvement with the design of wind turbines, allowing them to almost double their energy efficiency.

There are numerous engineering techniques that improve the energy efficiency of a wind turbine. Some of these techniques are already being used such as increasing the height of the turbine's hub (section 4.3.1). Other techniques exist only in theory and are yet to be implemented into a real life design, beyond experimental tests, for example bioinspired blades or the use of a dual-rotor (sections 4.3.5 and 4.3.3). It is possible to use more than one technique to maximise the energy efficiency, such as increasing the number of blades (section 4.3.2) and combining it with new aeroelastic blade design (section 4.3.4). Additionally, some design changes can be retrofitted to existing turbines which allows the existing wind power infrastructure to become more efficient without the need to entirely replace the wind turbines with newer, more energy efficient models. However, some energy losses such as friction are impossible to fully remove, so regardless of how many design changes are implemented it would be impossible to reach the exact energy efficiency value as Betz limit.

While the energy efficiency of wind turbines can be improved, it is not the only factor that is considered in the design of wind turbines. Manufacturing and design companies also take into account the power output, cost, weight, transport factors, noise, size, aesthetic, stability and carbon footprint. Some techniques that improve the energy efficiency of wind turbines adversely affect some of the factors listed above and may influence the manufacturers design decisions. For example, increasing the number of blades (section 4.3.2) may increase energy efficiency but it also increases weight. In this example more material would be needed to support the structure which could be expensive to a company, there could be logistic challenges when trying to transport the blades; and there may be a greater carbon footprint as a result which contradicts the whole goal of using wind turbines as a green source of energy. Often the best design is limited by other requirements thus making engineering not just a science, but the art of compromise. In the wind power industry where many of these factors have to be carefully balanced, energy efficiency is not the largest priority for a company trying to make a profit. In other industries like the petroleum industry, efficiency is the largest factor as fuel has a cost. Whereas in the wind turbine industry, the fuel is free so often companies are more concerned with overall power output rather than the energy efficiency.

Implementing just a few of these design changes may be too expensive to the wind turbine's owner for it to be worth the increased energy efficiency. For instance, a commercial 3.5 MW wind turbine in the UK can cost around £3 million with 60% of the cost being associated with just the wind turbine's blades, tower and gearbox.[40] By increasing the size of a wind turbine (section 4.3.1) or by increasing the number of blades (section 4.3.2), the overall cost of the wind turbine will increase massively. Across an entire wind farm, the total increased cost from adapting the wind turbines will be significantly higher than if the engineering techniques were not used. In many cases, the cost of using wind turbines with improved energy efficiency is much greater than the cost of just building an additional wind turbine, when the power output is basically the same.

In conclusion, the energy efficiency of wind turbines can be improved and the extent of potential improvement is significant. However, it is often not the most crucial design choice. Currently, methods of improving energy efficiency may not be fully implemented as they are too expensive or compromise other factors. This could change in the future as techniques of producing more energy from wind turbines using less land space and material advance and become more cost effective. The current prohibitive factors will become less of an issue as global resources become increasingly limited.

Human control exists over almost every aspect of a wind turbine's design and installation. However, the one factor that we cannot predict, especially given the changing climate, is how wind may change in the future. Since 2010, the global average wind speed has risen by 0.4 miles per hour, translating to a 17% rise in potential wind energy. However, prior to 2010, wind speeds had been gradually decreasing in parts of the world.[41] In some areas, wind turbines may become completely redundant. While in others, they may become the best available source of power. In the case of the latter, the energy efficiency of wind turbines will be crucial in the future of the generation of electricity.

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