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Wind Energy Technologies: A Complete review of the Wind energy technologies

*K.D.C. Sankalpa, H.M.D.M Herath, H.R.S.S. Somarathna, K.M.S.G.M.S. Wickramasingha, N.G.N.B Samarakoon

Department of Civil and Environmental Technology, Faculty of Technology, University of Sri Jayewardenepura, Sri Lanka.

chalindusan9228@gmail.com

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Abstract: Wind energy has emerged as a prominent renewable energy source, offering a sustainable alternative to fossil fuels. This review article provides a comprehensive overview of the current state of wind energy technology, its environmental and social impacts, and future prospects. The historical development of wind energy is discussed, highlighting key milestones and technological advancements. Various wind turbine technologies are examined, including horizontal-axis and vertical-axis designs, as well as recent innovations such as offshore wind farms and floating turbines. The environmental benefits of wind energy, such as reduced greenhouse gas emissions, are contrasted with potential drawbacks, such as wildlife impacts and noise pollution. Integration challenges, such as intermittency and grid stability, are also explored, along with strategies to mitigate these challenges. The review concludes with a discussion of current trends and future prospects for wind energy, emphasizing its role in a sustainable energy future.

Index Terms: Renewable energy, Wind energy, Wind energy conversion, Wind turbine

1 INTRODUCTION

Humans have valued renewable energy sources ever since the dawn of civilization. Biomass has been utilized for power generation, heating, cooking, steam raising, hydropower, wind energy for mobility, and eventually for the production of electricity for centuries. The Earth's biosphere receives energy from solar radiation and geothermal energy, which are the main sources of energy for renewable energy sources [1]. The potential of renewable energy sources is considerable, as they can frequently meet the current global energy demand. Fig. 1. Shows the modern renewable energy generation by source in the world. They can provide long-term sustainable energy supplies, increase market diversity in the energy supply, and lower both local and global air emissions. Additionally, they can offer economically viable solutions to address specialized energy service demands (especially in developing nations and rural areas), generate new job opportunities, and present potential for local equipment manufacture.

Numerous renewable methods exist. Even though they are frequently sold, the most are still in the early stages of development and lack technical maturity. They necessitate ongoing development, research, and demonstration activities. Furthermore, not many renewable energy solutions can rival traditional fuels. On price, with the exception of certain specialized marketplaces. Nonetheless, most renewables can experience significant cost reductions, which will close gaps and increase their competitiveness. That will necessitate increasing manufacturing capacities to mass production in addition to continuing technology development and market deployment [2].

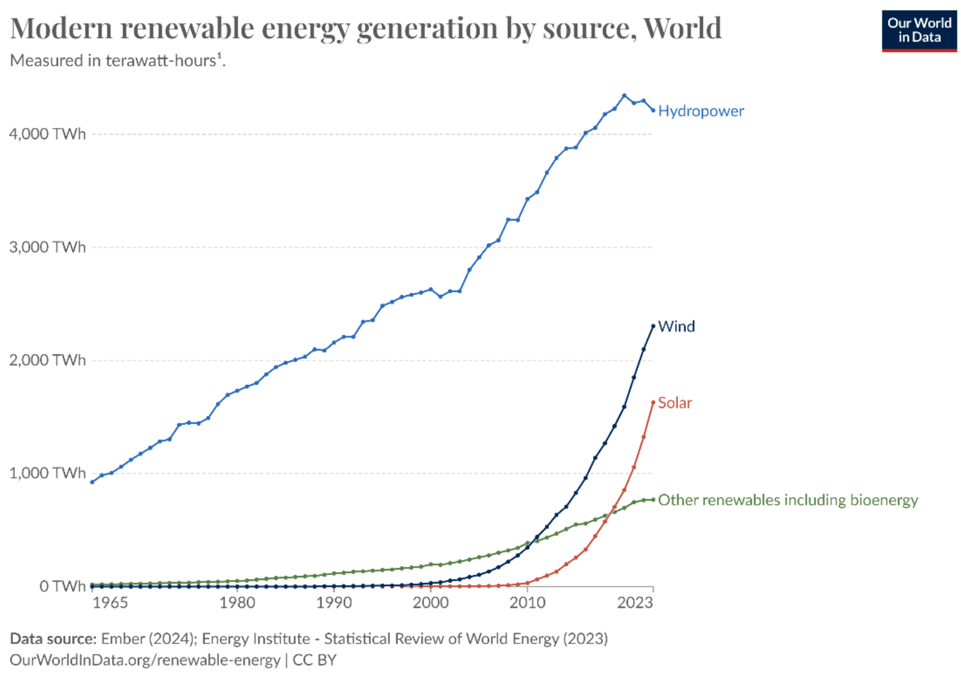

Fig. 1. Modern renewable energy generation by source, World [3].

1.1 Wind Energy

Wind is the movement of air. Temperature variations first produced the pressure differences that are the source of this movement. Put differently, the sun is the source of everything. The atmosphere warms in tandem with the earth's surface heat from the sun. In addition to the fact that the equator receives more solar radiation than the poles, the heating is unequal due to our hills and oceans [4].

Wind has been defined as the horizontal movement of air that is caused by differences in pressure. Since pressure differences are mainly caused by unequal heating of the earth's surface, solar radiation may be called the ultimate driving force of the wind. If the earth were stationary and had a uniform surface, air would flow directly from high-pressure areas to low-pressure areas. Because none of these conditions exist, the direction and speed of wind are controlled by several factors.

A. Uneven Solar Heating: Differential heating of the Earth's surface by the sun causes temperature variations, which in turn create pressure differences in the atmosphere. This pressure difference sets air in motion, creating wind. Regions with uneven solar heating, such as coastal areas or mountainous regions, often experience stronger and more consistent winds, which are ideal for wind power generation [5].

B. Coriolis Force: The Coriolis force is caused by the Earth's rotation and affects the direction of winds. In the Northern Hemisphere, winds are deflected to the right, while in the Southern Hemisphere, they are deflected to the left. This effect influences wind patterns on a large scale, such as the formation of trade winds and westerlies, which are important for wind power generation [6].

C. Local Geography: The local geography, including the presence of mountains, valleys, and coastlines, can significantly influence wind patterns. Mountains can cause winds to accelerate as they are forced over the terrain, leading to strong and predictable winds on the leeward side. Coastal areas can experience strong, consistent winds due to the temperature differences between land and sea [5].

Wind energy is clearly on the rise and could become a major source of electricity in years to come because wind is widely available and often abundant in many parts of the world. Fig. 2. Represents the share of electricity generation from wind energy sources worldwide from 2010 to 2022.Significant resources are found on every continent. Tapping into the world's windiest locations could theoretically provide 13 times more electricity than is currently produced worldwide, according to the Worldwatch Institute, a Washington, DC-based nonprofit organization [6].

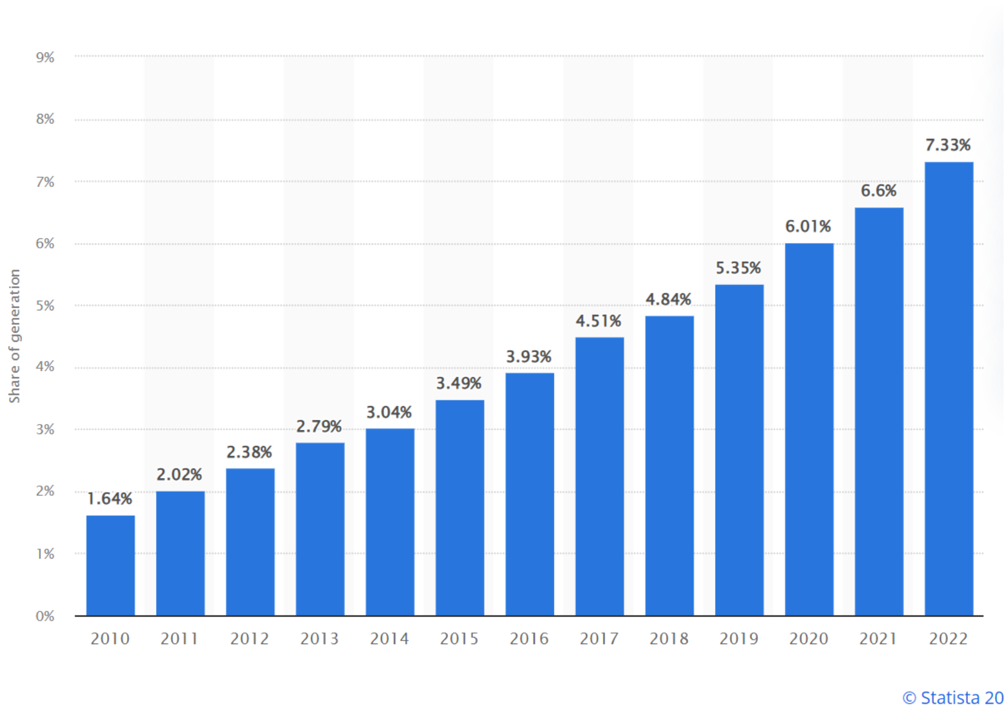

Fig. 2. Share of electricity generation from wind energy sources worldwide from 2010 to 2022[7].

Since the beginning of the third millennium, the total cumulative installed electricity generation capacity from wind power has grown quickly worldwide; by the end of 2022, it approaches 900 GW. Due mostly to the ongoing economic expansion in China and India, more than half of all new wind power installed since 2010 has come from sources outside of the traditional markets of North America and Europe. Fig. 3. Represents the country wise – installed wind power capacity. By 2022, China alone accounted for more than 40% of global capacity [8].

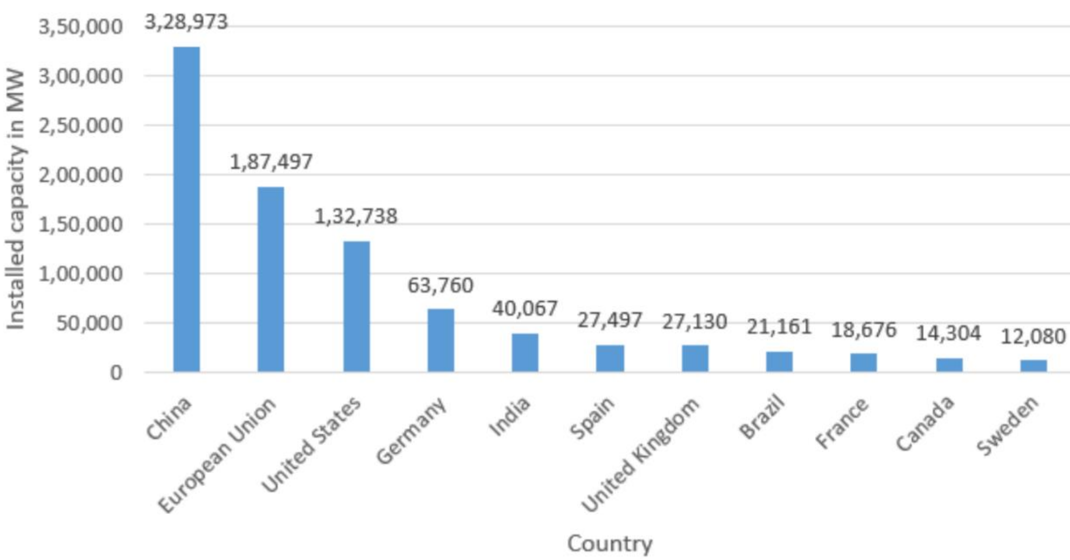

Fig. 3. country wise – installed wind power capacity (MW)[9].

2. FUNDAMENTALS OF WIND ENERGY

Wind energy harnesses the kinetic energy of moving air using turbines. The power generated depends on air density, turbine swept area, betz limit and wind speed guiding engineers in optimizing turbine designs while setting realistic efficiency expectations.

2.1 THE MATHEMATICS OF WIND POWER

To understand how important it is to mount a wind turbine on a tall tower, consider a simple mathematical equation. It's called the power equation and is used to calculate the power available from the wind. This equation shows us that three factors influence the output of a wind energy system: (1) air density, (2) swept area, and (3) wind speed

The power equation is: $P = ½ d x A x V3$ [6]

P stands for the power available in the wind (not the power a wind generator will extract — that's influenced by efficiency and other factors). Density of the air is d. Swept area is A. Wind speed is V.

2.1.1 AIR DENSITY

Air density is the weight of air per unit volume, which varies with elevation. Air density is also a function of relative humidity, although the difference between a dry and humid area is usually negligible. Temperature also affects the density of air. Warmer air is less dense than colder air. Consequently, a wind turbine operating in cold (denser) winter winds would produce slightly more electricity than the same wind turbine in warmer winds blowing at the same speed.

Although density is not a factor we can control, wind installers do have control over a couple of other key factors, notably, swept area (A) and wind speed — both of which have a much greater impact on the amount of power available to a wind turbine and the electrical output of the machine than air density [6].

2.1.2 SWEPT AREA

Swept area is the area of the circle that the blades of a wind machine create when spinning. It is a wind machine's collector surface. The larger the swept area, the more energy a wind turbine can capture from the wind. Swept area is determined by blade length. The longer the blades, the greater the swept area. The greater the swept area, the greater the electrical output of a turbine. As the equation suggests, the relationship between swept area and power output is linear.

Theoretically, a ten percent increase in swept area will result in a ten percent increase in electrical production. Doubling the swept area doubles the output. 30 Wind Power Basics When shopping for a wind turbine, always convert blade length to swept area, if the manufacturer has not done so for you (they usually do). Swept area can be calculated using the equation $\mathbf{A = \pi \cdot r^2}$. In this equation, A is the area of the circle, the swept area of the wind turbine. The Greek symbol is pi, which is a constant: 3.14. The letter r stands for the radius of a circle, the distance from the center of the circle to its outer edge. For a wind turbine, radius is usually about the same as the length of the blade. Because swept area is a function of the radius squared, a small increase in radius, or blade length, results in a large increase in swept area [10].

2.2 THE BETZ LIMIT

The betz limit is the theoretical maximum efficiency for a wind turbine, conjectured by germen physicist albert betz in 1919 [11]. betz concluded that this value is 59.3%, meaning that at most only 59.3% of the kinetic energy from wind can be used to spin the turbine and generate electricity. In reality, turbines cannot reach the betz limit, and common efficiencies are in the 35-45% range [11].

To capture energy, wind turbines slow down the wind as it passes. A wind turbine cannot be observed by gazing at it; if it were 100% efficient, all wind would have to cease totally upon contact with the turbine (fig. 4). The air wouldn't move out of the way to the back of the turbine, preventing more air from entering and causing the rotor to stop spinning, which would fully stop the wind.

Fig. 4. A wind turbine. The Betz limit gives the maximum amount of power it can convert into motion and electricity [12].

3.WIND ENERGY CONVERSION SYSTEM

The wind turbine blades, a gearbox (which can be avoided in some other systems), an electric generator, a power electronic system used as a converter, and an electrical transformer linked to the grid are the primary parts utilized in a conventional WECS as represented in Fig. 5. The WT blades harvest and convert kinetic energy from the wind into mechanical energy. Then, that mechanical energy generates electricity through rotating a generator [13].

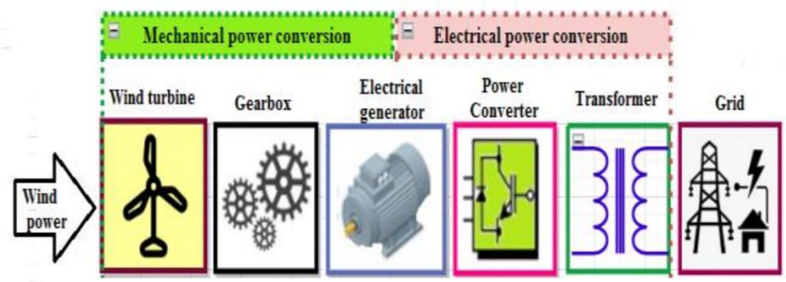

Fig. 5. The typical configuration of a conventional WECS [14].

3.1. Components of WECS

The mechanical and electrical components of the WECS work in harmony to form an integrated system. Certain components unite the many wind energy conversion system designs that were previously addressed. These systems do, in fact, share a large number of components that enable the efficient conversion of wind energy from kinetic energy to electrical energy for storage in the cells. Among the most significant portions of linked grid. The largest tangible component is WECS, which is the wind turbine assembly itself [15]. The wind turbines are complex mechanical devices consisting of multiple tiny parts that provide the electrical parts.

3.1.1. Mechanical Components

Mechanical parts of a wind turbine have a great role in conversion of the energy. The flow of wind has some energy in it due to their kinetic nature. The mechanical regime caters to introduce a ‘work’ in the system by allowing a mass to rotate and transmit it to the desired location to interact with the electrical components. The rotor subassembly is the rotating body, which includes rotor blades, rotor bearings, nose cone, hubs, and the pitch drive system. Some of the major mechanical components that are characteristics of WECS are:

A. Blade: Wind turbine blades play a crucial role in converting wind energy into mechanical energy, which is then used to generate electricity. The design and technology behind these blades have evolved significantly over the years, leading to more efficient and reliable wind turbines. This rotational motion drives a generator, producing electricity. The efficiency of a wind turbine depends largely on the design and performance of its blades [16].

Design Considerations:

I. Aerodynamics: Blade design is optimized for aerodynamic efficiency, minimizing drag and maximizing lift. Airfoil shapes, similar to those used in aircraft wings, are often used to achieve this.

II. Material Selection: Blades are typically made from composite materials such as fiberglass, carbon fiber, and epoxy resins. These materials offer a good balance of strength, flexibility, and light weight.

III. Length and Sweep: Longer blades capture more wind energy, but they also increase the stress on the turbine's components. Sweep (the angle of the blades relative to the rotor hub) affects aerodynamic performance and structural loads.

IV. Twist and Taper: Blades are often twisted along their length to optimize their angle of attack along the span. Taper (reducing the width of the blade from root to tip) can improve aerodynamic performance and reduce weight.

V. Control Systems: Modern wind turbines use advanced control systems to optimize blade pitch angle and rotor speed based on wind conditions, improving efficiency and reducing loads [16,17].

B. ROTOR : Rotor assembly is the aggregate of the barely distinctive elements that interact with the wind. The assembly consists of the blades, the hub and the nose cone. It is responsible for capturing the kinetic energy of the wind and converting it into rotational motion.

C. The Main Shaft: The main shaft is a solid extrude made from any of forged high carbon steel or cast iron/steel that attaches the gearbox to the rotor hub. At present, the megawatt size wind turbines rotate very slowly and the torque is high. Thus, the main shaft is also called low-speed shaft [15]. For example, in a 5 MW power turbine, the input shaft speed is about 12 rpm while the torque is in the range of 4000 kNm This torque value can be considered to be high from a structural point of view, as a torque transmission of 4000 kNm would require approximately a 9 m cross section of EN316 type steel [18].

D. The Gearbox : The gearbox in a wind turbine is a critical component that increases the rotational speed of the turbine's rotor to a speed suitable for generating electricity. The primary function of the gearbox is to take the relatively slow rotation of the turbine rotor (typically around 10-20 rotations per minute) and increase it to the speed required by the generator (usually around 1000-1800 rotations per minute for grid-connected turbines). This speed increase allows the generator to produce electricity efficiently. The gearbox consists of several key components, including gears, shafts, bearings, and lubrication systems [15,19].

E. Mechanical Brakes: Brakes are safety equipment installed inside the housing for emergency situations for stopping the turbine during storms or high velocity winds. They are installed directly on to the low torque high-speed generator shaft for efficient braking, rather than on the high torque low speed main shaft. This keeps them from overheating and failing during emergencies by keeping the braking torque low [15].

D. Nacelle: It is the enclosure housing most of the mechanical components. In horizontal axis wind turbines, the nacelle is the structure mounted on the tower behind the rotor. The size and shape of the nacelle is influenced greatly by the design of the gearbox and reduction required. This fiberglass construction is constructed to reduce turbulence to enable less vibration through the structure. Manolesos et al. demonstrated the aerodynamic properties of generic wind turbine nacelle designs [20]. Vertical axis wind turbines feature transmission and gearbox assembly at the base of the tower, thus, neither an aerodynamic enclosure nor light weight construction is necessary.

3.1.2. Electrical Components

Electrical components are separated into two segments, some of which are located inside the nacelle alongside the mechanical components, while others are placed on the ground away from the tower. The chief function of the electrical subsystem is to convert the mechanical energy gathered from the wind as torque and speed into electrical energy. Fig. 6. Shows the block diagram of a typical grid-connected WECS. Some of the major electrical components that are characteristics of WECS are:

A. Generator: A wind generator is an electromechanical component responsible for converting rotational motion into electrical power, thus converting rotational kinetic energy into electric potential. A typical AC generator works by moving a conductor loop in a static magnetic field based on the electromagnetic induction law of Faraday [15].

B. Power Converter: Depending on the wind speed, the generator's output electric parameters can fluctuate significantly. As a result, at any given time, each turbine would produce a distinct voltage and frequency of current, which cannot be directly connected without refinement to the grid. Therefore, a power converter serves as an interface to link the turbine and the grid. Using a rectifier, the power converter converts the output voltage from AC to DC. It then uses an inverter circuit to convert the rectified DC back to AC with a consistent voltage and frequency [21].

C. Step-up Transformer: The output from the generator in a grid connected MW turbine is rather low, in the range of 400 to 690 volts, which requires it to be stepped up since the grid connects directly to the high-tension lines [22]. The necessity of a step-up transformer can be annihilated by designing the generator and power electronic converter according to the wind farm collection point voltage, however it demands additional costs for medium voltage generator and power converter setup, diminishing the economic benefits of removing a step-up transformer from the circuit [23]. However, studies are being conducted in recent years to eliminate the needs of transformers in medium voltage grids in order to reduce transmission losses incurred from stepping up the voltages required for transmission

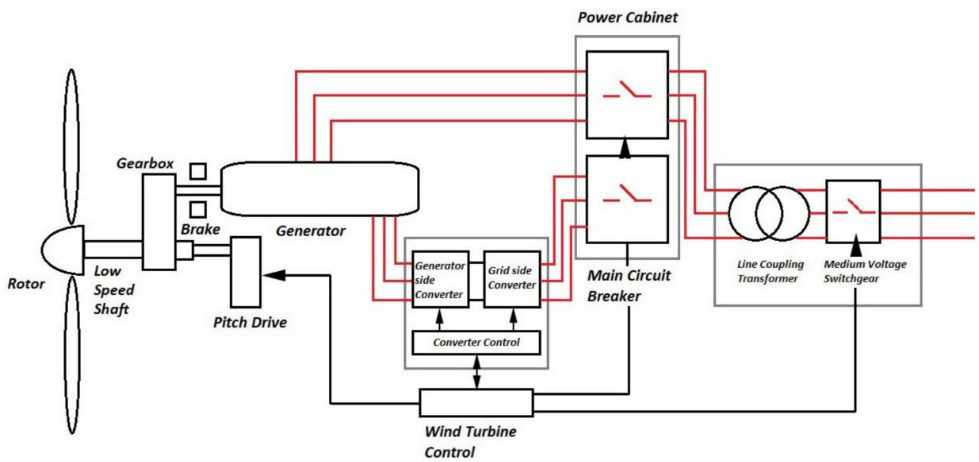

Fig. 6. Block Diagram of a typical grid-connected WECS [15].

4. Wind Energy Technologies

Wind energy technologies harness wind to generate electricity. Wind turbines are classified into several categories based on axis orientation, based on application and the direction from which the wind hits the turbine blades. Current trends include offshore wind farms and advancements in turbine efficiency and materials. Future prospects focus on integrating AI for optimization, floating turbines, and expanding renewable energy's role in sustainable power grids.

4.1. CLASSIFICATION OF WIND TURBINES

Based on application, axis orientation, and the direction the wind strikes the turbine blades, wind turbines are divided into multiple groups. Fig. 9. Represents the Classification of WECS.

4.1.1. Based on Axis Orientation:

A. Horizontal Axis Wind Turbines (HAWT): Blades rotate around a horizontal axis, perpendicular to the wind direction (Fig. 7). Most common type. The elevated height of the turbine also facilitates the turbine to rotate with enough clearance to the ground. The mechanical components of the turbine are enclosed in a housing, which is shaped aerodynamically called a nacelle. Generally, HAWTs are more efficient at converting wind energy into electricity compared to VAWTs. They can reach higher altitudes where wind speeds are higher. HAWTs require more space for installation and are typically mounted on tall towers to capture higher wind speeds. They can produce more noise due to the higher rotational speeds of the blades. Commonly used in large-scale wind farms, such as those found in many countries around the world [24].

B. Vertical Axis Wind Turbines (VAWT): Blades rotate around a vertical axis, parallel to the ground (Fig. 7). Less common but have certain advantages in specific applications. They can start generating electricity at lower wind speeds compared to HAWTs, making them suitable for areas with lower average wind speeds. VAWTs can be mounted closer to the ground, which can simplify maintenance and reduce the need for tall support structures. Generally, VAWTs are less efficient than HAWTs, especially at higher wind speeds.

Less common in large-scale wind farms but can be found in smaller applications, such as residential or urban settings, where their unique design and lower noise profile may be advantageous [6,24].

Fig. 7. Horizontal and vertical axis wind turbines [25].

4.1.2 Based on the direction from which the wind hits the turbine blades :

A. Upwind Turbines: In upwind turbines, the rotor (blades and hub) is located before the tower in the direction of the wind, facing into the wind (Fig. 8). The advantage of upwind turbines is that they can potentially capture more wind energy, especially at higher altitudes where wind speeds are typically higher. Upwind turbines require a yaw mechanism to turn the rotor into the wind, which adds complexity and maintenance requirements to the turbine system [26].

B. Downwind Turbines: In downwind turbines, the rotor is located on the leeward side of the tower, behind the tower relative to the wind direction (Fig. 8). Downwind turbines do not require a yaw mechanism since they align passively with the wind direction. They are typically quieter than upwind turbines because the blades do not pass close to the tower, reducing noise from turbulence. However, downwind turbines may experience more fatigue due to the cyclic loading caused by the tower shadow passing over the blades [24,26].

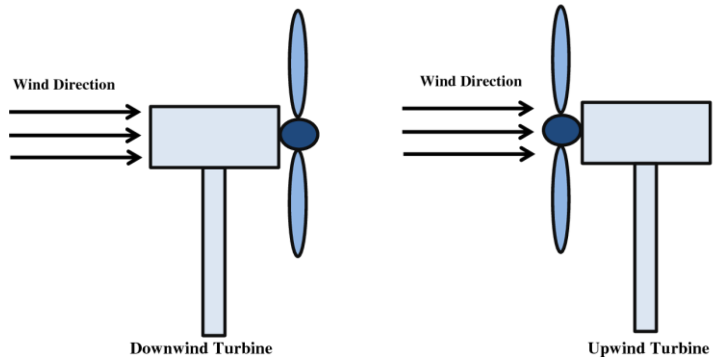

Fig. 8. Upwind and downwind turbines [27].

4.1.3. Based on Application:

A. Onshore Wind Turbines: Located on land, either in rural or urban areas. Most common type of wind turbine installation [28].

- Advantages of onshore wind power
    - cost-effective
    - boosts local economy
    - Quicker installation and easier maintenance

- Disadvantages of onshore wind power
    - Changing wind speeds
    - Effects on people and nature
    - Lesser power generation [29]

B. Offshore Wind Turbines: Located in bodies of water, typically in coastal areas or offshore wind farms. Generally larger and more powerful than onshore turbines [28].

- Advantages of offshore wind power
    - Offshore wind turbines are more efficient
    - Reduced environmental impact
    - More space to construct in

- Disadvantages of offshore wind power
    - Higher cost
    - Maintenance and repairs

- Less local involvement [29]

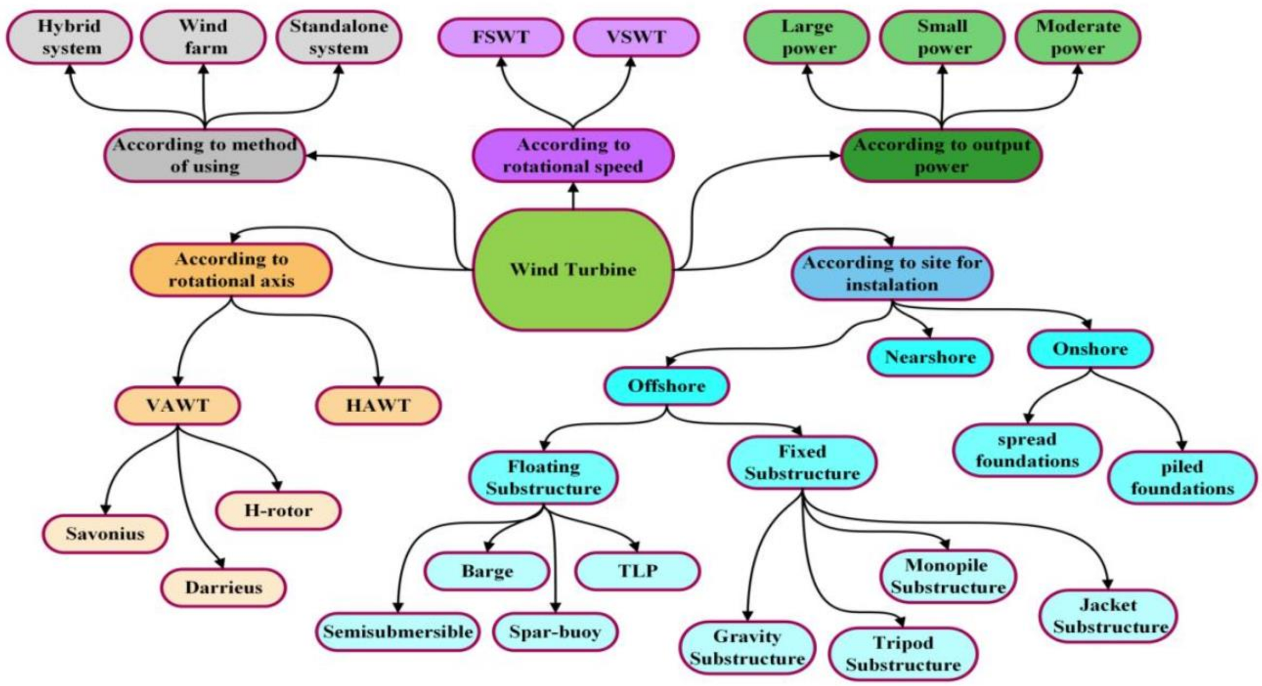

Fig. 9. Classification of WECS [14].

4.2. CURRENT TRENDS AND FUTURE PROSPECTS

Wind energy has emerged as one of the fastest-growing sources of renewable energy, playing a crucial role in the global transition towards sustainable energy systems. This growth is driven by advancements in wind turbine technology. Current trends in wind turbines include offshore installations, increased turbine size, and enhanced materials for greater efficiency and batteries as a recently developed energy storage technology. Future prospects focus on AI integration for optimization, floating wind farms for deeper waters, and improved grid integration, airborne wind energy aiming to make wind energy a cornerstone of sustainable power systems.

4.2.1. Current Trends

A sharp incline in the installation of wind energy firms have been observed within recent decades throughout the world, rendering a shift of dependence on clean energy [30]. The present trend of global wind energy production has been represented in Fig. 10 [31].

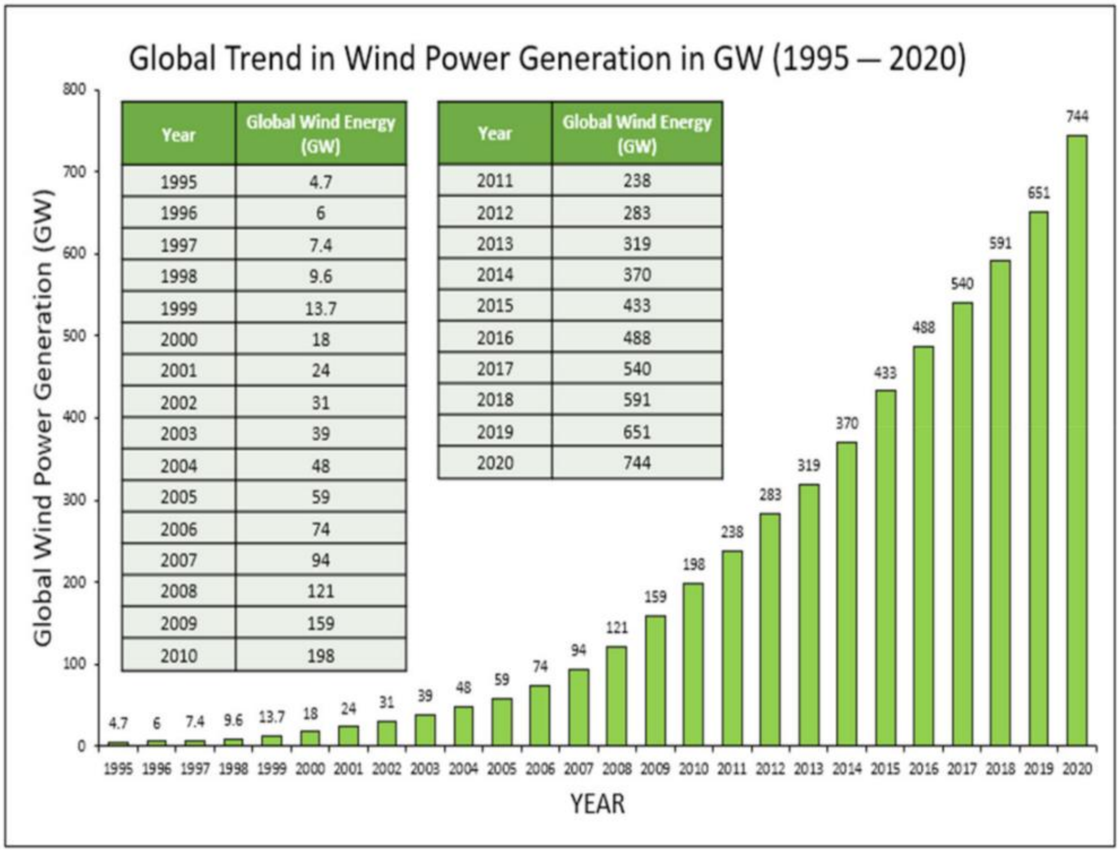

Fig. 10. Trend in Wind Power Generation in Giga Watt (GW) [31].

In the modern wind turbine technology, the HAWTs are highly developed and currently available in the entire existing wind farm. On the other hand, the VAWT in the present wind farm is very rare, and the majority of the research on its design was carried out in the late 1970s and early 1980s at the US Department of Energy Sandia National Lab and in the UK by Reading University and Sir Robert McAlpine and Sons Ltd. [32,33]. However, when it was proven that HAWTs are more efficient for large-scale wind energy production, interest in VAWT design was lost and after that a very little research on VAWT has been carried out [34].

The technical development of VAWTs lags significantly behind that of HAWTs, though VAWTs are aerodynamically more efficient than HAWTs. Moreover, it has been suggested that VAWTs are more appropriate in large scale (10 MW+) wind energy generation [35]. Very recently there has been a revivification regarding VAWTs and many researches have been carried out due to its aerodynamic efficiency and performance regarding flow separation and alleviating adverse effects on energy production [36-38]. It is observed that wind is always changing its speed, and direction is rarely uniform. VAWTs do not need any unidirectional wind speed to produce electricity from wind as its counterpart HAWTs very much needed. In other words, VAWTs are omnidirectional that negates the need for a yawing mechanism. Therefore, VAWTS can be more effective in the complex urban terrains to harness the wind energy that helps to increase the capacity of small-scale wind power generation [39,40].

4.2.1.1. Batteries as a recently developed energy storage technology

When an energy storage component is connected to a wind farm, the output power's spectrum and statistical distribution are altered. By expanding the quantity of storage devices to the wind power plant, the wind farm's output has improved in predictability and control. Wind turbines produce extremely unpredictable electric power since wind is stochastic, which can have an impact on power system planning and power quality. As a result, research on energy storage and conversion has taken center stage in an effort to address public concerns about the environment as well as practical uses like powering a growing number of portable electronic gadgets. Storage system will have to play an important role in the wind power plant by controlling wind power output that enables the increased penetration of wind power in the grid system [41].

A variety of storage technologies are available for storage of energy in the power system. Recently the electrical energy storage technologies include the following types of storage media [42]:

I. Batteries
II. Flow batteries
III. Fuel cells
IV. Flywheels
V. Superconducting magnetic energy storage (SMES)
VI. Super capacitors
VII. Compressed air energy storage (CAES)
VIII. Pumped hydro

However, by considering all aspects along with flywheel, fuel cells and batteries are the two most impacting energy storage devices in the RE systems. Batteries take in electricity from another producing source, convert the electricity to chemical energy, and store it as a liquid of solution. When operators need energy from the battery, an electric charge chemically converts the energy back into electrons, which then move back into a power line on the electric grid. There are several promising battery technologies for grid energy application including advanced lead-acid, nickel cadmium (NiCd), nickel metal hydride (NiMH), lithium ion (Li-ion), sodium–sulfur (NaS) and flow batteries [43-45].

4.2.2. Future Prospects

Since wind energy is a relatively newer source of energy, most of the resources that capture the energies have focused on the development of turbines and tower designs, as well as methods to increase the efficiency of existing systems. However, possibilities for the evolution of technologies are endless. However, a future emerging technology in this field of study would consider the following criteria to be accepted [46]:

a. Technologies based on supply and conversion of wind energy;
b. A technical overhaul, with new fundamentals, which cannot be a result of incremental research on prevalent technologies; and
c. A technology which is in its early developmental stages.

4.2.2.1. Airborne Wind Energy (AWE)

AWE systems are a collective group of devices that harness energy in a similar form as a regular WECS set-up, instead having the external features of an unmanned aircraft or an autonomous kite. An airborne wind turbine is schematically shown in Fig. 11. The system is suspended in air and attached to the ground by means of one or more tethers to keep it in place [47].

There are a number of advantages of AWE systems: Low material use, Additional wind resource, High-capacity factor and Low costs. The two broad categories of the AWE system involve ground-gen and fly-gen systems. The ground-gen concept aims at converting the mechanical power into electrical power at the ground level, while fly-gen systems do so in the airborne unit itself [48,49].

However, this will need to overcome a number of technological obstacles, including erosion from wind and water and the dependability and longevity of flexible components. Drone concepts are among the recent trends in this system's research. Aerodynamic modelling, sensors and electronics for tethered device autonomy, and controls for independent takeoff and landing.

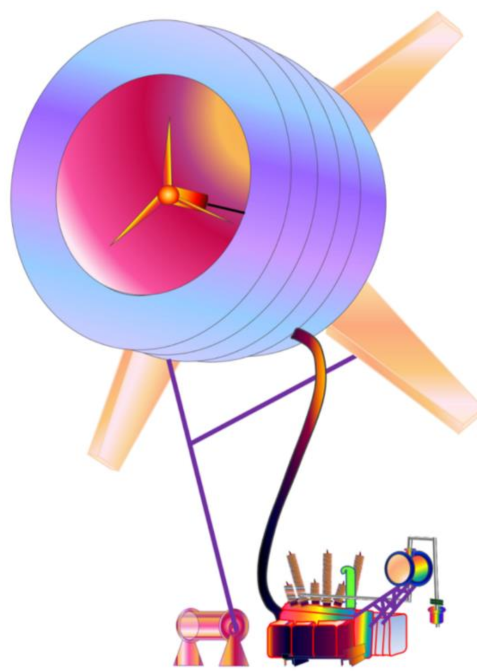

Fig. 11. Airborne Wind Turbine [50].

4.2.2.2. Offshore Floating Wind Concepts

This concept differs from traditional offshore concepts by the method of foundation. While the latter employs a fixed foundation to the floor of the ocean, this innovative design is a free-floating structure related to the semi-submersible tension leg or the spar platforms. The floating is controlled by various anchoring systems. Since it is a diversion from the existing fixed off-shore designs, there high potential for the exploration of newer techniques to integrate the tower to the floating base. Moreover, the impact of changing turbine parameters including TSR, blade designs and number of blades on the floating platform can be investigated [51].

A wind turbine mounted on a floating foundation is part of the FOWT idea, which enables the production of power in deep waters where bottom-fixed wind turbines are not economically feasible. Different floating wind turbine concepts are shown in fig. 12 [52].

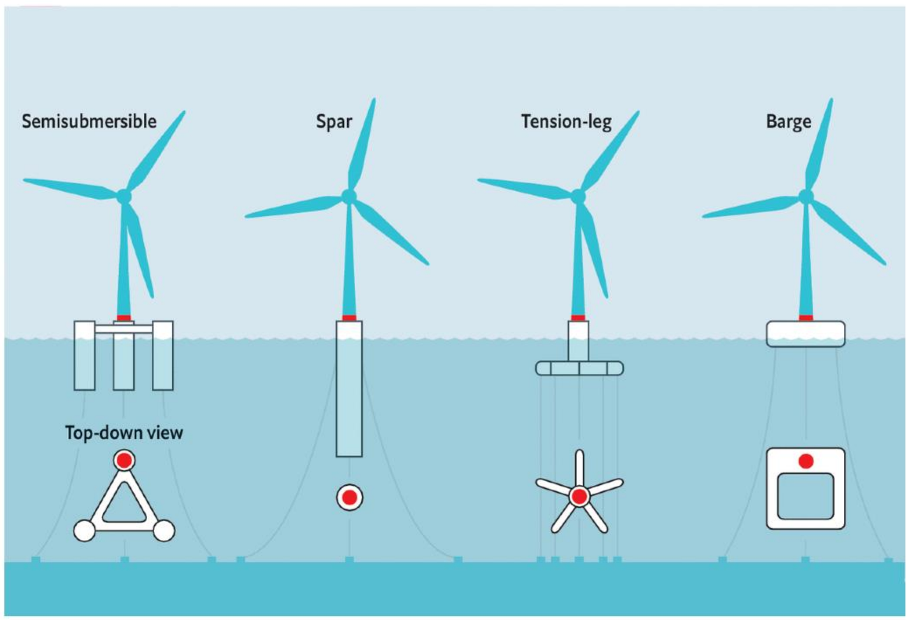

Fig. 12. Different FOWT design concepts [52].

4.2.2.3. Tip-Rotor Wind Turbine (TRWT)

This concept of wind turbine system integrates high speed, low torque rotors at the tip of the main blades. Therefore, the generator can be coupled directly without the necessity of torque reduction gearbox arrangements for these rotors. The efficiency of these rotors to extract wind energy can go beyond the Betz limit, since it is actually the thrust of these tip-rotors that provides reaction torque to the main rotor of the turbine [53].

4.2.2.4. Multi-Rotor Wind Turbine (MRWT)

Replacing the large size of a rotor with multiple smaller rotors is helpful to reduce the overall loads on the structure of the turbine. This concept made it possible to install a large power system of about 20-MW at a single site. A company like, Vestas, has adapted this concept to develop a 900 kW four rotor design, illustrated in Fig. 13. The most prominent advantage of this technology is the process of standardization as it allows the production process of these small-scale rotors to be industrialized. This process could help is saving production costs in comparison to present large scale rotors, since these large-scale rotors need to be customized for specific application, thus reducing probability of standardization. Studies have enlightened the advantages in maintenance by having smaller components[15,54].

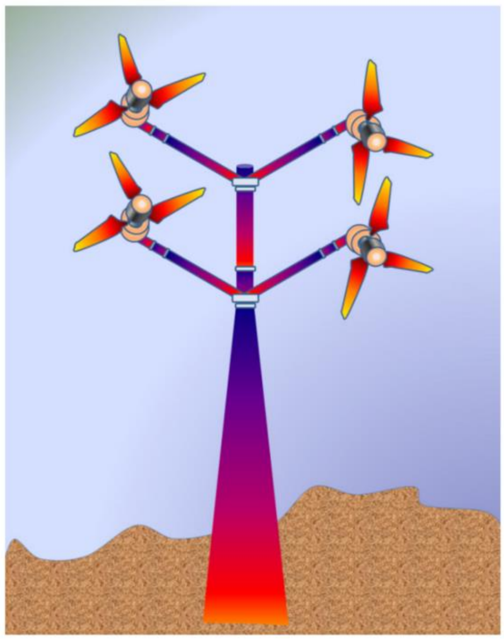

Fig. 13. Multi-rotor Wind Turbine [54].

4.2.2.5. Diffuser Augmented Wind Turbine (DAWT)

Diffuser Augmented Wind Turbines, chiefly abbreviated as DAWT is a modified design of normal horizontal axis wind turbines, with the addition of a diffuser structure around the rotor. A schematic diffuser augmented wind turbine is shown in Fig. 14 [56].

The diffuser is encased around with a diffuser that resembles the shape of a funnel, used to concentrate the approaching stream of wind. Modification can be introduced to this structure by adding a rim around the exit side of the diffuser and an inlet shroud at the entrance side (upwind). The diffuser has been proven to increase the generated power compared to traditional HAWTs [55].

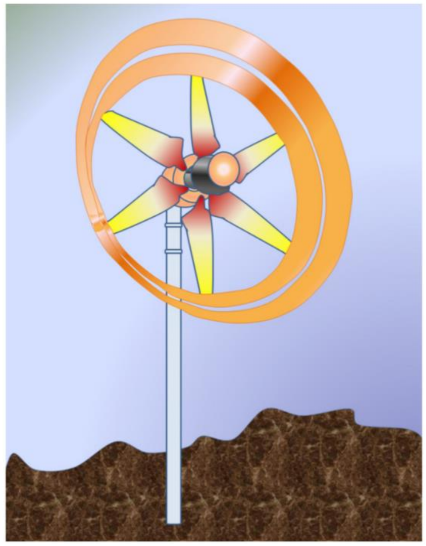

Fig. 14. A schematic diagram diffuser augmented wind turbine [56].

5. ENVIRONMENTAL AND SOCIAL IMPACTS

Wind turbines are a vital component of renewable energy infrastructure, contributing significantly to reducing greenhouse gas emissions and mitigating climate change. However, their deployment also brings various environmental and social impacts that need careful consideration and management. This section explores these impacts in detail, highlighting both the benefits and challenges associated with wind energy development.

5.1.Positive impact of wind energy

Wind turbine electricity does not emit any pollutants, in contrast to energy from other sources (such as coal, gas, and petroleum-based fuel).
When wind energy replaces current conventional energy sources, air pollution may be reduced.
Consequently,it is possible to cut emissions, particularly those of carbon dioxide, nitrogen oxide, and sulph ur dioxide.Research in the literature has shown that these gases' emissions are to blame for acid rain, global warming, the greenhouse gas effect, sea level rise, and erratic weather. . Wind energy is an infinite type of energy that can be harvested either in the mainland or on the ocean. It was estimated that a 2.5 kW system can save 1–2 tones of CO_2 and a 6-kW system can save 2.5–5 tones CO_2 [57].
In a suitable site, wind turbines represent a relatively low-cost method of micro-renewable electricity generation. They can bring increased security for electricity supply to non-grid connected locations and give some protection against electricity price rises. Renewable Obligations Certificates (ROCs) can be received by generating electricity. These can then be sold to electricity generators to allow them to meet their targets to derive a specified proportion of the electricity they supply to their customers from renewable energy sources [58].

5.1.1. Reduction of water consumption

Water consumption is important and a major worry in a world where clean water is becoming more and more limited, particularly in nations like Singapore. It should be noted that traditional power plants consume a lot of water.
for the thermodynamic cycle's condensing phase. Water is also utilized in coal-fired power plants for fuel cleaning and processing. Millions of liters of water can be utilized per day. Water can be conserved and used for other reasons by using less of it.

California energy commission [59] estimated the amount of water consumption for conventional power plants as shown in Table 1. From Table 1, it has been found that water usage for wind turbine is lower than the conventional power plants and solar energy system.

Table 1 : Water consumption of conventional power plant and renewable energy-based sources [59].

Technology	gal/kWh	l/kWh
Nuclear	0.62	2.30
Coal	0.49	1.90
Oil	0.43	1.60
Combined cycle gas	0.25	0.95
Wind	0.001	0.004
Solar	0.030	0.110

5.1.2. Reduction of carbon dioxide emission

Generally, wind energy has zero direct air pollution. A small amount of CO_2 emissions is released by the wind energy during its construction and maintenance phases. However, this amount of CO_2 is much less than other fossil-fuel based power plants. This amount of CO_2 produced can actually be absorbed by the tree by the process of photosynthesis. Every unit (KWh) of electricity produced by the wind displaces a unit of electricity which would otherwise have been produced by a power station by burning fossil fuel [60]. It does not produce carbon dioxide, sulfur dioxide, mercury, particulates, or any other type of air pollution, as do fossil fuel power sources [61].

5.1.3. Job opportunities

Other positive impact of wind energy is job opportunities. In Europe, between 2008 and 2016 more than 2.5 million jobs have been created with most jobs in the manufacturing stage at 58 % followed by operation and maintenance at 24 % and installation stages at 18 %. In the US, wind energy sector is projected to support approximately 201,000 to 265,000 jobs by 2030 and 526,000 to 670,000 jobs by 2050 [62].

5.2 Negative impact of wind turbine

It's crucial to research a wind turbine's negative effects in addition to its benefits. The worst-case scenario needs to be identified and forecast before any decisions are made. By doing this, the damage can be minimized. The most significant negative impact of a wind turbine technology is the wildlife, noise and visual impact which will be discussed in the following sections. Some other impacts include the distraction of radar or television reception due to magnetic forces generated by the wind turbine, and the increased possibility of being struck by lightning.

5.2.1. Impacts on wildlife

Many researchers found that wind energy is one of the healthiest and environmentally friendly options among all the energy sources available today. Wind energy is the energy source that is most compatible with animals and human beings in the world. However, there are some minor wildlife impacts reported by few researchers. The wildlife impacts can be categorized into direct and indirect impacts. The direct impact is the mortality from collisions with wind energy plant while the indirect impacts are avoidance, habitat disruption and displacement. However, the impacts are smaller compared to other sources of energy [63].

Wind farms have an enormous effect on avian life. These effects include mortality, change in migration patterns, and loss of habitats for the avifauna. Table 2 summarizes the mortality rates of birds and bats as observed in different wind farms worldwide.

Table 2 : Birds and bats mortality observed in different wind farms around the world [64].

Area affected	Mortality rate	Years observed	Species killed
South Africa	4.6 ± 2.9 birds/turbine/year	2014–2018	130 (30 %)
Quebec, Canada	1.29–1.84 bats/MW/year	2016	8
Romania	14.2 bats/MW/year	2013–2016	10
Isthmus of Tehuantepec, Mexico	9.06–12.85 birds/MW/year 20.47–43.79 bats/MW/year	June-Nov 2015	30 birds 20 bats
Spain	0.5 bats/MW/year	2005–2016	13
United States	5.26 ± 8.52 birds/MW/year	2019	–
India	0.478 birds/turbine/year	2011–2014	11
Texas, United States	16 bats/MW/year	March 2017–March 2018	8

5.2.2. Noise impact

The noise pollution caused by wind turbines is the most significant environmental impact. Property values could be negatively impacted by noise pollution at a range of distances from the construction. In order to protect participants and nearby landowners from noise and safety problems, turbines should be placed back from homes and property lines. The noise levels that wind turbines produce must be understood by engineers prior to construction.

This noise increases with wind speeds and turbine sizes. Additionally, the turbine machinery, such as gearboxes and generators, also produces some noise, which can annoy people and creatures living near the wind farm. WHO recommends that continuous noise levels should not exceed 30 dB for a good night's sleep (Fig. 15) [64].

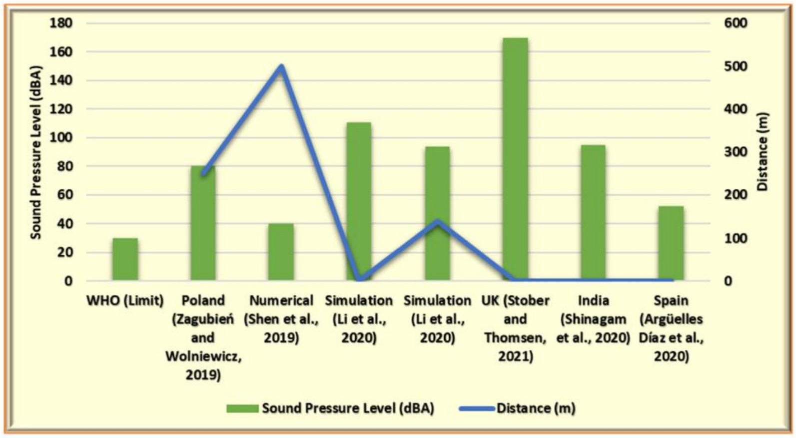

Fig. 15. Sound pressure levels at different distances from the wind turbines of wind farms from different locations and simulations compared with the WHO limit [64].

Noise emitted by a wind turbine can be divided into mechanical and aerodynamic types. Mechanical noise is produced by the moving components such as gear box, electrical generator, and bearings. Normal wear and tear, poor component designs or lack of preventative maintenance may all be factors affecting the amount of mechanical noise produced [65]. Aerodynamic noise is developed by the flow of air over and past the blades of a turbine. Such a noise tends to increase with the speed of the rotor. For blade noise, lower blade tip speed results in lower noise levels. Of particular concern is the interaction of wind turbine blades with atmospheric turbulence, which results in a characteristic "whooshing" sound [66].

Mechanical noise can be minimized at the design stage (side toothed gear wheels), or by acoustic insulation on the inside of the turbine housing. Mechanical noise can also be reduced during operation by acoustic insulation curtains and anti vibration support footings. Aerodynamic noise can be reduced by careful design of the blades by the manufacturers who can minimize this type of noise [67].

5.2.3. Visual impact

The installation of wind farms both onshore and offshore changes the environment's look. The people living nearby wind farms are affected by the visual impacts of wind turbines as they are large structures installed in their beautiful landscapes. Summary of surveys of people living near wind farms are summarized in Table 3.

Table 3 : Summary of surveys about wind turbines' visual impacts to residents of different locations [64].

Location	Visual impacts of wind turbines
Virtual reality	36 % of participants had negative attitudes
Iceland – Burfell windfarm	Most residents had negative attitudes
ETH Zurich	Wind turbines caused visual annoyance
Ireland	Wind turbines visible in over 40 % of the land
Australia	556 people agreed on negative visual impacts
Greece – Samothraki island	48 % of residents had negative attitudes

Authors [68] reported that the visual impact varies according to the wind energy technology such as color or contrast, size, distance from the residences, shadow flickering, the time when the turbine is moving or stationary and local turbine history.

6. CONCLUSION

wind energy is a vital renewable energy source that has gained significant attention due to its environmental benefits and potential to reduce reliance on fossil fuels. This review has discussed the fundamentals of wind energy, including the mathematics of wind power and the Betz limit, highlighting the importance of factors such as air density and swept area in maximizing energy generation.

The wind energy conversion system (WECS) plays a crucial role in harnessing wind power efficiently, with typical structures and components such as mechanical components being essential for converting wind energy into electrical power. The classification of wind turbines based on their design and technology has also been explored, illustrating the diverse range of wind energy technologies available.

Current trends in wind energy technology indicate a shift towards larger, more efficient turbines, while future prospects include advancements in offshore wind farms and the integration of wind power into smart grids. Despite its many benefits, wind energy does have some negative environmental and social impacts, such as visual and noise impacts from wind turbines.

Overall, the positive impacts of wind energy, including its contribution to reducing greenhouse gas emissions and creating job opportunities, outweigh the negative impacts. Continued research and development in wind energy technologies are essential for further enhancing its efficiency and mitigating its environmental and social impacts.

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