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A review of offshore wind turbines: global added capacity, monopile structure foundations stresses and deflection

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ABSTRACT

Offshore wind power is now a significant source of clean renewable energy. The paper summarizes the key findings from recent energy studies on the growth in offshore wind power's added capacity to the global energy system. The review paper referred to parts of the configuration of offshore wind turbines (OWTs) and their supporting structures, and focused on the monopole support structure due to its importance in building offshore wind farms and studying and discussing the most published research related to the mono support structure and its response to wind loads and wave loads affecting them. Recent studies have varied between numerical analysis research, research and master's theses and doctoral theses on calculating stresses on offshore wind turbines. Due to the importance of the topic, studies on computational fluid dynamics (CFD), which have developed greatly in recent years, have been reviewed (simulation and simulation research). Hybrids (RTHS) and experimental research. The paper concluded with the conclusion that the interest in experimental studies and research close to the conditions of marine turbines is through the construction of special laboratories that include advanced equipment with quantitative measurements, with high technical standards and good reliability, developments of simulation tools of various forms in order to approach efficient and low-cost design.

Keywords: Wave Kinematics, (computational fluid dynamics) CFD, Hydrodynamic Forces, Offshore wind turbine, Stress and Bending Moment on the structure, Horizontal axis wind turbine, Monopile foundation.

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1. Introduction

With a speedy depletion of natural resources, climate change, and energy shortages, access to clean and renewable energy has become a critical problem to address [1]. To meet new infrastructure needs and achieve sustainable development targets, researchers are looking for renewable energy sources to replace fossil fuels, developing new energy growth strategies, and promoting a new round of energy revolution [2]. According to a related study, the cheapest onshore wind power is currently between $26 and $31 per megawatt-hour, while offshore wind power is currently between $53 and $64 [3]. However, the interest and tendency to use marine wind energy has realistic reasons, including the lack of exploitation and occupation of areas on land, and the sea winds are higher and more stable than on land [4]. Offshore wind costs are quickly diminishing. Notwithstanding, there is a requirement for a superior comprehension of the vital components behind these expense decreases. The 5 most significant boundaries while making a business case for putting resources into offshore wind will be wind speed, target pace of profit for value, turbine costs, penetrating expenses and obligation administration inclusion proportion [5]. Quickly falling expenses each kilowatt-hour (both onshore and offshore) have made breeze energy perpetually serious and permitted coastal breeze ability to contend no holds barred with petroleum derivative age in an enormous and developing number of business sectors around the planet, frequently without monetary help [6].

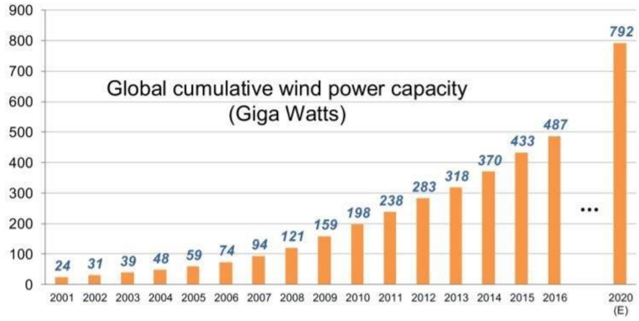

Figure 1. Wind power capability in the world from 2001 to 2020 [7]

For the eleventh successive year, Asia was the biggest territorial market, see Figure 2 [6]. Near the coast wind power plays a significant role in growing wind energy capacity additions, accounting for a record 10% of new wind energy farms in 2019. As a result, the wind energy industry grew by 19% in 2019, reaching 60 GW with a total capacity of 650 GW (621 GW on onshore and the rest offshore) [6].

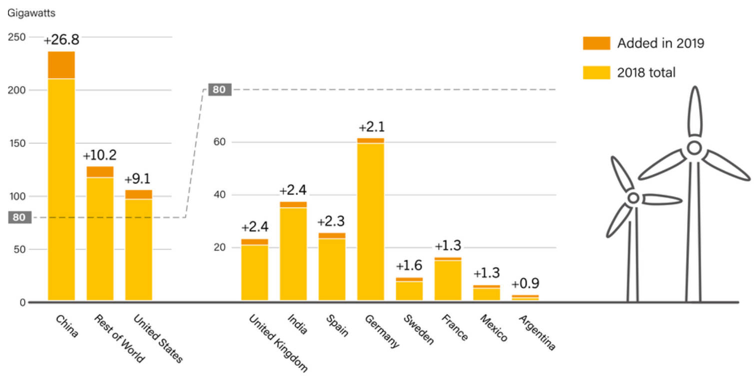

Figure 2. Top 10 Countries' Wind Power Capacity and Additions, 2019

Be that as it may, because of the cruel climate, troublesome transmission technique, etc., the utilization of offshore wind energy is additionally intensely compelled [8]. Power generation is feasible when wind speeds exceed 7 m/s, according to previous studies. However, offshore wind power development costs are substantial, ranging from 1.5 to multiple times those of inland wind power, with the establishment cost accounting for around 15% of the total cost of offshore wind power development [9].

The sea energy ranches, on the other hand, make better use of wind energy, producing 20 percent to 40 percent more energy than coastal breeze windmills [10]. According to the World Wind Energy Council's annual report, the world's cumulative installed capacity doubles every three years, and growth is expected to continue at this rate [11]. Despite the Coronavirus, Covid-19, wind capacity additions increased in 2020, with annual additions forecast to hit 65 gigawatts by the end of the year, an improvement of 8% over 2019.[12]. The offshore wind sector was slightly affected by the Covid-19 crisis, it is expected that offshore wind additions will increase by 2025, reaching 20% of total wind additions [12]. Forecasts show a decline in annual wind additions in the Middle East & Africa area in 2020 relative to 2019 [12]. In 2017, the world's first huge scope business coasting offshore wind power project Hywind Scotland skimming wind ranch [13].

2. Wind power

Wind systems and their size, both in terms of unit power and total farm capacity, began to grow in the 1980s. Although inland wind farms were first developed, environmental requirements (such as not exploiting other areas of land, reducing noise, and so on) led to the development of offshore wind farms. Wind turbines with three blades and a horizontal column are currently the most common, and the attached generators are either asynchronous or synchronous. In the turbine room there is also a gearbox and it may not. Modern designs have been designed for variable speed operation. Wind farm construction has been backed by national regulatory bodies in several countries, and the new technology has been incorporated into industry standards. The International Electro-technical Commission (IEC) [IEC61400] has released the related documents internationally. Over the years, specialists, scholars, and technicians have established these principles [14]. The following equation is being used to approximate the wind turbine's yield power:

$$P = 0.5CpAV^3 \qquad (1)$$

The energy leaving a wind turbine is calculated by factors such as the power factor CP, air density, rotor area A, and wind speed V, according to Equation (1). As a result, the output energy is proportional to the rotor field. To obtain a higher wind speed and for the same ground border area, the height of the turbine tower is one of the solutions, and also increasing the rotor area gives the ability to absorb the faster winds [15].

3. Numerical tools and simulation approaches (computational fluid dynamics) CFD

Hydrodynamics, aerodynamics, structural flow, and mooring lines are all taken into account and fathomed when considering the complex analysis of offshore wind turbines. Cordle and Jonkman worked on all numerical tools capable of double numerical analysis in all its details [16].

CFD has become a viable tool for measuring wave, current, and wind loads thanks to rapid advances in the development of private and server-based computers and computational methods, as well as the development of commercial applications in recent decades. The solution of equations governing and subject to instantaneous boundary conditions is referred to as CFD. Although their definition is generally reserved for viscous flows, the (Navier – stokes) equations can be used as accurate governing equations [17].

Tande J. completed his master's thesis on the aerodynamics of wind turbines on a blade of a 10MW offshore turbine with the Computational Fluid Dynamics method, CFD, at the Norwegian University of Science and Technology in 2011.The student set four objectives for his thesis. The first was to create a computer-assisted design using a CAD program. This was accomplished using models created by PhD student Froyd for a 70-meter-long blade designed for a 10-megawatt wind turbine. The second goal was to do CFD calculations by developing a mesh surrounding the blade. The third objective was to verify the correctness of the rotor performance by calculating the CFD of the previously performed wind turbine as well as the results of the blade element method for the respective rotor. The fourth goal was to create a guide for drawing the code's CAD model, as well as explaining mesh working procedures and CFD analyses. The first goal yielded positive results, while the second and third goals proved to be more complicated than expected. It was not possible to check the CFD results of the 10MW offshore turbine blade because none of the three validation methods were accurate in comparing the results of the CFD calculations to previous results of the same turbine. The MSc thesis is important because it serves as a foundation for future CFD blade simulations of offshore wind turbines [18].

Make et al. published a paper in 2015 that used RANS CFD to analyze flow on two floating wind turbines under Reynolds conditions numbers and full-size terms. To eliminate all possible uncertainties, numerical sensitivity tests were conducted. To evaluate these uncertainties and validate numerical findings against experimental evidence, modern validation procedures were used. Moreover, for either the model or the full range, the flow around the turbine and its output were examined. The results were good in terms of comparing CFD results to experimental evidence, and the important effects Reynolds had on the flow of these turbines were demonstrated and explained. Under model scale conditions, the MARIN STOCK wind turbine has been verified to perform as anticipated [19].

In 2016, a PhD student Al-Esbe, Israa completed her thesis, based on studying the effect of environmental conditions on the aerodynamic and water dynamic loads operating on static offshore wind turbine structures using the Inner Limit Element (BEM) method, the PanMARE code. The construction of a 5 MW NREL offshore wind turbine is now complete. RANSE simulations using ANSYS CFX software, which is based on the finite volume approach, were used to investigate the BEM effects. The thesis' findings demonstrated the BEM symbol's ability to model aerodynamic and water dynamic flow on complex 3D offshore wind turbines [20]. She also published research in 2017 with others in which simulations were performed under the same environmental atmospheric wind shear and rotor angular velocity, with the characteristics of a 4-meter high wave with a 7.16-second length. The effects of the wave on the environment are investigated in this paper. In addition, on every OWT case, the pressure distribution was shown, along with detailed info about the local flow fields. In each section of the OWT, the temporal background of forces in the direction of flow and their moments along the mud line is presented in a dimensionless manner. The results show that the rotor force is lower in the tripod case and higher in the casing case, and that the measured hydrodynamic load affecting the foundation type of the framework is less [21].

In 2017, Nigam P. et al. used the k-ω SST model to complete a Computational Fluid Dynamics (CFD) study of a propeller and wing. A NACA 634-221 airfoil profile was taken for code blade and then analyzed. The study's main goal was to determine the cost of lifting forces and blade drag for various angles of attack. The outcomes of the CFD simulation are compared to previous years' experiments conducted, and the simulation is run using the ANSYS Fluent 12.0 program. According to the study's findings, the coefficient of lift and drag coefficients increase as the angle of attack increases. The findings also revealed that the pressure on the below surface of the airfoil is higher, while the speed on the top surface is higher [22].

In 2019, Pichitkul et al they completed their analysis of a 2MW large scale wind turbine designed to operate on a 120MW North Sea wind farm project. The performance of the developed design was studied independently by classical blade aspect- momentum (BEM) theory and (CFD) computational fluid dynamics analysis in order to study the optimum aerodynamic performance of the turbine. It results showed that the proposed design is effective in order to conserve energy, with a maximum power factor of about 0.47 for various sustained winds, tip speeds, and blade pitch settings. The study concluded that the planned project is economically feasible because the cost of generated energy would not exceed 9.7 cents per kilowatt-hour, which is significantly less than the current cost of 18 cents per gw/h for the year 2018 [23].

Joel H and others wrote their important and useful book in the field of Computational Fluid Dynamics (CFD), and the book has been printed until 2021, four times, and the book is based on lectures given by authors in the past in international universities and a number of short courses [24].

3.1 Aerodynamics:

Numerical analysis combined with wind turbines is used to measure the aerodynamic forces on the turbine and rotor. The calculations are done using either the classical element momentum theory (BEM) or the recently developed generalized dynamic wake model. The theory (BEM) was built from two theories: the blade element theory and the momentum theory, both of which were used to measure the velocities caused on a wind turbine's blades. The hypothesis that the blade is divided into small, independent elements that behave as 2D airfoils is the foundation for the theory's success. Hence, the aerodynamic forces on each part are determined based on the local flow conditions. As a result, the number of forces and torques equals the force exerted by each part along the blade. The momentum theory also assumes that air passing through the rotor plane causes momentum loss in the rotor. We can measure the velocities caused by the lost momentum in the axial and tangential directions using all of this information. The internal flow in the plane of the rotor is affected by the induced velocities, which influences the forces acting on the wind turbine.

The theory has limitations, which makes it generally imprecise despite its simplicity. The expansion loads are ignored, and the forces acting on the element are assumed to be two-dimensional. As a result, if there are heavy rotor loads along the expansions, this will not be correct. When there are significant deviations, the theory also assumes that momentum is balanced in the plane parallel to the rotor, which contributes to modeling errors.

Another limitation in the theory is that the computations assume that the area across the airfoil is in equilibrium and will always react to the flow, when in fact, the airfoil takes time to adjust to the change. As a result, there is a time interval that must be adhered to.

A new dynamic stimulation model has been designed to overcome the limitations imposed by element and momentum theory. This theory has led to the development of a number of computational methods for calculating aerodynamic forces.

FAST is a horizontal-axis wind turbine simulation tool developed by the National Renewable Energy Laboratory (NREL). It was originally designed for static wind turbine dynamic analysis, but it has since been expanded to provide floating offshore wind turbines [16][25].

3.2 Hydrodynamics

3.2.1 Wave kinematics

Airy's linear wave theory, second and fifth order Stokes theory, and flow function theory are examples of kinematic theories. Because of its simplicity, most models use the linear wave theory, which calculates particle velocity, acceleration, and dynamic pressure satisfying the free surface boundary conditions with first-degree approximation. Stokes theory of second and fifth degree includes the inclusion of nonlinear higher degree terms. The kinematics of wave particles are restricted to the mean sea level (Z = 0) in the linear wave theory. The principle also applies to the average water level when Z is positive. The particles' velocity and acceleration in the apex, or trough area, are calculated and reduced.

Wheeler came with a stretch to calculate the forces between the free surface and the mean of the water level, to avoid a limitation in the linear wave theory.

As a result, point Z, which is used in the linear theory, changed to point Z ', which is the new point in which calculations have been shifted between mean sea level and sea floor, vertically relative to its height above the sea floor.

$$Z' = (Z - \eta)\frac{d}{d + \eta} \qquad (2)$$

Where: η the instantaneous height of the sea surface, d the level of the sea depth.

Dean developed the flow function theory for fully nonlinear wave kinematics [25]. Its applicability is more than the fifth degree Stoke theory. The theory uses the Laplace equation (the governing formula) there are two nonlinear conditions in this formula (constant pressure and wave height), thus it can completely solve the nonlinear water wave problem [26].

Theories (methods for solving wave problems), mentioned above are for small amplitude waves and a small range of nonlinear waves. As for the problems of waves that are not very linear in nature, when the waves enter a shallow water wave, and expose them to phenomena such as shallow water, break waves, or run over a slope, higher degrees of expansion are used at the fixed depth [26].

There are many ways to completely solve the nonlinear problem, one of which is to use the theory of potential flow with complete nonlinearity at the boundaries of the free surface. It is called the theory of fully nonlinear potential flow FNPF. Its applications are numerous such as water narrowing, wave breaking, and overturning by deep water, with good degree of precision. ADAMS, SIMO, SIMPACK are all based on linear wave theory. GH. Bladed used linear wave theory with free surface corrections using Wheeler dilation[25][26].

3.2.2 Hydrodynamic forces

To calculate the design loads of a wave, one must pay attention to the appropriate load model, wave kinematics and structural model.

Calculations of hydrodynamic forces in addition to these forces include hydrostatic recovery force, wave load on the structure, linear radiation adds mass and damping, while linearly deflection excites the incident wave.

Morrison's equation does the task of calculating wave loads in most cases within the time domain field. As a result, when applied to lean systems, several equivalent numerical models are used to measure hydrodynamic loads (the diameter of the structure is small in relation to the wavelength). The inertia and drag coefficient terms in the equation imply that the force is made up of both inertial and drag forces.

The parameters of the equation are determined by the flux characteristics and the surface roughness. When the drag force is high, Morrison's equation applies, with the inertial force proportional to the water molecule's acceleration and the drag force proportional to the water particle's velocity.

When the structure's diameter is large in comparison to the wavelength, the structure's presence is felt near to the fluid, and the diffraction of waves from the structure's surface must be taken into account.[27]. The possible flow theory was commonly used to solve the diffraction problem.

On the basis of a static wind turbine, Erik Jan de Ridder et al. conducted a study that focused on measuring the impact of wave loads. The study's methodology included developing a frequency domain method for calculating total stress damage. The method gave results that compare well with the results of the time domain, as it reduced the time required for the calculation by the computer to perform the fatigue calculation from several hours to only two minutes, which made it possible to improve the support system by adjusting the parameters and verifying the sensitivity of the design choices, lowering costs and risks dramatically. The study recommended further work to determine the size of aerodynamic damping more accurately [28].

Krishnaveni et al. published a report in 2017 with the main goal of estimating the initial dimensions of the wind turbine structure in the initial cost estimation to determine the project's economic viability. Via non-linear static analysis of the infrastructure, parametric studies were performed on various configurations of the circular monopile by adjusting water depths and sand properties, taking into account the aerodynamic and hydrodynamic strength of various structural factors and soil. The importance of the research comes through a simplified methodology that is applicable in the prior studies for the establishment of wind energy farms [29].

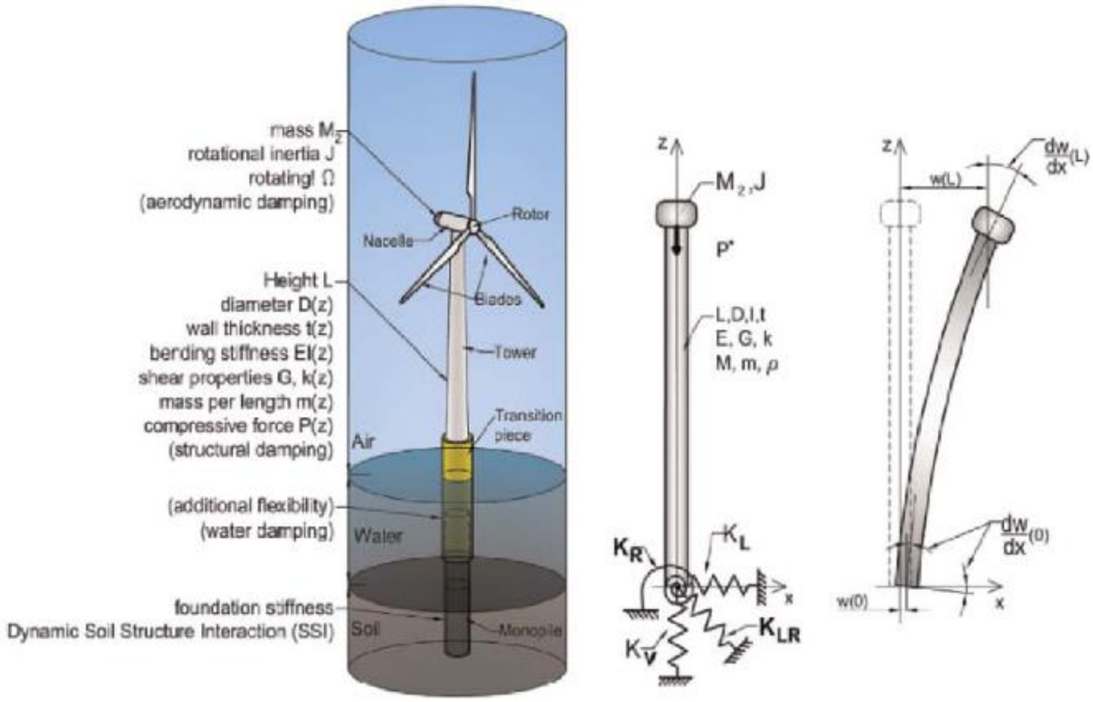

Figure 3. Simplified mechanical model of an OWT [29]

In the year 2020, Alwan et al. conducted research on the analysis of wave intensity on the basis of a mono-surface offshore wind turbine (NREL 5 megawatts), with the basis chosen in the middle water region with a water depth of 25 meters. The wave will be numerically simulated using the (AQWA) solver in the (ANSYS-19.0) workbench in accordance with the research methodology. The findings revealed that wave forces are linked to wave height and frequency, and that they increase as one or both of these factors increase [30].

4. Offshore wind turbine structures

As shown in Figures 4, 5, and 6, modern offshore wind turbine structures (OWTSs) are primarily made up of four components: blades, nacelle, tower, and support structure, with the tower carrying the nacelle and blade and the support structure transferring the placed loads on the structure to a subsea base. Despite the fact that the ability of using tall execution concrete or a half breed of prestressed concrete and steel has been demonstrated to make strides in the execution of structure of offshore wind turbines, compared to traditional tubular steel towers, most of the major wind structures are designed by funnel shaped tubular steel towers [31].

Offshore wind turbines must be located above the highest point of the most significant waves, with sturdy bolster connecting devices to the seabed by bases. For erection and upkeep work, submarine cables and other power transmission frameworks are needed, which may result in far higher costs for offshore wind installations than near shore towers.[6] Research to finance the floating wind turbine industry began in the mid-1990s, after William of the University of Massachusetts Amherst proposed the initial concept for these structures in the early 1970s [32].

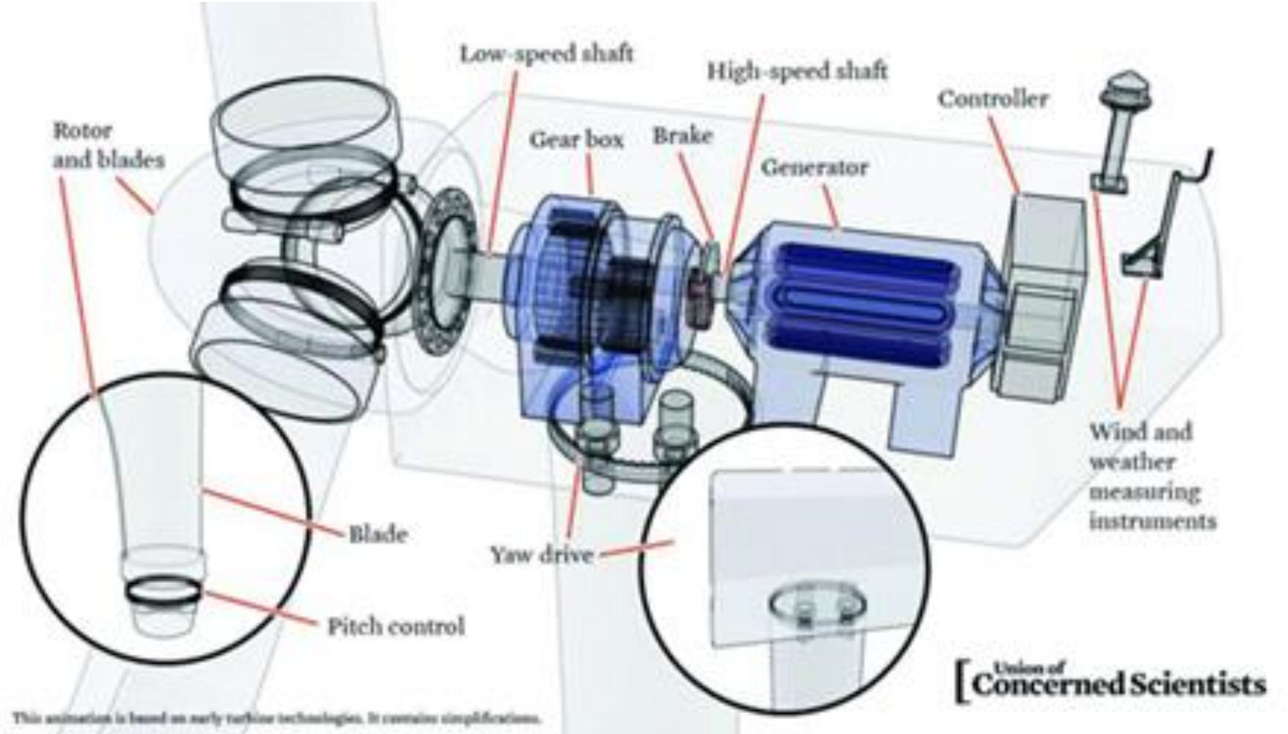

Figure 4. Components of an upwind-facing, horizontal-axis wind turbine with a gearbox motor, simplified [33]

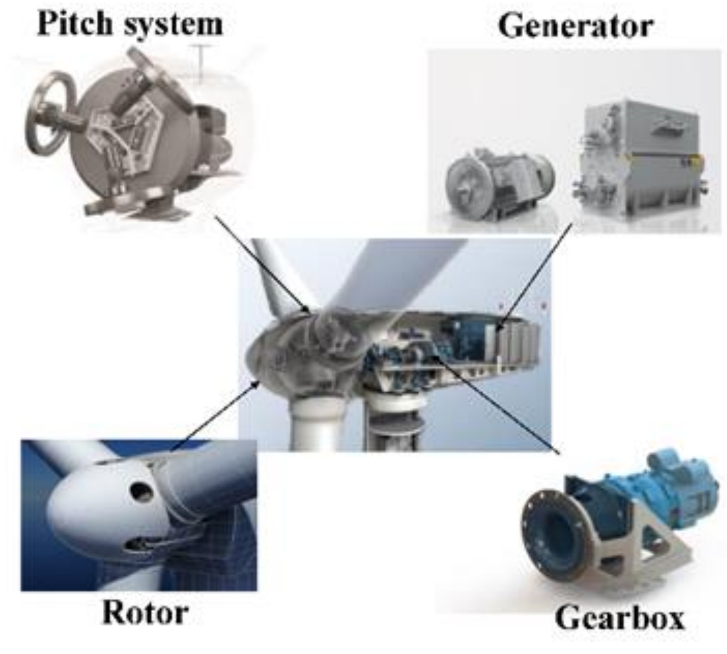

Figure 5. Components of the offshore wind turbine (OWT) system [34]

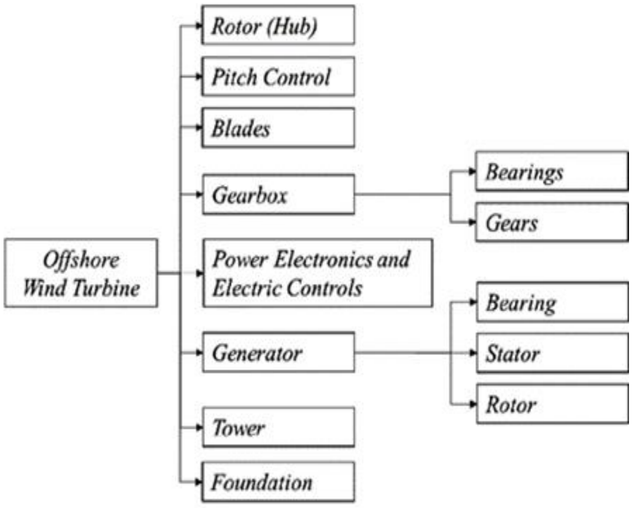

Figure 6. Subsystems and key components of an offshore wind turbine are broken down [35]

There is no consensus on the idea or kind of floating offshore winds that could be widely deployed in the future, according to both Straw Santos and Diaz Casas. As a result, it becomes apparent that there is a need for further research into the interest and care for floating wind technology before it can be widely used [36].
Tiny, medium, large, and giant wind turbines are categorized into small, medium, large, and giant wind turbines, and wind turbines are graded into variable speed fixed frequency wind turbines and fixed speed fixed frequency wind turbines based on operating characteristics and control methods.
Classification by operating mode:

- Wind turbines changeable pitch.
- A wind turbine with a static pitch.

Classification via structural features:

- Horizontal-axis wind turbine (HAWT), Vertical-axis wind turbine (VAWT), Cross-axis wind turbine (CAWT) [37].

It's important to remember that (CAWT) is still in the concept and design stage [38].

Table 1. Three different types of wind turbines [36]

Available wind turbines	HAWT	VAWT	CAWT
Wind path that is available	a single route (Need yaw mechanism)	All direction	Wind from every direction, including vertical wind
Self-start performance	Good	Poor lift-type Drag-type: Excellent	Good
Maintenance	Difficult	Simple and safe	Simple and safe
Quality of conversion	around 45%	Lift-type: About 40% Drag-type: About 25%	40%-45%

CAWT stands for cross-axis wind turbine; HAWT stands for horizontal-axis wind turbine; VAWT stands for vertical-axis wind turbine.

4.1 Stresses, and bending moment of the structure of offshore wind turbines

In 2010, Gkoumas K. et al. conducted a study focused on the theory of inquiry into the fundamental parts and core issues of offshore wind turbine structure design. Since offshore wind turbines are relatively complex structural and mechanical structures placed in a hostile climate, they use a system approach to incorporate structural parts design. To control quality and quantitatively analyze various sub-problems, the system (environment, configuration, loads) and structural performance were decomposed. For the purpose of comparison, numerical models were designed to test the safety efficiency under aerodynamic and hydrodynamic loads, using three types of turbine support structures: monopile, tripod, and jacket. The study produced findings, the most significant of which is that the macro-level model's results can predict the fundamental aspects of structural response. However, due to the key capabilities of the adopted finite elements and the high engineering accuracy of the models, the middle-level model offers an additional and more accurate image of structural action [39].

In 2011, Nicholson J. presented in his Master's thesis from the University of Lowa in the United States of America in which he mentioned the most important laws and relationships in calculating the stresses resulting from the different loads on the structure and foundation of the wind turbine. The message included important conclusions, such as how to use Microsoft Excel's enhancement principles and optimization capabilities to achieve realistic concept level designs with cost estimates, as well as how to consider the tower and base as an integrated device, which results in a more costly yet safer design [40].

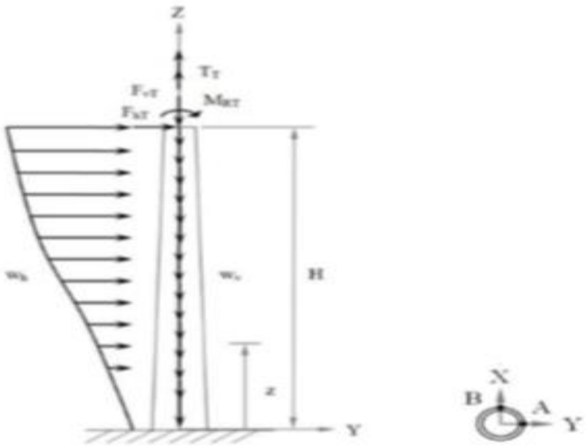

Figure 7. Assumed tower loading [40]

Bachynski E. et al. conducted research in 2017 on the analysis of nonlinear wave loads on single-surface OWTs in storm conditions, using two models of marine turbine structures in medium and shallow water depth conditions in the design. The approach that the researchers followed was an experimental one that included a solid model, a flexible model of the swing type and one degree of freedom. A high level of repetition is observed in the resonance events. The random difference in three-hour maximum bending torque at the seafloor was substantially higher than the random difference in repeat experiments [41].

Brennan F. et al. developed an inter-laboratory research program to describe the mechanical properties and fracture characteristics of S355 structural steel welds in 2018. The tests were performed on samples derived from each of the materials' three microstructures and included a Charpy test, chemical installation analysis, hardness examinations, tensile examinations, and a fracture stiffness examination. The tests are important because they measure the structural strength of OWT shafts. The impact energy values of Charpy and Jmax decreased as the yield stress increased from the base metal to the heat influenced region to the weld metal, according to the findings. Furthermore, the JIC fracture stiffness values in the heat influenced zone and weld metal are, on average, 60% higher and 40% lower than the base metal value. The findings are addressed in terms of the impact of material properties on monopile OWT structural design and safety assessment [42].

In 2019, Stieng L. et al. published a study on load condition reduction to determine the stress of offshore wind turbine supporting structures. They suggested a new approach for reducing the number of simulated ecological cases (pregnancy cases) while preserving reasonable accuracy. The proposal was based on a comprehensive fatigue study of a basic design, the OC3 monopile with (NREL 5MW turbine). The stress damage distribution can be used for each load condition to estimate the lifetime stress damage for this group of updated designs, which was applied to seven different designs that were modified in the simulation of the optimization loop iteration. The findings show that sampling less than 1% of all pregnancies will yield harm estimates with an average error of below 2%. Used the 3% of environmental conditions results in a cumulative error of 10% except for extreme conditions. In first-design and design-improvement applications, the approach is deemed suitable [43].

Trojnar K. published a scientific paper in 2019 focused on a new paradigm for OWT hybrid basises. The research was focused on the investigation of three-level hybrid bases. The research was able to establish the basis for evaluating the accuracy of the lateral rigidity of modern and low-cost hybrid bases for OWT using a small scale laboratory model, a full field investigation, and a three-dimensional simulation analysis. The phenomenon that occur in low-cohesion soils were also investigated, as well as a quantitative assessment of the laminate effect caused by horizontal force, and bending moment. The study's results helped to improve existing design methods for regular monopiles under side load [44].

In 2020, Huang S. et al. conducted their research into developing an innovative hybrid foundation to avoid the shortcomings of the conventional monopile for OWTS offshore wind turbines in harsh offshore environments. The research relied on a series of numerical analyses of the hybrid base, which consists of a traditional normal bucket and a shallow wide bucket, to investigate its behavior under static and dynamic loading while accounting for various loading deviations. According to the results of the dynamic response, adding the bulldozer to the base effectively reduces rotation and lateral displacement. The research also demonstrated the hybrid base's supremacy in terms of wave and current resistance [45].

In this review we only deal with horizontal wind turbines.

4.2 Horizontal axis wind turbine (HAWT)

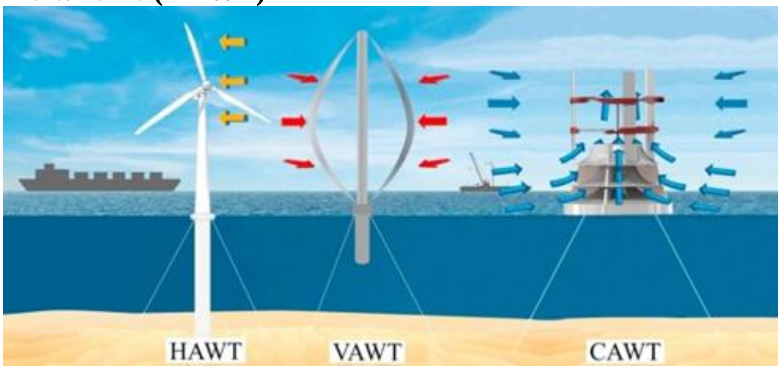

Figure 8. The HAWT, VAWT, and proposed CAWT are all examples of offshore wind turbine applications [38]

HAWT refers to wind turbines whose pivoting fundamental shaft of the wind rotor is parallel to the oncoming wind heading, as shown in Figure 8. In general, as the number of blades increases, the RPM and strength of the wind turbine decreases, while the strength increases [36].

Figure 9. China's biggest offshore wind farm [Colour figure can be viewed at wileyonlinelibrary.com]

Actually, the Haliade-X wind turbine, with a rated power of 12 MW, is the world's largest powering wind turbine [6].

The combined effect of gravity and inertial force causes the direction of gravity to remain unchanged as the blade rotates, but the inertial force's orientation changes constantly. As a result, the blade isn't exposed to a constant but rotating load, which is bad for fatigue resistance [46].

A variety of academics and researchers have worked on wind turbine blade optimization in the past. Hendriana and colleagues improved the wind turbine by adjusting the blade width and pitch angle of the inner and outer limits [47]. To reduce energy consumption and advance the overall execution of the blade, Zhu al et al proposed a multi-purpose aerodynamic and structural optimization process [48].

Mohamed et al. propose a system design for tiny HAWT blades, and the technique was used to enhance the chord and twist distributions of wind turbine blades, thus increasing the wind turbine's aerodynamic efficiency and, as a result, the produced power [49].

Israa Al-Esbe et al. studied the erratic flow activity of HAWTs in two cases in 2016. The rotor was the first example. The rotor with the tower was the second case, which was solved using a panel method and a RANSE method. The RANSE solver ANSYS CFX 14.5, which simulates viscous flow, is used. The first case's results allowed for the calculation of global integral torque and thrust values, as well as descriptions of the local flow area. The use of viscous and non-viscous flow methods allowed for the prediction of forces on HAWT, as well as the evaluation of viscous effects on HAWT measured flows [50].

Jackson et al have through a study mission in 2017, an experimental simulation of the HAWTs small, have investigated the impact of low-speed beyond wind turbines on energy production. and the efficiency of the wind farm. The Reynolds stress model (RSM) for shutting off turbulence was successfully applied to completely different wind turbines and produced an accurate and numerically stable solution, according to the report. The relationship between the tower and the rotor has been shown to cause substantial turbulence that may be present in the long run, both experimentally and via wind tunnel studies. As a result, in CFD simulations, tower effects should not be overlooked [51].

In 2019, H. Tang et al. published a paper in which they investigated the wake characteristics of HAWT a 3-blade and the influence of static on the turbine's output in a wind tunnel. The paper came out with five good and important results, the most important of which came in the fifth point, which was the focus of the research greatly. It concentrated on the waking properties of wind turbines whose efficiency was solely measured in terms of energy generation. The Reynolds number in wind tunnel tests was also much lower than in most commercial wind farms, according to the study [52].

In 2019, Castellani et al, conducted their experimental and numeric research on the yawning behavior of HAWTs to understand the dynamic behavior of these types of turbines. The experiments were conducted on a small 3-bladed HAWT model with a rotating diameter of 2 meters in the wind tunnel of the University of Perugia. They were selected for two numerical groups, the first is a special symbol based on the theory (BEM), and the second is the aero-elastic simulation software (FAST) program. The wind turbines in the wind tunnel were subjected to a constant air time series of three different diffraction angles with respect to the wind flow: 45, 22.5, and 0 degrees. Where was looked at power factor Cp, thrust coefficient Ct. The research produced useful results after comparing the results of the experiment with the predictions of numerical simulation, the most notable of which is an increase in information about the static behavior of HAWT under diffraction outputs conditions, as well as the limits of low resolution models in reliably repeating the dynamic characteristics of HAWT [53].

5. Offshore wave energy converters' benefits and drawbacks

Onshore wind energy has advanced significantly over the years, but with the limited space available for onshore wind turbines, offshore wind power has become critical to the production of wind energy.

- ❖ Basic advantages for offshore wave energy converters (OWEC):
- A strong breeze.
- Consistent wind direction.
- There is no wind shear.
- Offshore wind noise is low.
- A lot of output.
- They are near the load core, and hence, easy depreciation of the power grid [54][55].
- It does not occupy areas of land.
- • Since the air speed at sea is 25% higher than on land near the sea, power towers can be reduced [56].
- ❖ Disadvantages of offshore wave energy converters (OWEC):
- ❖ Despite the positive future growth, the OWEC framework is not without its difficulties [57]. The following are the major drawbacks to the production of OWE:
- **Expensive OWEC equipment installation and preservation**

The prices of constructing wind farms vary from one farm to the next, since they are determined by the project and its circumstances. In the sea wind projects are typically much more expensive than land wind projects.[36] Companies working in the field of developing OWT models are already working to decrease the cost of in the sea wind farms, with the issuance of investment decisions to the governments of several countries, and the results are inspiring optimism and excellent prospects [5].

- **Turbine base technology**

The high technological standards for OWT foundations are also a major stumbling block to the production of OWE. The requisite shapes of OWT foundations are floating and fixed, and there are several unique shapes for fixed and floating turbine bases, which have been compared in Tables 2 and 3. The fixed form is primarily used in shallow waters and marine areas with suitable geological conditions, and the floating type is primarily used in shallow waters and marine areas with suitable geological conditions. Monopiles, for example, have a depth limit of 20 to 30 meters.[58] The floating wind power base is ideal for deep sea regions, where certain environmental condition on the seabed make the static form unsuitable. Most offshore installations, including the 160 MW wind farm in Horns Reef on Denmark's west coast, use monopoles [59].

Table 2. List of fixed turbine foundation [36]

Foundation type	Applicable water depth	Technical maturity	Impact on the environment
Steel pipe with a single pile foundation	Shallow to medium water depth	Proven technology, small structure	Owing to a combination of water depth and seabed surface conditions, piling creates underwater noise, which could be theoretically impossible.
Gravity foundation	Shallow to medium water depth	Known and proven technology	A large number of dredging and seabed preparations will affect the water quality and affect the bottom ecology
Tubular foundation	Shallow to deep water	There is less offshore equipment available, and it is simple to install and remove.	No major harm
Multi-pile foundation	Medium water depth to deep water	Known and proven technology, no need to prepare for the seabed	The bottom noise created by pile driving would have an effect on marine life, and it might not be possible to pile drive at the top of the deep water / shallow rock layer.

Table 3. A list of float turbine bases [36]

List of float turbine bases	Suitable for water depth	Positioning	Advantages	Disadvantages The
Spar	≥100 m	Mooring	Good heave output, low vertical wave power, and base draught	Because of the small area of the waterline, the roll and pitch motion response is relatively high. This results in a large, large installation size, which is difficult to produce and inconvenient mobile and expensive.
Semi-sub	≥50 m	Mooring	Good stability, dependable service, simple construction and installation, and a wide range of water depths suitable	Large-scale structure, large-scale wave load, and large-scale motion response
Tension Leg Platform	≥50 m	Tension leg	Good stability and low dynamic response to wave force	The tension of the tension leg varies with the tide, making it possible to come into contact with the foundation coupling. The mooring mechanism is often complicated and costly.

Applications based on gravity, such as the 160 MW Nysted project in Zeeland, southeastern Denmark, and the Samsoe project in northeastern Denmark [60].

The structural load of the floating offshore wind turbine has increased significantly due to platform movement caused by turbulent wind and waves. As a result, a number of researchers have looked into the vibration damping of floating wind turbines in detail. For example, Wu et al used dynamic dampers to create floating offshore wind turbines with tension-leg platform stability and reduced vibration.[60]

For fixed wind power, the cost of the unit, foundation construction, heaping, and raising, among other things, is generally fixed in size, and the optimal opportunity is limited. Although coasting wind control has fetched optimization, a floating wind turbine arrangement can be used for general establishment and by and wide towing without heap grapples under the introduction of ensuring execution, which can reduce the cost of creation and establishment. At the same time, the costs and risks of gear, production, service, and maintenance have increased as the seaward wind control industry has progressed. According to the International Energy Agency's (IEA) predictions, the cost of improving and developing offshore coasting wind control will be reduced by about 50% by 2050 [61].

Wind power has been one of the most cost-competitive choices for new generation capacity due to technological advancements and cost reductions. Wind energy also has a lot of cost-cutting potential. Indeed, the global weighted average cost of electricity (LCOE) for offshore wind could drop by 35% by 2025 [62].

- **Wind power fluctuation**

When a wind turbine's asynchronous generator sends dynamic control, it absorbs reactive energy from the device, creating a load on the power grid [63].

- **profound-sea energy transmission**

Also, one of the factors limiting the development of offshore winds is the problem of transmitting energy in the deep sea [64]. As a result, it was important to focus on expanding the power transmission network and improving the level of power transmission and storage network construction in order to improve OWE. High direct current technology used voltage (HVDC) which have advantages over (AC) technology, featuring many advantages, including high reliability, good stability of, few losses, there is no interactive energy [65][66].

6. OWT foundations

The foundations of marine wind turbines are one of the most significant pillars of their designs. The construction of foundations for supporting OWTs started with foundations for the offshore oil and gas sector is a multibillion-dollar industry[67]. OWTs are also about twice as expensive as onshore turbines, and the cost of foundations and towers is higher in OWTs than onshore [20].

Set foundation wind turbines, such as gravity base, monopile, jacket foundations, and tripod foundations, are currently used in most offshore wind farms and are built at water depths of less than 50 meters [25].

Many coastal countries, including Japan, the United States of America, and Western European countries (located on the Atlantic coast), have coastal territorial waters with depths of just under 50 meters. As a result, in the last decade, these countries' emphasis has shifted to the use of floating offshore wind turbines.

Figure (10) depicts examples of traditional offshore wind turbine support structures in different water depths. Similar to offshore oil and gas platforms, the supporting structures are often made of welded tubular steel members. The design and structural specifics of the oil and gas platforms, on the other hand, vary from the second since the first was designed to minimize aerodynamic loads, while the second has the effects of high aerodynamic loads caused by rotational forces and thrust acting on the blade [68][69]ز

The supporting structures of OWTs are often derived from structures in the oil and gas sector.

Figure (10) shows how OWT structures can be divided into bottom-fixed support structures and floating support structures from a structural standpoint.

Bottom fixed supporting structures (strictly linked to the bottom):

1 - Structures that are based on gravity.

2- Structures made up of monopole.

3 - Multipod is a term used to describe a (i.e. tripods and braced frames).

4 - Buckets for sucking.

Floating Support Structures:

1 - Spar floater.

2 - Platforms that are semi-submersible and have friction legs.

The appropriate support structure shall be approved or chosen according to the specific site for the construction of the marine farm, in terms of water depth and geotechnical conditions [15].

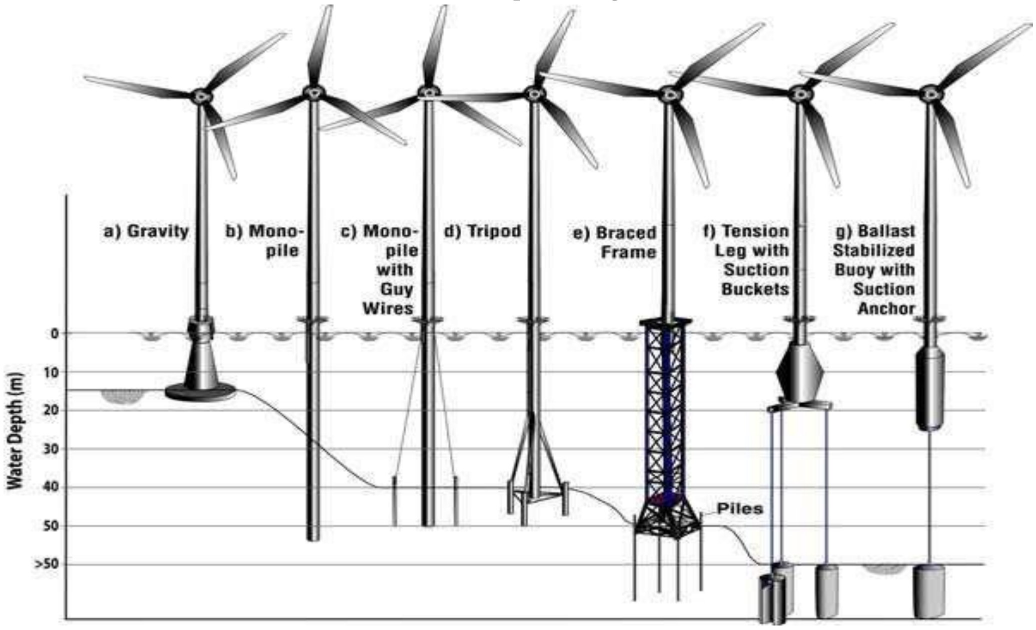

Figure 10. Support structure/foundation options for OWS, as well as their water depth requirements [70]

The (GBS) is the first type of static support structure developed to support (OWT) in very shallow waters (less than 20 meters). These structures are usually made up of a wide steel pipe pile with a concrete slab base connected to the sea floor by low cut tops. This form, as shown in Fig. (10a), relies on its own weight to resist overturning loads and hold the wind turbine tower upright [54].
While (GBS) overcomes structural versatility better than monopoles in shallow waters (less than 30 meters), the cost of their construction increases rapidly in deep waters, and they are extremely sensitive to sea conditions. Monopiles have a straightforward nature and are inexpensive [71].

6.1 The monopile foundation
For example, in an offshore wind farm, it may be a wide diameter steel pipe with a diameter of up to 7.4 meters and a wall thickness of up to 150 mm [15]. Due to the existence of one end of the monopile on the sea floor, the tube pile is attached to the wind tower directly or via a transitional piece via a wadding link. This foundation resists the periodic lateral loading and moment loading of the wind turbine through the packed horizontal soil compaction on the combined length. One of the advantages of the monopile foundation system is the fast installation speed, its installation speed reaches 24 hours.[72] It also has little local and environmental impact [73]. Tension wires are used with the base of monopiles in deep waters, as shown in figure (10c), to reduce the monopiles' lateral flexibility and thus help stabilize the wind turbine[74].
In 2017, Mingjun Bi. conducted a research study of NREL 5MW offshore wind turbine modeling, and analysis and design using SACS (Computer System for Structural Analysis) for the purpose of nonlinear static analysis and multivariate MLRA (linear regression analysis) using statistical tools, such as MS Excel and Minitab, the study data were available from the NIWE published literature, and for turbines, such as those used on the Gujarat state farm, although the study did not correctly understand the response of monopiles under dynamic load, but it provided a precise calculation of the design's preliminary study of monopiles (OWTs) for a specific site, and thus equations and extensive diagrams for the rapid initial design of a monopile are reduced, reducing the effort and time needed for a pre-feasibility analysis [73].
Hallowell et al. conducted their significant research in his data in 2018, which included parts of the nine offshore wind farms dotted along the Atlantic coast within the United States of America. This is to address a gap in quantitative hurricane risk assessments for offshore wind turbines (OWTs). The risk was assessed using a methodology adapted from a well-known performance-based earthquake engineering framework.
The study found that for hurricane-induced winds and waves, the risk of structural failure of the tower or mono of the OWTs built inside the nine wind farms varies between 7.3 10-10 and 3.4 10-4 for a functional yaw control system and between 1.5 10-7 and 1.6 10-3 for a non-functional yaw control system over the average lifespan (i.e. 20 years) [75].
Sergio Sanchez et al. published a study of offshore wind power installations around the world in 2019, highlighting the various types of foundations used. As a result, a database was developed, and the data was processed to construct a clear diagram that illustrates the existing use of various types of foundations, taking into account distance to the coast and water depth. The paper included an examination of monopile construction design and requirements, as well as the specifications of offshore wind turbines and the monopiles that support those turbines. The paper came to six major conclusions, the most critical of which is that monopiles are still the most popular alternative in use today (60% of offshore wind foundations around the world) [32].
Frick Dennis et al. published a pilot study in 2020 in which they provided a brief summary of existing design code practice as well as other proposed methods for predicting anomalies or cumulative rotations. Furthermore, a typical systematic study was identified and evaluated that dealt with the reaction of a monopile to lateral cyclic loading in medium density sand with various cyclic loading ratios. The study included the results of a wide range of experiments on side-loaded sand piles using a small 1 gram model.

The study came to four conclusions, the most important of which is that the explanation for the increase in asymmetric loading accumulation rates is bidirectional, as observed by PIV deformation patterns in the soil around mono mass. Around the mound, the net soil pressure is at its lowest. More studies should be carried out to prove this theory, according to the researchers [76].

In 2020, Song and colleagues used RTHS technology to conduct a hybrid simulation to test the efficiency of the structure of (OWTs), which is a challenging task due to the simultaneous loading of both wave and wind, as well as the difficulty of reproducing the conditions of this loading in the laboratory, and provide real-time RTHS hybrid simulation. A new place for the study of the structural behavior of OWTs, which incorporates physical testing and numerical simulation in real time. The study presented useful details for potential implementation and advancement of RTHS technology for similar marine structures, thanks to the proposed framework and sensitivity analyses [77].

Cevasco D. et al. presented a thorough analysis and discussion in 2021 to identify essential components of the currently installed generation and the next generation of offshore wind turbines. Initially, a systematic review of the reliability, availability, and maintainability of onshore and offshore wind turbine data was performed, with the findings gathered from 24 initiatives. The study contained a lot of considered and related sources on the topic of onshore and offshore wind energy. It came with the recommendations of the study on offshore wind energy. Despite the fact that there were more delays in general than onshore projects, statistics recently obtained from the industry-led RAM database indicate an increase. When compared to the first generation of marine turbines, there is a significant increase in operational availability. Another relevant subject covered in the study was estimating availability for offshore wind farms. The disparity between expected results and literature reference values suggests that a high degree of detail is needed [78].

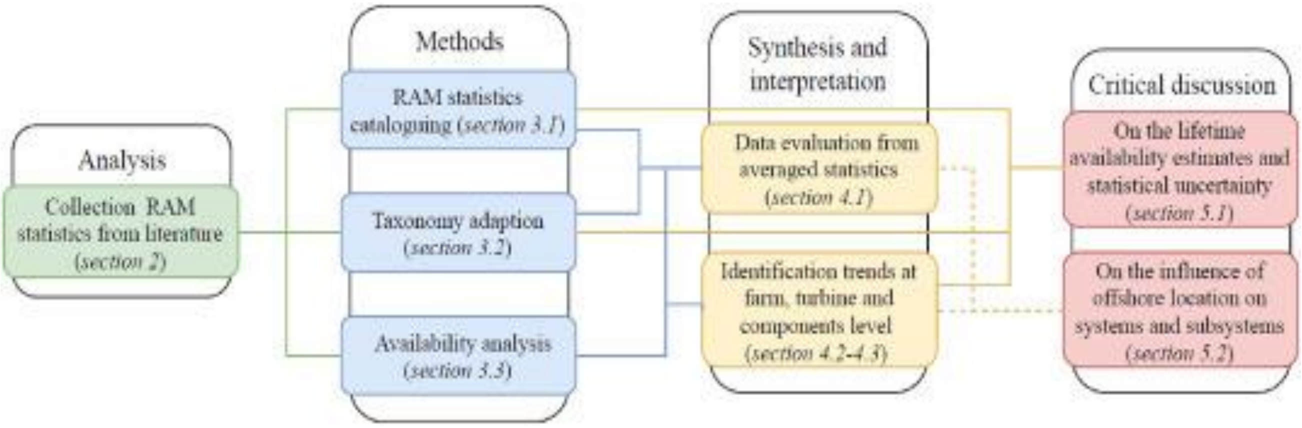

Figure 11. Methodological framework [78]

7. Discussion and conclusion

The analysis paper examines the most significant economic and industrial innovations in the field of offshore wind energy design and manufacturing, which now play an important role in the provision of clean renewable energy. The recent expansions in the capacity of electric energy produced from wind energy in the field of offshore wind energy, as well as the scope of growth over two decades, were discussed. They also discussed the most important computational theories used to quantify the wind loads and wave loads affecting offshore wind turbines and their support structures by listing the common words for theoretical calculations. The analysis emphasized the most important benefits and drawbacks of offshore wind energy, as well as the flaws, so that they could be studied and suitable solutions developed. Since monopile support structures are the most common and widespread in offshore wind farms around the world, the paper based on previous research studies that focused on them.

The review concluded through reports and research, that countries interested in manufacturing and constructing offshore wind turbines continue to support research of various kinds (simulation, experimental, numerical analysis, etc.), but this research is lacking in approaching reality by building experimental farms that operate as gigantic laboratories.

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