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Comparative analysis of wind energy towards sustainability

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Abstract: This paper emphasizes the importance of wind energy in the transition to a sustainable and renewable energy future. While wind energy is a reliable, cost-effective, and environmentally friendly energy source, it has some negative effects on the environment, society, and the economy that need to be minimized. Social acceptance is crucial for successful wind energy deployment, and challenges such as environmental and ecological impacts must be carefully managed. Despite these challenges, the future perspectives for wind energy technology are promising, with advances in turbine design, energy storage, artificial intelligence, and machine learning as advanced technologies making wind energy more efficient, cost-effective, and reliable. The development of larger turbines, offshore wind farms, and floating wind turbines offer exciting possibilities for the future of wind energy. This paper also gives an overview of the current drawbacks associated with wind energy and future perspectives toward sustainable ways of generating wind energy as an alternative to reduce the harmful environmental impacts of the usage of fossil fuels.

Index Terms: Environmental impact, Offshore wind energy, Renewable energy, Wind energy turbine

1. Introduction

Nowadays, the improvement of generating power through harnessing the natural kinetic energy of wind has rapidly increased as it reduces the requirement of electricity generation using other sources of energy by a considerable amount due to its effective and advantageous features. Wind energy reduces extremely harmful environmental impacts such as water pollution and atmospheric production, including the generation of greenhouse gases and nuclear waste, the destruction of landscapes associated with mining activity, and the damming of rivers [1],[2]. A large number of governments, organizations, and individuals are interested in producing electricity using wind energy since, unlike generators that utilize fossil fuels, it does not produce thermal pollution or atmospheric pollutants. This has the potential to harm the environment. Others, however, have concentrated on the negative environmental effects of wind energy associated infrastructure, such as the visual and noise effects on people; the effects on surrounding, such as the destruction of wildlife, particularly birds and bats; and some harmful environmental effects of wind energy associated infrastructure, particularly those relating to transportation. Nuclear energy has a lot of social and environmental drawbacks. Due to their role in reducing emissions of greenhouse gases and providing national energy security without the limitations of nuclear power, renewable energy sources are absolutely preferred.

2. RENEWABLE ENERGY SOURCES

Sustainable energy is defined as something that never loses out or is unlimited, like the sun. In simply, a renewable energy source can be mentioned as any sustainable energy source that derives from the natural surroundings. Alternatives to fossil fuels that are pure and unlimited include renewable energy. Alternative energy can be used in places where non-sustainable sources are frequently used, like coal. Nowadays, recognized alternatives to the generation of energy from fossil fuels include nuclear and renewable energy [3]. Although nuclear energy is not renewable, it emits zero carbon in percentage, which means that, like renewable energy sources, it releases little or no CO_2. Nuclear energy has a lot of social and environmental consequences [1]. Due to their role in lowering greenhouse gas emissions and providing national energy security without the drawbacks of nuclear power, renewable energy sources are recommended. Although formal definitions of renewable energy sources differ greatly across countries, there is widespread agreement that wind, photovoltaic, and solar thermal energy are included. Hydropower and biomass are two more sources that are frequently considered renewables. The implementation of renewable energy sources is impeded by several obstacles. Wind energy is the most applicable and widely used source due to its availability and renewability out of other renewable energy sources. For thousands of years, man has utilized wind energy for various applications. Therefore, it is crucial to discuss the wind energy revolution from the earliest eras to the present time. The way that the wind energy was developed from past to now is mentioned below.

3. WIND ENERGY

Since the wind is a renewable, widespread, and economically friendly source, wind farms have been increasingly established throughout the world and its contribution to the national power supply should be highly considered. Turbines produce electricity from wind energy and generators also transmit power to the national grid [4].

The early stages of wind power applications and electricity generation date back to the 19th century. One of the earliest known wind-driven generators was built by Charles Brush in 1887, which was capable of generating 12 kilowatts of electricity. In the early 20th century, wind turbines were primarily used for pumping water on farms and ranches, as well as for generating electricity on remote sites such as lighthouses [2].

During the oil crisis of the 1970s, interest in renewable energy sources, including wind power, increased. This led to the development of larger and more efficient wind turbines, and also the rapid growth of the wind energy industry [5].

According to the previous records, in 1981, the first commercially established wind farm was recorded in California and consisted of 20 turbines with 30 MW total capacity. Since then, the technology and the size of wind turbines have continued to evolve and improve, and the capacity of wind farms has grown significantly. As of 2021, the wind energy capacity of the world has surpassed 600 GW, and wind energy has become a key source of renewable energy [4].

The early stages of wind power applications and electricity generation were focused on a small-scale, isolated system, and were primarily used in remote locations such as lighthouses or farms. However, with the advancement of technology, wind power has become a mainstream source of electricity, and it is now being used in large-scale projects and commercial wind farms.

With the usage of wind turbines, the electricity generation process by harnessing the power of wind is known as wind energy. The conversion of kinetic energy of wind into mechanical energy by the turbine is ultimately transformed into electricity [6]. A wind energy turbine typically consists of the following main parts:

1. Rotor: As the major part of the wind turbine, this is capable of converting the wind's kinetic energy into electricity. Typically, the rotor is revolving around a shaft and is made up of a number of blades fixed on a hub.
2. Nacelle: The gearbox, generator, and control systems are all housed inside the nacelle, which is the main housing and mounted on the top surface of the tower and rotates with the rotor.
3. Tower: The tower provides support for the rotor and nacelle and holds them at the required height above the ground. The tower is typically made of steel or concrete and can be either freestanding or guyed, depending on the design.
4. Gearbox: The gearbox is capable of facilitating the rotor's rotation to power the generator. The gearbox is typically located in the nacelle and contains gears and bearings that performs transferring the rotational energy generated from the rotor to the generator.
5. Generator: The transformation of the rotor's rotational energy into electrical energy is performed by this component. The generator is typically an alternating current (AC) generator and can be either induction or permanent magnet type, depending on the design.
6. Control Systems: The control systems manage the operation of the wind turbine and ensure that it is operating safely and efficiently. The control systems include components such as sensors, electronics, and software that monitor various aspects of the wind turbine, such as wind speed, generator speed, and rotor position.

There are some main components of a wind energy turbine, while other components, such as brakes and yaw systems, may also be present, depending on the design.

Generating electricity by wind energy turbine involves the following steps:

1. Capturing wind energy: The rotor captures the kinetic energy of the wind as it rotates. The wind speed and the blade design are dependable factors for the rotational speed of the rotor.
2. Driving the generator: To transfer the rotational energy from the rotor to the generator through the gearbox, this step involves. The gearbox increases the rotational speed of the rotor to drive the generator, which transforms the rotational energy into electrical energy.
3. Converting to electrical energy: The function of an alternating current generator is to transform rotational energy into AC electrical energy. For distributing generated electrical energy, the power grid is used.
4. Controlling the wind turbine: The control systems manage the operation of the wind turbine and ensure that it is operating safely and efficiently. The control systems may adjust the pitch of the blades, apply brakes, or shut down the wind turbine in response to changing wind conditions or other factors.

TYPES OF WIND TURBINES

In wind energy facilities, a variety of wind turbine types are utilized, each with specific features and uses. Some of the most common types of wind turbines include:

1. Horizontal-axis wind turbines (HAWT): This is the most commonly used wind turbine type, where the rotor is mounted on a horizontal axis and revolves around a vertical tower. HAWTs are well suited for large wind farms and are available in various sizes, ranging from a few kilowatts to several megawatts.
2. Vertical-axis wind turbines (VAWT): This wind turbine type has a rotor that rotates around a vertical axis. VAWTs are less commonly used than HAWTs and are typically smaller in size, but they can be more suitable for urban and rooftop applications.
3. Offshore wind turbines: Offshore wind turbines are designed for installation in the ocean, where wind speeds are often higher than on land. Because of the challenging offshore circumstances they must resist, offshore wind turbines are typically larger in size and have more durability compared to onshore wind turbines.

The choice of wind turbine type for a specific wind energy site relies on various factors, such as available land area, mean wind speed, and local regulations. In brief, HAWTs are often used in large wind farms where high wind speeds can be expected, while VAWTs can be used in urban areas or on rooftops where land area is limited [2]. Offshore wind turbines are used in offshore wind farms, where they can take advantage of high wind speeds and open water.

Table 1. Advantages and Limitations of Horizontal Axis Wind Turbines and Vertical Axis Wind Turbines

Wind Turbine Type	**Advantages**	**Limitations**
Horizontal-Axis Wind Turbines (HAWT):	1. High Efficiency: HAWTs are highly efficient at converting wind energy into electrical energy due to their optimized blade design and efficient gearbox. 2. Widely Available: HAWTs are readily accessible in a range of sizes, making them appropriate for a variety of applications, from residential wind turbines that are small in size to big wind farms. 3. High Wind Speeds: HAWTs are well-suited for high wind speed locations, as they can capture more energy from the wind compared to VAWTs. 4. Low Maintenance Costs: HAWTs have relatively low maintenance costs, as they are designed to withstand harsh weather conditions and have fewer moving parts compared to VAWTs.	1. High Costs: HAWTs are generally more expensive to manufacture and install compared to VAWTs. 2. High Visual Impact: HAWTs can have a significant visual impact due to their large size, especially in scenic areas. 3. Complexity: HAWTs have more moving components and are more sophisticated than VAWTs, which can raise the chance of failure and raise maintenance costs.
Vertical-Axis Wind Turbines (VAWT):	1. Simple Design: VAWTs have a simple design compared to HAWTs, with fewer moving parts, which can reduce maintenance costs. 2. Low Visual Impact: VAWTs can have less visual impact and are often smaller than HAWTs, making them suitable for urban and rooftop applications. 3. No Yaw Mechanism Required: It's not required a yaw mechanism to align with the wind blowing direction, as the rotor rotates around a vertical axis, making them simpler and less expensive compared to HAWTs.	1. Lower Efficiency: VAWTs are less efficient than HAWTs at converting wind energy into electrical energy, as they are typically designed to operate at lower wind speeds. 2. Less Common: VAWTs are less common than HAWTs, making them less widely available and less well-established in the market. 3. Limited Capacity: VAWTs are typically smaller in size compared to HAWTs, and are limited to lower power outputs, making them less suitable for large-scale wind energy project

ENVIRONMENT IMPACTS OF WIND ENERGY

Wind energy farms, like any large-scale energy generation projects, can have both positive and negative environmental impacts. Some of the potential impacts include:

Positive impacts:

- Low greenhouse gas emissions: Since, wind is a clean, inexhaustible, renewable energy source, which does not form harmful emissions or toxic substances anymore, thus helping to reduce the overall carbon footprint of the energy sector.
- Reduced air pollution: wind energy provides more assistance to reduce the usage of fossil fuels, which are a major source of air pollution.
- Habitat preservation: wind energy facilities can be made to have as minimal of an impact on wildlife and habitats as possible, and in some cases, they can even provide benefits to local ecosystems by creating new habitats or corridors.

Negative impacts:

- Impact on wildlife and bird populations: birds and bats may die directly as a result of the action of wind turbines, however, the rate of collision is relatively minor than other human activities. Some species such as eagles and other raptors are more sensitive [7]. Birds have a high risk of death and inconvenience due to the establishment of wind turbines. Since, they fly into the turbine towers, nacelles, as well as other parts such as connecting cables, observational towers, and utility poles, birds can be killed when they come into close touch with both the moving rotors of a wind turbine [8]. Bird species, geographical circumstances, wind turbine design, and layout are only a few of the elements that affect bird death caused by wind turbines. According to the reported details, lattice turbines have a higher rate of bird fatality than other types of turbine towers [9]. As well as the height of the turbine tower was more closely related to bat mortality than the size of the rotor. As tower height increases, the bat fatality rate goes up significantly [10].
- Habitat fragmentation: the construction of wind turbines and associated infrastructure can result in habitat fragmentation, which can negatively impact local wildlife populations [11]. As an example, most wind farms generally create physical obstacles which prohibit birds from migrating to the areas where they habitually feed and rest. Birds' foraging behavior may be impacted by the noise and turbulent air currents generated by operating wind turbines, which can panic them away and reduce the size of their territories. Additional barriers for birds may be built during the construction of power lines and roadways for wind farms.
- Disruption of migratory patterns: wind turbines can also disrupt the migratory patterns of birds and bats, which can have negative consequences for populations of these species
- Noise pollution: wind turbines can generate some noise, which can be disruptive to local wildlife populations, especially for those species that use sound to communicate or locate food. Although modern turbines are designed to minimize this impact.
- Visual impact: large wind turbines can be visually striking, and some people may find them unsightly.
- Impact on migratory patterns: wind turbines can also disrupt the migratory patterns of birds and bats, which can have negative consequences for populations of these species.

It's important to note that many of the adverse effects combined with wind energy can be mitigated through careful planning and design, such as by choosing the appropriate location for a wind farm and by implementing measures to protect wildlife and habitats. Additionally, the advantages of wind energy in terms of reduction of greenhouse gas emissions and air pollution considerably exceed the potentially harmful consequences of wind energy farms.

IMPACTS ON HUMAN AND HEALTH

Wind energy affects both the positive and negative manner of humans. Some of the potential impacts include:

Positive impacts:

- Job creation: wind energy projects facilitate several jobs in the fields of construction, operations and maintenance, and manufacturing.
- Economic development: wind energy projects can provide a source of revenue for local communities and can stimulate economic development.
- Energy independence: Dependence on fossil fuels and imported oil can be minimized with the continuous utilization of wind energy.
- Reduced air pollution: wind energy helps to reduce the usage of fossil fuels, which are a major source of air pollution and can have negative health effects on humans due to the emission of greenhouse gases and other harmful gases.

Negative impacts:

- Noise pollution: Residents may be disturbed by the noise that wind turbines generate, especially if they are located close to homes or other buildings.
- Visual impact: large wind turbines can be visually striking, and some people may find them unsightly.
- Property value: Some studies suggest that the proximity of wind turbines to homes can negatively impact property values.
- Health effects: This may be related to the noise or vibration generated by the turbines. However, studies have not found a clear causal relationship between wind turbines and these symptoms. Other factors, such as stress or pre-existing health conditions, cause these symptoms.

The World Health Organization (WHO) has determined that the noise generated by wind turbines is not likely to cause harmful health effects as long as it is kept below certain levels. WHO recommends a maximum level of 40 decibels (dB) for outdoor noise in residential areas during the night [12],[13]. The noise levels generated by wind turbines typically fall within this range and are not expected to cause significant health effects.

Additionally, other studies have shown that the noise levels generated by wind turbines are similar to those generated by other common sources of outdoor noise, such as traffic and other industrial activities, and are not likely to cause significant health effects [7]. Exposure to high-frequency causes serious headaches, fatigue and immune system difficulties.

It is cruical to remember that the possible health impacts of wind energy projects should be carefully evaluated on an individualized level, taking into account the specific location and design of the wind farm, as well as the characteristics of the local population. Wind turbine installation that takes into account the proximity to sensitive receptors, such as residences schools, or hospitals, and monitoring and assessing the noise levels generated by the turbines are some of the ways to minimize the potential impact on human health.

CULTURAL IMPACT

Wind energy can have both positive and negative cultural impacts. One major positive impact is that it can provide a source of clean, renewable, inexhaustible energy that can help to restrict the continuous utilization of fossil fuels and decrease greenhouse emission of gas and other harmful gases [14]. This has the ability to improve sustainability and be beneficial to the ecosystem. As well as, from construction to servicing of wind turbines make job opportunities that result in job growth in these fields.

Some cultural impacts may not be so positive but not negative. For example, the noise generated by wind turbines can be a concern for some people, and the flashing lights on the turbines can be disruptive to wildlife or people living nearby. In addition, some people may feel that wind energy is not as reliable as traditional forms of energy and may be concerned about the effects of wind energy on the power grid.

Overall, the cultural impact of wind energy can be complex and can depend on a variety of factors, including the wind farm location and establishment, the size, the design of the turbines, and the needs and values of the local community.

VISUAL AND NOISE IMPACT

The visual and noise impacts of wind energy can be significant for some people. Wind turbines are quite large, and the sight of a wind farm may be striking, especially when located in a rural or natural setting. Some people may find the turbines unsightly or disruptive to natural landscapes. Additionally, the construction of wind farms can disrupt traditional land use patterns, such as farming or grazing, and may negatively impact local communities [15]. To mitigate this, developers may choose to install turbines in less visible areas, such as offshore or in mountainous regions, or to use turbines with smaller blades and lower hub heights. Moreover, the selection of appropriate colors for wind turbines is also important because it contributes to minimizing visual impacts caused by wind turbines as it facilitates good visibility.

Wind turbines can generate noise, both from the rotation of the blades and from the mechanical systems within the turbine. Some people, particularly those who live close to a wind farm, may be concerned about the noise made by wind turbines [15]. Aerodynamic noise and mechanical noise are both two types of noise generated by the wind turbine. The sound of the aerofoil-shaped turbine blades moving through the air, and aerodynamic noise generates. The size of the turbine, the mean wind speed, and the rotation speed all affect this noise, which is perpendicular to the blade’s rotating surface [16]. Obviously, a large turbine and high wind make more noise. Noises can originate from different directions at different times since new turbines can turn to face the upward direction of the wind. With a change in wind direction, some turbine blade pitches can also automatically vary, producing noise at various decibel levels. Internal gears of the turbine, the generator, and other auxiliary parts are caused to mechanical noise [17]. To mitigate noise impact, developers may choose to install turbines in less populated areas, or to use quieter turbine models. As well as to mitigate aerodynamic and mechanical noises respectively, improving the blade design of turbines and applying insulations inside the turbine towers are important strategies.

It is cruicial to discuss that these impacts are highly dependent on the location of the turbines, the design, and the size of the wind farm because they significantly affect the design of a wind farm layout, by considering suitable parameters [18]. The available distance of the turbines from the nearest residents, the meteorological conditions, and the topography of the area are some of the factors that can affect the level of noise and visual impact.

IMPACT ON LAND USAGE

The impact of wind energy on land usage can vary depending on the site location and the wind farm size. However, in general, wind energy can have both positive and negative impacts on land usage. As well as the influence of wind-energy facilities on the environment is multifaceted and can differ depending on various factors such as location, time of year, weather, type of ecosystem, and species [19]. Additionally, the effects of these facilities on the environment are likely to accumulate over time and can interact in intricate ways with other ecological influences at wind energy sites and other locations that have changed land use practices and other human activities.

As previously mentioned, the construction of wind farms can disrupt traditional land use patterns, such as farming or grazing. This can harm local communities and biosystems, particularly those that rely on the land for their livelihoods. The turbines can cause collisions and also the construction of the wind farm can cause habitat destruction [20]. Therefore, these may be affected in a bad manner on the land usage. Wind energy sites can lead to soil erosion and land degradation if surface plants are removed and proper precautions and mitigation measures are not taken during construction and operation [7]. For example, during construction, activities such as grading and excavation can expose the soil to wind erosion. Operation of wind turbines can also result in soil erosion due to the creation of microclimatic situations, such as changes in wind speed and direction [21]. For the prevention of soil erosion and land degradation, wind energy developers can implement best management practices, such as using windbreaks, planting vegetation, and stabilizing the soil after the construction of the wind farms. Additionally, regular monitoring of the site is essential to detect and address any issues before they become major problems.

To mitigate these negative impacts of wind energy on land usage, developers may choose to install turbines in less populated areas, or to use turbines with smaller blades and lower hub heights. They may also choose to install turbines in areas that are already industrialized or that have been previously disturbed. Additionally, developers can also make efforts to minimize the impact on wildlife by considering bird and bat migration patterns, and by installing deterrents such as radar or ultrasonic systems. Overall, the impact of wind energy on land usage can be complex and can depend on a variety of factors, including the wind farm location, the size and design of the turbines, and the needs and values of the local community. Careful planning, site selection, and mitigation measures can help minimize the negative impacts of wind energy on land usage.

4. DISCUSSION

IMPROVEMENTS IN WIND ENERGY TECHNOLOGIES AND THEIR ASSOCIATED INFRASTRUCTURE

Wind energy technology has undergone significant improvement in recent years, and innovations are continuing to emerge. Some of the key areas of improvement include:

1. Increased efficiency: Wind turbines have become more efficient and effective in generating electricity using wind energy. Advanced blade designs, better material usage, and improved control

systems have allowed for more energy to be generated from a single turbine.

2. Larger turbines: Wind turbines have become larger, allowing for more energy to be generated from a single location. Larger turbines also have a lower cost per unit of energy generated, making them more economically viable.
3. Improved reliability: Wind turbines have become more reliable, reducing downtime and maintenance requirements. This has been achieved through the use of better materials, improved design, and enhanced monitoring systems.
4. Grid integration: Wind energy systems have become better integrated into the grid, allowing for more consistent and predictable energy generation. Improved control systems have also helped to make wind energy more viable by minimizing its negative effects on the grid. Offshore wind energy: Offshore wind energy has become increasingly popular, as it allows for the harnessing of stronger and more consistent winds, while also reducing the impact on the visual landscape. Improvements in technology have made offshore wind energy more economically viable, and the associated infrastructure (such as substations and transmission cables) has become more robust.

Overall, the improvements in wind energy technology and associated infrastructure have focussed a more viable and sustainable source of energy, and the expectation is to continue this trend in the future.

CONSERVATION OF WIND ENERGY

While wind is an energy source that is renewable and pure, it's still essential to conserve and optimize its use to reduce waste and increase efficiency. Here are some conservation methods for wind energy:

1. Regular maintenance: Regular maintenance of wind turbines is essential to ensure that they are functioning efficiently. Maintenance includes cleaning the blades, replacing damaged components, and ensuring proper lubrication. Proper maintenance can reduce energy waste and increase turbine lifespan.
2. Energy storage: Energy storage systems can help conserve wind energy by depositing excess power at the occasions where low demand is available and releasing it during the occasions of high energy demand is required. This can help reduce energy waste and improve the efficiency of wind energy systems.
3. Turbine placement: Proper placement of wind turbines is critical to their effectiveness. Wind turbines should be placed in locations with consistent and strong winds to optimize their energy production. Improper placement can lead to inefficient energy production and waste.
4. Complementary energy sources: The wind can be complemented with other energy sources that are renewable, such as hydroelectric or solar, to create hybrid energy systems. These systems can reduce waste and increase efficiency by providing a more consistent and reliable source of renewable energy.
5. Smart grid technology: Smart grid technology can help optimize wind energy usage by dynamically adjusting energy demand and supply to match available energy. This can help reduce energy waste and increase the overall efficiency of wind energy systems.

CURRENT DRAWBACKS OF WIND ENERGY TECHNOLOGY AMONG OTHER RENEWABLE ENERGY SOURCES

Like every other technology, wind energy has a unique collection of difficulties and limitations with respect to the other sources of renewable energy which are as follows;

1. Intermittency: Because, the wind is an erratic energy source, meaning the energy quantity produced through the assistance of wind turbines can significantly fluctuate based on variable wind conditions such as wind speed, and wind direction. This can make it difficult to incorporate wind energy into the grid and provide a continuous and reliable source of energy.
2. High initial cost: Due to the high cost of the installation of wind turbines, and associated infrastructure, wind energy can be more expensive to implement with respect to other renewable energy sources, such as hydro energy.
3. Land usage: Wind turbines require large amounts of land to be installed, which can be a challenge in densely populated areas or areas with limited land availability.
4. Environmental impact: Wind turbines can have a visual impact on the environment and can also have an impact on wildlife, such as birds and bats.
5. Maintenance and operation costs: Due to the continuous operation of wind turbines, frequent maintenance is required, which is a main component of the overall cost that depends on the size and design of the wind power plants and the turbines.

Although it has some shortcomings, it is nevertheless regarded as a valuable renewable energy source, and attempts are being made to resolve these issues and develop the technology. Wind energy is still a more sustainable and environmentally friendly choice than non-renewable sources like fossil fuels, and it is predicted to keep expanding and play an important role in supplying our energy demands in the future.

CHALLENGES ASSOCIATED WITH WIND ENERGY TECHNOLOGY

Wind turbine technology has undergone several advancements since its commercialization in the early 1980s [4]. Wind turbines, either horizontal axis wind turbines (HAWTs) or vertical axis wind turbines (VAWTs), harness wind energy to produce electricity. HAWTs have a horizontal rotor and a three-bladed rotor connected to a gearbox and generator. VAWTs have a shaft mounted on a vertical axis. Despite the numerous improvements in wind turbine design, the industry still faces technical challenges in designing efficient turbines. The size of wind turbines has gradually increased while the cost of energy production has decreased throughout the past 30 years. The wind energy industry has rapidly shifted from a niche task to a large-scale, mainstream industrial electricity generation. The future holds many more technical challenges and achievements for the wind turbine industry. Some important factors which affect the wind turbine's efficiency can be discussed as follows;

Number of blades

Aerodynamic efficiency, material costs, trustworthyness, and aesthetics are factors that determine the number of blades on a turbine. There are three blades installed on present wind turbines. But, in the past, one and two-bladed designs were attempted [2]. Single-bladed designs are structurally efficient but require counterweights and complex dynamics for load relief. With increasing the number of blades, aerodynamic efficiency increases respectively.

The number of blades on a wind turbine can affect its efficiency in several ways. Generally speaking, more blades will result in a slower rotational speed and higher torque, which can be advantageous in areas having lower mean wind speeds. However, more blades also create more drag, which can reduce overall efficiency, particularly in locations with higher wind speeds. The optimal number of blades for a wind turbine is based on different factors, consisting of wind speed and the size of the turbine [22]. In general, three blades are interconnected with modern wind turbines, as this is often a good balance between efficiency and cost.

Three blades provide a good balance between air disturbance and energy gathered for electrical generation. The number of blades is a compromise between various design considerations.

Power control Systems; pitch versus stall

Production of electrical energy efficiently and effectively is the key objective of any wind turbine design. To maximize energy output, turbines are generally designed to extract maximum amount of energy from wind. However, strong winds can cause damage to the turbine, so power control methods are used to regulate the energy output. There are two types of power control methods installed in modern wind turbines: pitch control and stall regulation used in wind turbines to control the power output and rotor speed [2]. Pitch control adjusts the rotor position in response to changes in wind speed. To keep the rotational speed and power production consistent, it also regulates the blades'angular position. This is accomplished by modulating the blades' pitch angles so that the attacking angle remains unchanged regardless of variations in wind speed. Pitch control is more commonly used in modern wind turbines because it allows for more precise control of power output, and it can be used in a wider range of wind speeds [23].

Stall regulation relies on the aerodynamic design of the rotor to prevent excessive energy output during strong winds. The objective of these systems is to minimize damage to the wind turbine while still maximizing energy output. As the second method, stall control, works by allowing the blades to "stall" or lose lift when the wind speed gets too high. This reduces the amount of power that the turbine generates and helps prevent damage to the blades and other components. Stall control is typically used in smaller, older wind turbines, and it is less commonly used in modern turbines because it can result in more abrupt changes in power output and rotor speed, and it is less efficient than pitch control [24].

FUTURE DIRECTIONS FOR WIND ENERGY DEVELOPMENT

Energy is an essential component for humans in their daily lives to fulfill various tasks, such as cooking, lighting, and communication as well as the industrial applications as discussed earlier. However, since around 1985, fossil fuels have been the primary source of energy, contributing to a significant increase in carbon dioxide levels in the atmosphere, leading to environmental pollution. Moreover, as fossil fuel sources are depleting, energy generation from these sources is expected to decrease daily. The International Energy Agency (IEA) predicts an annual global energy demand increase of 1.6%, with developing countries contributing approximately 65% to the increase. According to the IEA's demand scenario, the world's total energy consumption will rise by 75% from 2008 to 2035. In 2004, the world's total electrical energy production quantity was 17,450 TWh and it is estimated the production quantity of 31,675 TWh by the end of 2030. Energy demand distribution is shifting, with Europe, Japan, Korea, and North America experiencing more energy usage. In contrast, Asia, Africa, the Middle East, and Latin America are some countries which consume an increasing amount of energy [25]. Fortunately, the deployment and application of sustainable energy technologies is rapidly increasing, and shares are expected to increase substantially under the most ambitious mitigation scenarios.

In 2021, the global wind sector had been experienced its second-best performed year, generating about 94 GW of additional capacity globally, underperforming the record increase of 2020 by just 1.8%, in accordance with the Global Wind Statistics 2022 report by GWEC. Although Europe, Latin America, and Africa & the Middle East had recorded quantitative data for new onshore wind farm installations, there was a significant reduction in total onshore wind installations as it was 18% lower than the previous year's records due to a rapid slowdown in onshore wind development in the two capital wind power markets in the world like China and the US,. In 2021, the expected offshore wind capacity was three times higher than the capacity in 2020, keeping records as the best year in offshore wind history records in global new establishments with an accounted market share of 22.5%. In 2021, China has contributed by adding 80% of offshore wind capacity worldwide, reaching its cumulative offshore wind installations capacity to 27.7 GW, which becomes a remarkable point of development. The total global wind power capacity now stands at 837 GW, preventing more than 1.2 billion tonnes of CO_2 emissions annually, equivalent to the annual records of South America's CO_2 emissions.

When almost 88 GW of global wind capacity offered in 2021, a 153% increase compared to the previous year, wind auction operations also experienced a resurgence [26]. Although there is a positive market growth for the global wind industry, with the expectation of an estimated energy amount of 557 GW of new capacity in the period of next five years. To achieve the 1.5C pathway related to the global greenhouse gas emission towards net zero emissions by 2050, as the major goal, this growth is required to increase four-fold, especially after the renewed urgency for achieving energy security and the global momentum gathered by net-zero commitments.

As of 2021, there are two established wind farms in Sri Lanka, namely the 10 MW Hambantota Wind Farm and the 100 MW Mannar Wind Farm. The Hambantota Wind Farm, which consists of eight turbines, was commissioned in 2014 and is located in the southern province of Sri Lanka. The Mannar Wind Farm, which consists of 30 turbines, was commissioned in 2019 and is situated in the northern province of Sri Lanka. It is currently the largest wind farm in Sri Lanka, and was developed with the aim of reducing the country's reliance on fossil fuels and ugrading the market share of renewable energy in the country. Annual estimated energy production from this wind farm is nearly 400 GWh, which is equivalent to the energy consumed by around 130,000 households [27].

When focusing on the near future of wind energy, is bright, and there are many exciting developments and directions for improvement that are being explored. Some of the future directions for wind energy improvement include:

1. Digitalization: The future of wind energy is predicted to be significantly influenced by the incorporation of digital technologies like artificial intelligence, machine learning, and the Internet of Things (IoT). Digital tools will be used to enhance wind turbine performance, track wind patterns, and forecast maintenance needs..
2. Floating wind turbines: This is a comparatively new technology that has the potential to completely transform the wind energy sector. They also minimize the harmful visual impacts of wind turbines on the landscape by enabling the installation of wind turbines in deeper waterways with higher and more reliable wind speeds.
3. Advanced materials: The use of advanced materials such as composites, ceramics, and smart materials is expected to act a key role in the future of wind energy. These materials will be used to upgrade the credibility, efficiency, and durability of wind turbines.
4. Hybrid energy systems: The integration of wind energy with other forms of renewable energy systems, such as hydro or solar energy and energy storage systems, is projected to fulfill a major role in the future of wind energy. This will allow for more consistent and reliable energy generation and will help to further reduce our dependence on non-renewable sources of energy.
5. Energy storage: Energy storage is a critical component of any renewable energy system, and wind energy is no exception. Advances in energy storage technology, such as batteries and pumped hydro storage, will make it possible to store excess wind energy and use it when needed.

6. Artificial intelligence and machine learning: These technologies can be used to optimize wind turbine performance and reduce downtime. AI and machine learning can be used to predict maintenance needs, optimize turbine settings, and improve overall efficiency.
7. Larger turbines: Wind turbines have become increasingly larger over time, and this trend has been increasing. Larger turbines can capture more wind energy, making them more efficient and cost-effective.
8. Offshore wind farms: Offshore wind farms have the possibility of generating large amounts of renewable energy. These farms are located closer to population centers, reducing the need for long-distance transmission lines.

In terms of future perspectives, as a South Asian country, Sri Lanka has set a target capacity of generating around 70% of the country's increasing electricity demand from renewable energy sources by 2030, and wind energy acts a significant role in achieving this target. The government has identified several locations across the country with high wind potential and taken many actions for the installation of new wind farms to increase the electricity supply. One of the potential areas for the commencement of new wind projects is the Jaffna Peninsula, located in the northern province of the country. Studies have shown that the peninsula has a high wind potential, with wind speeds ranging from 7 to 10 meters per second. In addition to the Jaffna Peninsula, other areas such as Hambantota, Kankesanthurai, Pooneryn, Point Pedro, and Mannar Island have also been identified as potential locations for new wind farm development. Hambantota, located in the Southern Province, has a relatively high wind potential with average wind speeds ranging from 5 to 7 meters per second. The Hambantota Wind Farm is the first commercially established wind farm in Sri Lanka, is located in this area. Mannar Island is located in the Northern Province of Sri Lanka, and has one of the highest wind potentials in the country, with average wind speeds ranging from 6 to 8 meters per second. Kankesanthurai is also located in the Northern Province and has a high wind potential with average wind speeds ranging from 6 to 8 meters per second. Pooneryn, located in the Northern Province, has a high wind potential with mean wind speeds ranging from 7 to 8 meters per second. Considering average wind speeds, these areas can be suggested for the new wind farm installation [27].

The establishment of new wind farms in these locations will not only help the country to achieve its renewable energy targets but also create employment opportunities and contribute to the economic development of these areas. However, some challenges need to be addressed, such as land availability, transmission infrastructure, and financing.

Sri Lanka's wind energy sector has made significant progress in recent years with the establishment of two major wind farms. The identification of potential locations for new wind farm establishment and development is a positive sign for the continuous growth of the sector, but addressing the challenges is critical to the successful placement of proper wind projects in the country. The main challenge behind the new wind farm establishment in Sri Lanka is the economic crisis. It can have a significant impact on the establishment of wind farms due to some reasons such as financing, government funding, and reduced investments. Banks and other financial institutions may become more cautious and risk-averse, leading to reduced lending for wind farm projects. This can make it more challenging for wind farm developers to obtain the necessary funding for their projects, which can delay or even halt the establishment of wind farms. Governments may have to redirect their budgets towards other areas of the economy, reducing the funding available for renewable energy projects. This can make it more challenging for wind farm developers to obtain the necessary support and funding from the government, which can delay or even halt the establishment of wind farms. Economic crisis can also lead to reduced investment in renewable energy projects, including wind farms. Investors may become more risk-averse and less willing to invest in new projects, leading to a reduction in the amount of capital available for wind farm development. This can make it more challenging for wind farm developers to obtain the necessary investment to fund their projects, which can delay or even halt the establishment of wind farms. In addition to these strategies, careful consideration of global wind energy policy is a key point because it gives a significant contribution to mitigating harmful impacts such as global warming and a crisis of energy availability as well as enhancing the generating of wind power. Therefore, it is noticed that the implementation and development of various elements of wind energy policy optimize the usage of renewable energy.

5. CONCLUSION

Wind energy is a crucial component of our transition to a sustainable and renewable energy future. It has proven to be a reliable, cost-effective, and environmentally friendly energy source, with the possibility to meet a considerable portion of our energy needs. The choice for electricity production should prioritize the minimal environmental impact of wind energy when compared to other renewable energy sources. As the most developed and economically viable form of renewable energy, wind energy has negative effects on the environment, society, and the economy. However, to ensure that wind energy remains sustainable, it is crucial to minimize its impact on the environment, including the preservation of protected areas, as well as its impact on human health such as noise and visual disturbance. The deployment of wind energy technology is not without its challenges. As the challenges, environmental and ecological impacts must be carefully managed, and social acceptance is essential for successful wind energy deployment. Additionally, continued improvements in technology and energy storage will be necessary to optimize wind energy's potential. Despite these challenges, the future perspectives for wind energy technology are promising. Advances in turbine design, energy storage, and application of complementary technologies such as artificial intelligence and machine learning will make wind energy more efficient, cost-effective, robust and reliable. Furthermore, the development of larger turbines, offshore wind farms, and floating wind turbines offer exciting possibilities for the future of wind energy. This paper has also discussed the current challenges associated with wind energy and future perspectives toward sustainability ways of generating wind energy.

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