Review and Evaluation of Offshore Wind Energy: Resources, Markets and Technologies

Qiang Gao, Nesimi Ertugrul, Boyin Ding

Abstract— **Offshore wind energy is rapidly emerging in the global shift towards sustainable energy, offering vast potential to meet increasing energy demands with minimal environmental impact compared to other onshore renewables. Australia has demonstrated world-class offshore wind potential; however, its industry remains relatively immature compared to major offshore wind regions in the EU and Asia, particularly in terms of resource assessment, technology readiness, market development, and regulatory framework. This paper aims to provide a comprehensive review and evaluation of offshore wind, encompassing resource assessment, market development, and technological advancements, offering valuable insights for major stakeholders in Australia. This study first reviews global offshore wind development, highlighting regions with significant wind resources, and then examines the offshore wind resources and potential markets in Australia. The key technologies in offshore wind, including wind turbine generators, foundations (both bottom-fixed and floating), power electronics, control topologies, and transmission technologies, are comprehensively evaluated and discussed with a focus on development in Australia.**

Keywords— **Offshore wind resource, Offshore wind markets, Offshore wind technologies, Review.**

I. Introduction

RENEWABLE energy development has experienced significant growth and increasing competitiveness in recent years, propelled by the imperative to address climate change and to achieve net zero targets and to meet rising energy demands for economic progress [1]. As the onshore wind energy resources have saturated, offshore wind stands out as abundant to provide long-term contributions to future energy supply. Some of the primary reasons for this uptake are that offshore wind offers unique benefits, including stronger and steadier wind resources, feasibility for larger wind turbines (WTs), and minimized conflicts over land use and community acceptance. Therefore, offshore wind is rapidly growing, with installed capacity increasing over 20% each year, reaching 35.3 GW by 2020, and is projected to exceed 380 GW by 2030 [2].

Offshore wind technology has been extensively studied and reviewed and is emerging at an increasing rate, and far-shore development has also attracted significant research efforts. These activities include the further modelling techniques [3], floating structures and foundations [4]–[6], and the application of scaling laws for floating structures [7]. The electrical conversion systems associated with offshore wind have also been reviewed for different subsystems, such as the electrical collection system [8], power electronics [9], and transmission systems [10]. Moreover, the feasibility of offshore wind energy has been conducted via a lifecycle financial analysis model with detailed cost components [11], [12]. Additionally, a multi-criteria evaluation framework has been employed to assess the viability of offshore wind projects [13].

In late 2022, the Australian government introduced a suite of regulations [14], [15] designed to streamline the licensing process, spatial referencing, treatment of infrastructure, and regulation fees for offshore renewable energy projects. These regulations aim to boost investment and provide greater regulatory clarity for developers in the sector. Concurrently, the Australian Energy Market Operator (AEMO) published its engineering roadmap to achieve 100% instantaneous renewable generation by 2030 [16] and identified several offshore renewable energy zones in its 2022 Integrated System Plan for the National Electricity Market [17]. This period also saw a surge in offshore wind farm proposals along the Australian coastline, culminating in the granting of feasibility licenses to six projects in May 2024, enabling them to begin detailed assessment work. Other projects remain in the pre-planning phase. On a regional level, the state of Victoria made notable progress toward its offshore wind energy targets in 2022, with plans to

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develop at least 2 GW by 2032, 4 GW by 2035, and 9 GW by 2040 [18]. Victoria is in a leading position in establishing Australia's first offshore wind industry, backed by a new implementation statement and forthcoming announcements for 2023. These initiatives cover critical aspects such as transmission infrastructure, port development, local supply chains, and legislative support [19]. Since a variety of initiatives and policies have been initiated in recent years, it is anticipated that the offshore wind industry is anticipated to grow significantly in Australia in the following decades.

To support offshore wind industry development in Australia, the primary aim of the paper is to provide a comprehensive review and evaluation of offshore wind energy, which covers resource assessment, market development, and technological advancements, offering valuable insights for major stakeholders in Australia. The paper thoroughly examines critical offshore wind technologies, including wind turbine generators, foundations (both bottom-fixed and floating), power electronics, control topologies, and transmission technologies, with a particular focus on their suitability in the Australian scenario.

The structure of this paper is below: Section II introduces an overview of offshore wind energy resources potential globally and in Australia's offshore regions, followed by Section III, which examines the offshore wind market development and costs parameters globally. This section also presents a review of offshore wind energy development in Australia in terms of development targets and a framework for regulations. Section IV focuses on the state-of-the-art offshore wind energy technologies, including turbine generator, foundation, control topology and network connection and transmission systems. Section V concludes the research.

II. OFFSHORE WIND ENERGY RESOURCES

As illustrated in Fig. 1, offshore wind energy resources are primarily concentrated in the middle to high latitudes, forming an east-west belt that spans across the westerlies of both the Southern Hemisphere and the Northern Hemisphere. These regions hold significant importance for the utilization of offshore wind energy. Notably, there are noticeable seasonal variations

in global offshore wind resources. During the winter season (DJF), the Northern Hemisphere exhibits relatively higher wind power density, surpassing 800 W/m2, compared to the Southern Hemisphere. Representative regions with notable wind resources include the North Atlantic, the North Sea, Western Australia and the Northern Pacific. Conversely, during the summer season (JJA), the Southern Hemisphere experiences higher wind power density, particularly in regions such as Southern Australia, Southern South America and Southern Africa, which are of great significance for the utilization of offshore wind energy.

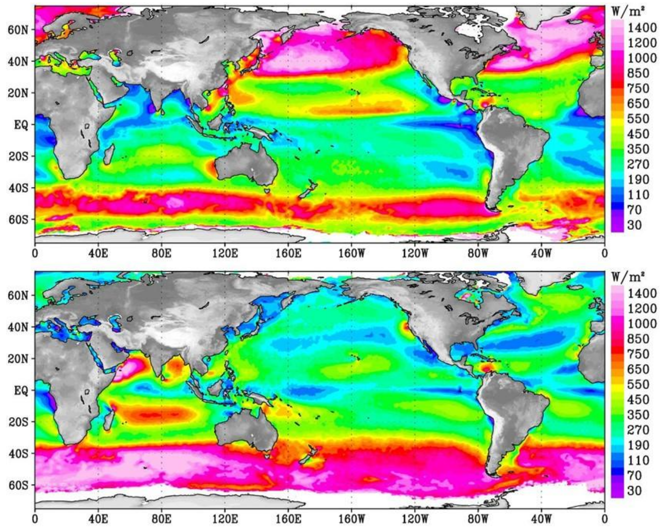

Fig. 1 Offshore wind power density over global oceans for winter (top) and summer (bottom), by NASAJPL [20].

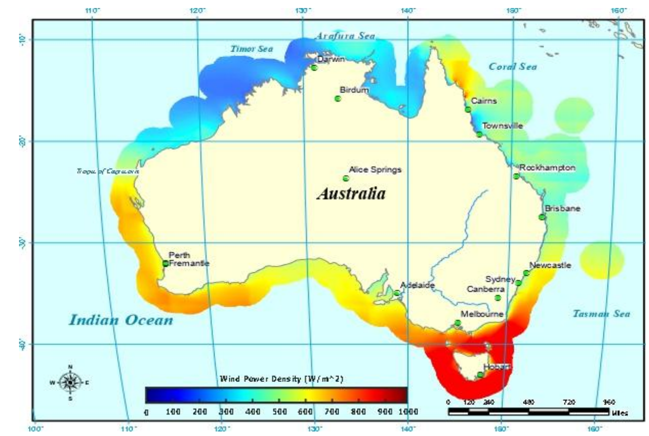

Fig. 2 Distribution of annual mean wind power density in Australia, adapted from [21].

Offshore wind resources are abundant in the Australian region. Fig. 2 shows the offshore wind power density map at 100 m height in Australia. It can be seen that offshore wind energy is more abundant in the Southern Australian coastal region compared to that in Northern Australia, particularly in Southeast Australia (covering part of South Australia, Victoria, Tasmania and New South Wales), with an average of above 800 W/m2 and South of West Australia with generally ≥ 700 W/m2). Additionally, according to the international standards for wind speed defined by the International Electrotechnical Commission (IEC), Class I (High Wind) are observed in these regions, which have an annual average wind speed of over 10 m/s [21].

III. OFFSHORE WIND MARKET DEVELOPMENT

Globally, the offshore wind energy sector has experienced significant growth over the past decade. Fig. 3 illustrates the new offshore wind installations and accumulated capacity worldwide from 2011 to projected figures up to 2031. The data shows an annual increase of 21% in installed capacity over the last decade, with a projected total of approximately 370 GW of offshore wind capacity by the end of 2031. Additionally, the share of offshore wind energy in global new wind capacity is expected to rise from 23% in 2021 to 30% by 2031 [23].

Based on the cost database from the International Renewable Energy Agency (IRENA) [28], the global

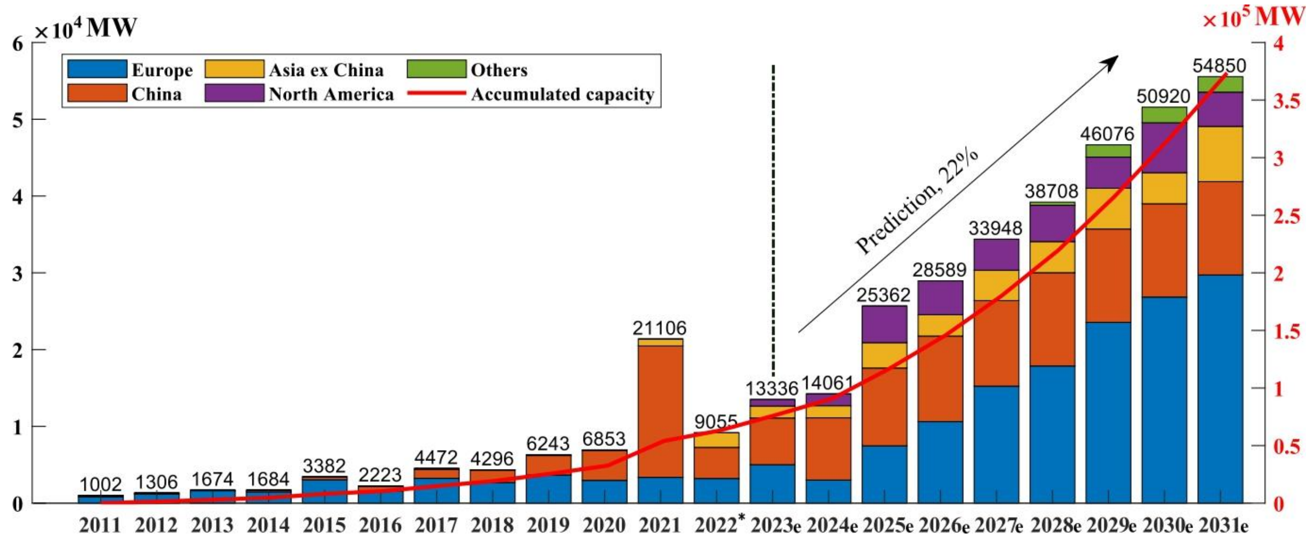

Fig. 3 : New offshore wind installations and accumulated capacity, global from 2011 to 2021 and estimation from 2022 to 2031 [22].

Notably, 2021 marked a new record in the offshore wind industry with the connection of 21.1 GW of offshore wind to the grid worldwide. China remained at the forefront, installing nearly 17 GW of new offshore wind capacity in 2021, which was driven by a policy change implemented in May 2019, indicating that offshore wind projects would no longer receive feed-in tariffs from the central government starting in 2022. Looking ahead, Europe, China and the rest of Asia are expected to be major players in the offshore wind industry. Global Wind Energy Council (GWEC) estimates that by the end of 2031, Europe will lead offshore wind development with an annual new installed capacity of over 29.3 GW. Asia is projected to have a new market capacity of 19.1 GW in 2031, with China accounting for 12 GW of that capacity in the same year. North America is also anticipated to have 4.4 GW of offshore wind capacity. Additionally, emerging markets such as Ireland [24] and Australia [25] show great potential for offshore wind energy development. For instance, in Australia, over 2000 GW of offshore wind potential is available within 100 km of the existing electricity substations [26], and supportive policies [27] and clear targets [19] are defined in recent initiatives.

Offshore wind energy generally incurs higher total costs compared to its onshore counterparts. The installation and operation of offshore WTs are particularly costly due to the challenging marine environment, requiring specialized vessels and technicians. Additionally, the equipment costs associated with offshore WTs and foundations are considerably higher compared to onshore wind, with approximately 20% and 350% higher costs, respectively [4]. Moreover, obtaining permits and environmental licenses, as well as managing the logistical and supply chain, can be complex, time-consuming and/or costly. Consequently, offshore wind projects necessitate robust infrastructure and supply chain requirements, including suitable ports and transmission facilities.

weighted average total installed cost of offshore wind has experienced a significant decline, decreasing from 5025 USD/kW in 2015 to 2858 USD/kW in 2021. Regarding the levelized cost of energy (LCOE), the global weighted average LCOE of offshore wind has decreased by approximately 60%, going from 0.188 USD/kWh in 2010 to 0.075 USD/kWh in 2021. This notable cost reduction can be attributed to three primary factors. Firstly, advancements in WT technology have enabled the deployment of larger turbines situated farther from the shore, resulting in increased energy production. Secondly, the industry has gained substantial project experience, fostering competition among market players. Lastly, strong regulatory and financial support, including favourable policies, subsidies and the establishment of an optimized supply chain and labour market, have contributed significantly to the cost reduction in offshore wind energy.

Currently, no existing commercial offshore wind farm constructed in Australia waters. To facilitate offshore energy development, Australia Government has proposed or declared six offshore energy zones, including the Gippsland and Southern Ocean Offshore zones in Victoria, Hunter and Illawarra Offshore Zones in New South Wales, Bunbury Offshore Zone in West Australia and Bass Strait Offshore Zone in Tasmania. The total offshore wind energy potential in these declared or prioritised zone is over 100 GW.

IV. OFFSHORE WIND TECHNOLOGY

A. *Wind Turbine Generator Technologies*

As it is known, power generated by WTs, whether they are onshore or offshore, is directly proportional to the cube of wind speed and the square of rotor diameter. Therefore, larger WTs have the capability to harness more wind power while occupying less space compared to an array of smaller turbines, which also benefit from higher

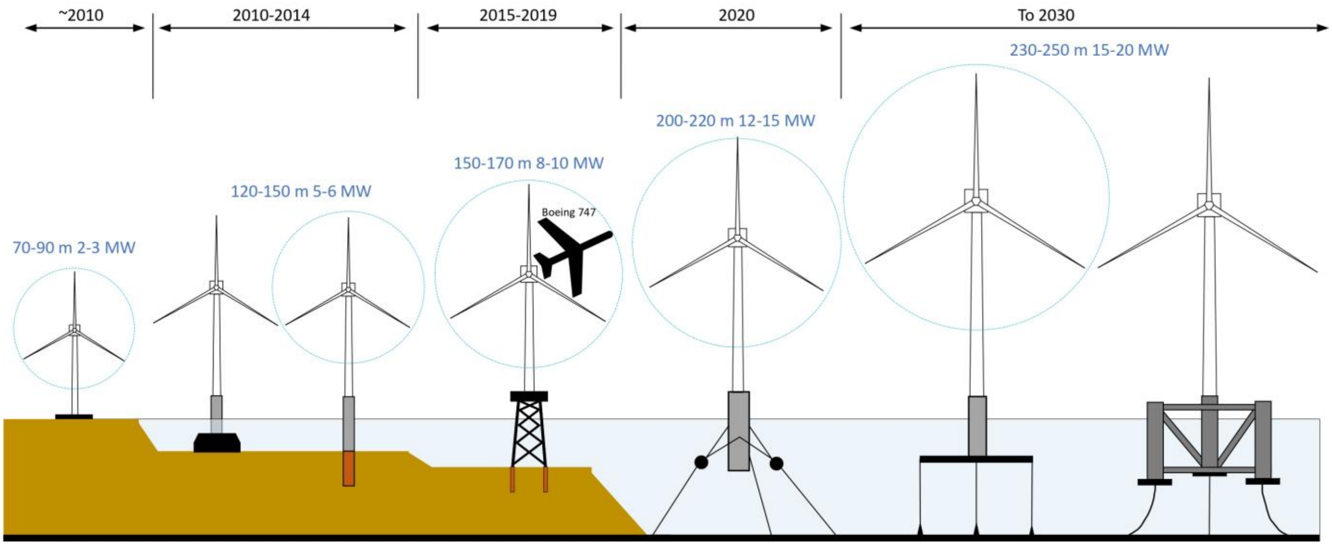

Fig. 4 Different topologies of WT sizes and foundations from left to right: Onshore reference, Gravity-based type, Monopile type, Jacket type, Spar type, Tension leg platform and Semi-submersible platform.

and consistent ocean wind resources. These two factors have driven the continuous increase in the size of offshore WTs, evolving from hundreds of kilowatts to 14 MW [29] and beyond 16 MW [30]. Analysis by the GWEC reveals that the average size of offshore WTs worldwide surpassed 1.5 MW in 2000, then increased to 2.5 MW in 2005 and reached 6.0 MW in 2020. However, it should be noted that China and Vietnam have installed a significant number of smaller offshore turbines. By excluding these installations, the average rating of new turbine installations in 2021 was 8.1 MW. Projections indicate that the average turbine rating is expected to surpass 12 MW by 2025 and potentially reach 20 MW by 2030.

The primary driving force behind this trend of increasing turbine size, as depicted in Fig. 4, is imperative to reduce the LCOE and enhance the competitiveness of offshore wind compared to other renewable sources such as solar and onshore wind. Notably, a larger WT with a higher power rating and taller tower can significantly augment annual energy production. Furthermore, it reduces the number of turbines required for a given capacity wind farm, resulting in decreased capital expenditure for foundations, inter-array cables, installation and operations. Additionally, the utilization of fewer specialized vessels and technicians contributes to reduced OPEX. By leveraging these advantages, the offshore wind industry strives to enhance cost efficiency and solidify its position as a competitive renewable energy resource.

Fig. 5 provides an overview of various generator types used in offshore wind systems, categorized based on electric machine topology: synchronous generator and induction generator. These generators can be further classified based on different criteria such as direct-drive (DD) machine versus geared machine (related to drive-train technologies), variable speed generator versus fixed speed generator (related to speed control) and fully-rated (fill-scale) power control generator versus partially-rated power control generator (based on power electronics topologies).

The fixed-speed squirrel cage induction generator (SCIG) is the oldest and simplest generation technology utilized in the wind industry. The doubly-fed induction generator (DFIG) technology, which was commonly used in onshore wind farms in and higher efficiency [33], [34]. In a DD PMSG wind turbine, the blades are directly connected to the low-speed generator, typically rotating at around 20 rpm, as exemplified by Siemens Gamesa's SG 14-222 DD [35] and GE's Haliade-X 12-14 MW [29]. In an MS PMSG-based wind turbine, the generator rotates at speeds ranging from approximately 100 to 500 rpm, often coupled with a compact gearbox featuring fewer stages. Notable examples include GoldWind's 16 MW [30] and Vestas' V236- 15 MW [36]. It is noted that as the most

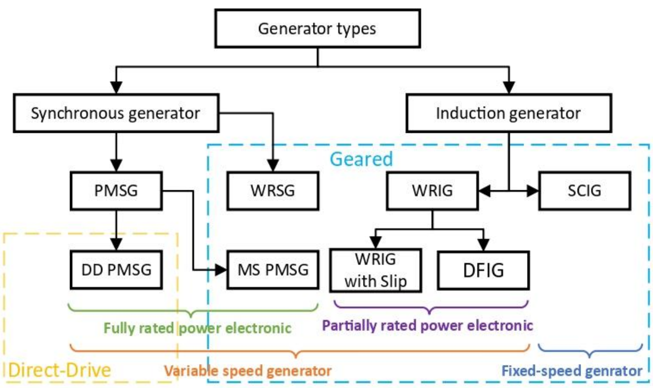

Fig. 5 Types of generators used in WTs: Permanent magnet synchronous generator (PMSG), wounded rotor synchronous generator (WRSG), wounded rotor induction generator (WRIG) and squirrel cage induction generator (SCIG).

offshore wind projects proposed in Australia are in their early planning and feasibility study stage, the adoption of DD/MS topologies appears to be the mainstream for deploying large size wind turbines with size over 10 MW. These technologies replace the conventional gearbox arrangements and hence has significantly reduced drive-

TABLE I COMPARISON OF MAJOR WIND TURBINE TECHNOLOGIES [9], [31], [32]

Generators	Advantages	Disadvantages
SCIG	• Simple and robustness in construction • Low initial and operation cost • Metallic rotors are resistant to vibration and dirt	• Limited to high-speed operation • Need soft starter and reactive power compensation • Sensitive to the power fluctuation caused by wind gusts • Lower power density.
DFIG	• Mature mechanical and electrical systems • Less mechanical stress • No soft starter needed • No reactive compensator	• Gearboxes and slip ring are needed (increased O&M cost) • Sensitive to the grid faults • Medium reliability and reduced longevity • Limited variable speed • Low power density.
PMSG	• Low O&M cost • Improved robustness and longevity (elimination of gearbox) • High efficiency and low rotor losses • High power density • No external excitation	• More expensive than other types • Demagnetization may occur if not protected •

train failure rates, as well as operation and maintenance costs, while minimizing energy losses associated with the drive trains. These factors are of utmost importance in far-shore or sparsely distributed wind farms in different Australian waters, where access windows may be limited due to logistical challenges. The detailed comparisons between the major generator topologies are summarized in Table. I.

B. Foundation Technologies

One of the key distinctions between onshore WTs and offshore WTs lies in the foundation requirements, with offshore installations necessitating suitable supporting structures in the ocean environment. Broadly speaking, WT foundations can be classified into two categories: bottom-fixed foundations and floating foundations, based on the water depth of the deployed sea site. Table. II provides a comparison of the characteristics of recent major foundation types, outlining their suitability, applications, as well as advantages and disadvantages.

It should be noted that bottom-fixed foundations are suitable for deployment in water depths below 50 meters. These include gravity base foundations (GBFs), monopile foundations and jacket foundations. GBFs rely on their self-weight to counteract extreme overturning moments and maintain the structure in an upright position. They are typically used in water depths of less than 10 meters and require specific geotechnical conditions, such as a seabed with high-bearing capacity, such as compacted clay, sandy soil, or rock. It is worth mentioning that the majority of GBF wind farms were commissioned before 2013. Monopile foundations, on the other hand, consist of a single steel tube pile and are commonly deployed in water depths ranging from 15 to 25 meters. The monopile concept has been widely adopted in the offshore industry due to its ease of manufacture and cost-effectiveness in terms of transmission and construction [4]. Jacket foundations are typically utilized in intermediate water depths between 30 and 50 meters. They consist of a welded tubular space frame with vertical legs supported by a lateral bracing system. Jacket foundations are relatively cost-effective due to lower steel consumption compared to monopile type in deeper water. It is worth noting that jacket foundations are usually fabricated on land, then transported and piled into the seabed.

For water depths exceeding 50 meters, floating foundation concepts are more economically viable than bottom-fixed foundations. Floating foundations consist of a floating structure that provides buoyancy to support the entire WT and stabilize the structure's motion, along with a mooring system that employs anchors to secure the foundation to the seabed. Fig. 4 illustrates the three main floating concepts for offshore WTs: spar type, tension leg platform and semi-submersible platform.

The spar type foundation features a cylindrical structure with a low water plane area, ballasted to maintain the centre of gravity below the centre of buoyancy. Mooring lines, either catenary or taut spread, along with drag or suction anchors, keep the foundation in position. This concept was first implemented on the Italian coast in 2008 with an 80 kW capacity, followed by the installation of the Hywind (2.3 MW) with a Spar foundation in the North Sea near Norway.

The tension leg platform (TLP) consists of a central column and arms connected to tensioned tendons that secure the foundation to suction or pile anchors. The TLP structure offers greater stability compared to other floating concepts due to its un-extendable mooring lines. However, a key operational risk for TLP structures lies in ensuring that the mooring lines remain taut and straight.

The semi-submersible platform is typically described as a floating jacket or space frame. It can be constructed with either three or four primary columns, with the turbine positioned either in the centre or over one of the columns. In 2011, the semi-submersible 2 MW offshore wind platform, WindFloat 1, was first demonstrated in Portugal [41].

The IRENA renewable cost database [28] reports that the average size of offshore wind farms in Europe in 2021 was 591 MW. These wind farms had a weighted average water depth of 39 m and were located at an average distance of 23 km from the shore. In China, the average

TABLE II COMPARISON OF OFFSHORE WIND FOUNDATION TYPES.

Foundations	Applications	Advantages	Disadvantages
Gravity-based Types	• Suitability: shallow water (depth ≤ 15m), solid seabed • Applications: Kårehamn (Sweden, 2013), Vindpark Vänern (Sweden, 2012), Nysted II (Denmark, 2010) and Thorntonbank (Belgium, 2009)	Simplicity of the structure Suitable for rocky or sandy soils (avoid complicated pile driving)	• Special geotechnical requirement (such as sufficient load-bearing capacity) • Very limited water depth (≥ 20 m) • Very heavy and expensive to support vary large WTs [37]
Monopile Types	• Suitability: relatively shallow water (depth below 30 m) • Applications: most utilised for offshore WT foundations.	• Low cost • Ease of manufacture and construction;	• Uneconomic with water depth above 30 m • Bored pile and drilling are required on the rocky seabed;
Jacket Types	• Suitability: intermediate water (depth between 30 and 55 m) • Applications: Saint-Brieuc (France, 2023), Seagreen (Scotland, 2022), East Anglia ONE (UK, 2020), Wikinger (Germany, 2017) Ormonde (UK, 2012)	• Adopted in the deeper water • Relatively economic in terms of mate- rial consumption;	• Larger footprint and require more scour protection • Installation challenges such as in shallow water and highly dependent on soil types • Limited manufacture and installation experience.
Spar Types	• Suitability: deep water (depth ≥ 100 m) • Projects: Hywind Scotland WT (Equinor [38]), SWAY (Inocean [39]), Deepwater Wind and Advanced spar foundation (Japan Marine United Corporation).	• Lower critical wave-induced motions • Simple design • Lower mooring cost;	• Deeper water required than other floating concepts • Stability issues (vertical and pitch motions) • Installation challenges such as requirements on special heavy-lift vessels and sheltered wave conditions
Tension Leg Platform	• Suitability: Relatively deep water (depth between 50 and 70 m) • Applications: GICON-SOF [40],	• Stable platform-class than other floating concepts • Lower critical wave-induced motions • Low mass and ease of installation (assemble onshore).	• Special installation vessels are required • Vulnerable to instability during the installation process • Higher cost and mooring system requirement (due to low stiffness against surge and sway force).
Semi-submersible platform	• Suitability: Deepwater • Projects: WindFloat (Principle Power [41]) and Fukushima FORWARD [42] (phase 2 Floating Wind Farm).	• Higher platform stability • Fully equipment construction onshore • Ease of transportation and offshore installation • Lower mooring system cost;	• Higher critical wave-induced motions • More material (e.g. steel) and larger structure design (resulting in high cost) • Complex design and manufacture.

size of offshore wind farms was 245 MW, with a weighted average water depth of 31 meters and an average distance to the shore of 12 km. As of 2021, fixed-bottom foundations were used in nearly all operational offshore wind energy projects. Monopiles accounted for 64.4% of the total installed projects, followed by jacket substructures at 11.6% of operating substructures [43]. However, when considering the globally announced substructure capacity in 2021, semi-submersible foundations would represent 16.2% of the total announced future offshore wind projects.

While there is no consensus on which types of floating concepts have the greatest potential for future large-scale offshore WTs, stability and cost savings are two significant factors. It is crucial to limit dynamic motions, such as pitch, roll and heave, within strict limits, even during extreme weather conditions, to avoid structural damage. Additionally, cost reductions in floating platforms can be achieved through improvements in manufacturing, transmission and installation procedures. For example, designing the floating wind platform for full assembly at the quayside and towing it to the offshore location with a pre-installed mooring system can eliminate the need for massive vessels during offshore installation. In Australia, both bottom-fixed and floating foundations are needed in its different declared offshore energy zones, where Gippsland offshore zone and Great Southern Ocean zone require the bottom-fixed foundations due to shallow water less 50 m, while Illawarra offshore zone and the Hunter offshore zone requires floating platform technologies given water depth in average over 100 m.

C. *Power Electronics and Control*

Power electronic (PE) converters, which utilize semiconductor devices such as insulated gate bipolar transistors (IGBT), MOSFETs, MOS-gate thyristors, etc., are essential components in WTs. They are responsible for driving, protecting, and controlling electrical circuits to regulate voltage and current, perform frequency conversion and control, and enable the decoupling of the WT from the grid [44].

Due to the variable nature of wind speeds, maintaining a constant rotation speed in WTs is challenging. Power electronic converters address this issue by allowing the WT to operate independently of the grid. These converters also enable voltage control, reactive power support and the ability to track the maximum power available from the wind energy resource.

Over the past decades, power electronics has played different roles in WTs, ranging from serving as a soft starter in fixed-speed SCIG-based turbines to providing dynamic rotor resistance control for WRIG-based turbines, rotor power control in DFIG-based turbines and full power control in PMSG-based turbines. Based on their configuration, there are two types of power converters used in wind energy conversion systems: partially rated power electronic converters and full-scale power electronic converters, as illustrated in Fig. 6.

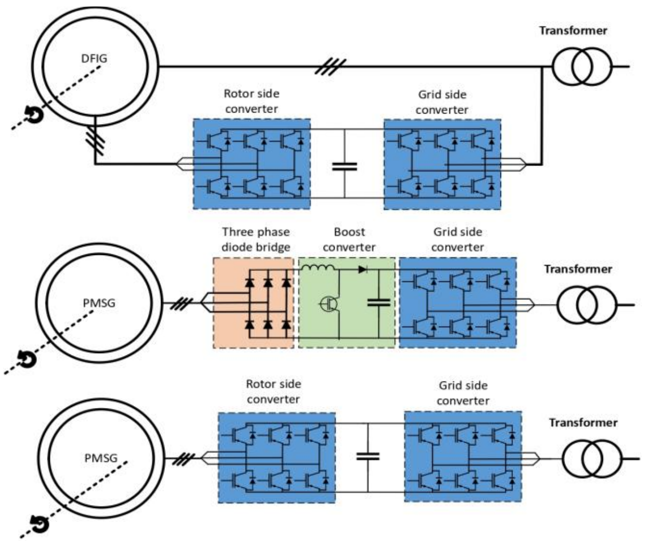

Fig. 6 Power electronics circuit topologies applied in individual WT: partially rated power converter arrangement (top), fully- rated PE with rectifier and boost converter (mid) and fully-rated PE with voltage source converter (bottom).

Partially rated PE converters are used in DFIG-based WT configurations. As depicted in Fig. 6 (top), a back-to-back converter is used to connect the rotor and grid via slip rings, allowing for approximately ±30% variation in synchronous speed (or rotor speed) to accommodate the fluctuating turbine speed. This setup enables active and reactive power control, eliminating the need for reactive power compensation and resulting in improved grid performance. In this configuration, a soft starter is not required. The rotor side converter (RSC) is responsible for controlling the active and reactive power output of the induction machine, while the grid side converter (GSC) maintains a constant DC link voltage and provides limited reactive power support to the grid. Additionally, a Crowbar [45] is used to protect the RSC, which acts as a short circuit across the rotor circuit in case of severe voltage sag on the grid side, diverting a large current away from the RSC and preventing damage.

On the other hand, fully-rated PE converters are used in PMSG systems, capable of handling the full voltage and current ratings of the generator and controlling the full power in all four quadrants for grid feeding. As illustrated in Fig. 6, a back- to-back (BTB) voltage source converter provides speed flexibility in WTs, allowing for optimal capture of wind energy while controlling active and reactive power flow to the grid through the GSC. The control levels in the wind energy conversion system for PMSG are summarized in Fig.7. The configurations of full-rated BTB power converters can be categorized based on low voltage operation (below 1 kV) and medium voltage operation (3-4 kV). A comprehensive review of back-to-back power converters in high-power wind energy conversion systems is available in [9].

It is important to note that the utilization of fully-rated converters comes with a few drawbacks, including higher costs, increased voltage stress on the switches and higher converter losses. However, ongoing technological developments in switch technologies (such as the use of wide bandgap devices) and converter topologies (such as resonant converters) aim to mitigate these drawbacks in the future.

In wind energy conversion systems, various levels of control are involved, as summarized in Fig. 7, ranging from converter control and generator/grid code control to turbine control, farm control and transmission system operator (TSO)/distribution system operator (DSO) control. The control levels of power electronics and generator control are closely intertwined and difficult to define separately. These two groups of control schemes commonly used are vector control and model predictive control. Maximum power control (level III), also known as maximum power point tracking control (MPPT), encompasses various strategies such as optimal tip-speed ratio, optimal torque, WT power curve-based control, power signal feedback, generator signal feedback and speed sensor-less control. WT control includes mechanical control aspects such as pitch angle and yaw system control, electrical control aspects such as reactive power control and fault ride-through control, as well as other controls such as ancillary services and cooling systems. Wind farm control and TSO control are higher-level control strategies aimed at effectively regulating wind power generation in compliance with grid codes.

As it is observed well, onshore wind technologies are mature and well-developed. However, direct-drive systems and the application of DC-coupled converters are evolving for large-scale WTs [46]. Note that direct-drive systems eliminate the need for a conventional gearbox, reducing the risk of drive-train failure and resulting in lower operation and maintenance costs and reduced energy losses, particularly in far-shore wind farms with limited access windows. In addition, such systems also enable variable rotor speeds and the use of DC-DC converters allows for system integration with the energy storage system (ESS) or WEC [32], [33].

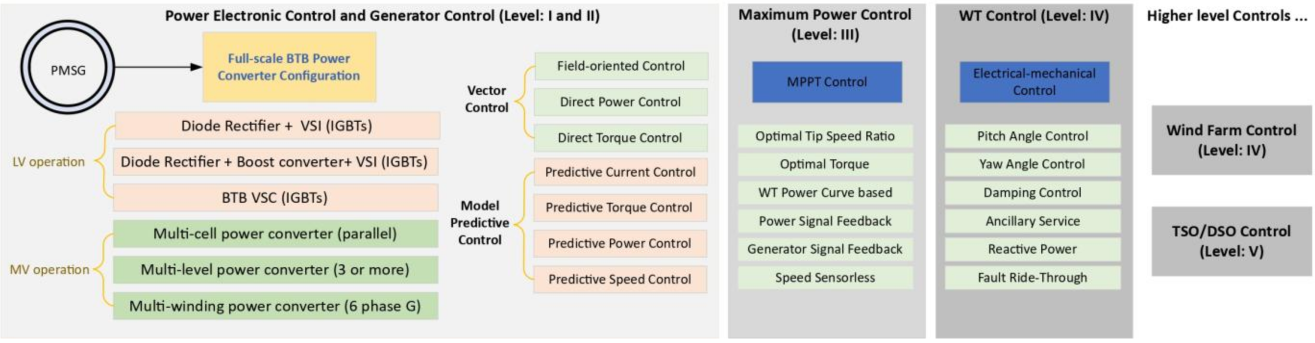

Fig. 7 Control levels in wind energy conversion system.

Furthermore, the utilization of power electronic converters with high switching frequencies is desirable to increase the power density (gravitational and volumetric) of the converters operating in harsh environmental conditions. Wide bandgap devices are expected to replace silicon-based power switches in future converters [47]. These devices offer advantages such as higher reliability (due to higher operating temperature and faster switching characteristics), higher dv/dt and di/dt, and flat-efficiency characteristics with improved energy efficiency.

D. *Offshore Wind Farm Configuration*

The electrical infrastructure of an offshore wind farm can be divided into two main sections: the interconnection system and the transmission system [48]. The interconnection system is responsible for collecting the power output from each WT generator within the wind farm, while the transmission system connects the offshore wind farm as a whole to the onshore grid. The design of offshore wind farm configurations is a complex process that considers technical and economic factors, which takes into account project-specific details such as location and interconnection facilities and provides reliable and efficient solutions for power collection and transmission from offshore wind farms. Cost-effectiveness is particularly important for the development and deployment of future large-scale (up to GW) offshore wind farms [25]. Four different wind farm configurations and two transmission technologies are given in Fig. 8.

1) *Local Power Network:*

Fig. 8(a) shows a typical AC collection system, which consists of WT generators, back-to-back converters and transformers. In this system, the power generated by each WT is collected by the medium-voltage AC system at the offshore substation. Additionally, various inter-array designs can be employed within this connection system [8], such as radiation WT layout (e.g., Horns Rev OWF, BARD 1, Walney 1), radial-looped WT layout (e.g., London Array, En Baltic 2, Butendiek, Amrumbank West, Alpha-Ventus) and star WT layout (e.g., Borkum Riffgrund 1, Gwynt-Y-Mor, Walney 2). The radial collection system offers simplicity and low cost but has lower reliability due to the absence of system redundancy. Radial-looped and star layouts are more reliable but come with higher costs and cable losses. As WT ratings increase significantly, studies have considered higher voltages for inter-array cables (48-66 kV) to enhance the transmission capacity of the AC collection system [49], [50]. However, this introduces additional costs and space requirements for accommodating high-voltage transformers and switch gear within the turbine tower/platform (as highlighted in Fig. 8).

Fig. 8(b) shows a DC-linked AC collection system, where DC cables are used to aggregate the power from each WT. This configuration eliminates the need for a large AC transformer within the turbine tower. Instead, an intermediate substation is required to accommodate the DC/AC converter and step-up transformer when a significant number of WTs are installed in an offshore wind farm. It is worth noting that the consideration of an AC system in this topology is primarily due to the current high cost of DC system control and protection. However, if the DC system becomes more cost-effective, an all-DC collection system is a viable option [46], [51].

Fig. 8(c) presents a DC string collection system, where each individual WT is connected to a step-up DC/DC converter. This configuration allows for reduced cable losses during the collection stage, as the voltage is directly stepped up behind each WT. Additionally, the DC converter decouples the offshore WT from the grid, thereby enhancing the fault withstand capability of the WT system [52]. However, due to the two-stage conversion process, the efficiency of this system is relatively lower. It is worth noting that there is an alternative DC collection configuration, where a centralized DC/DC converter is connected instead of individual DC/DC converters [8], [53]. This configuration offers the advantage of reducing the number of converters for individual turbines, improving energy efficiency and reducing associated costs.

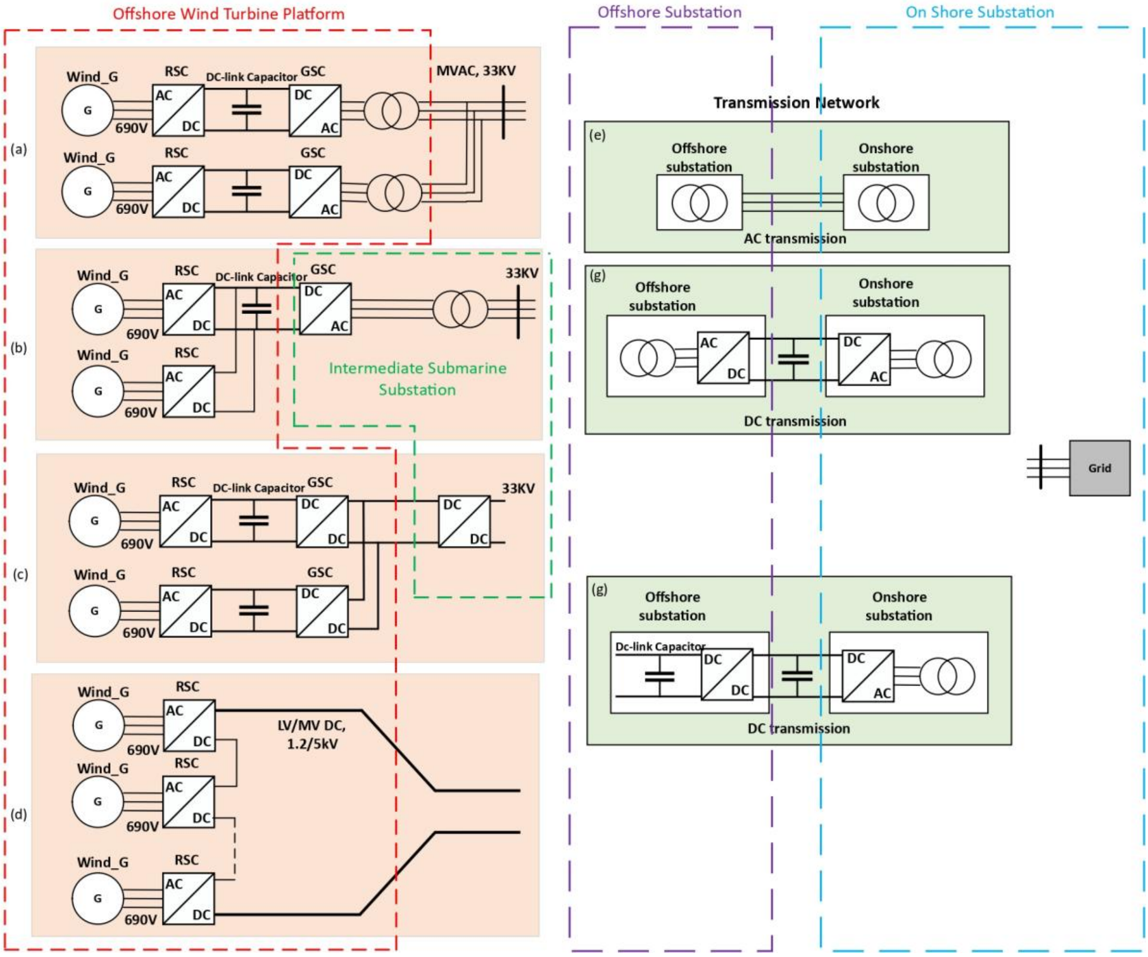

Fig. 8 Offshore wind farm power configurations and major system components: a) parallel AC collection system, b) hybrid DC-AC collection system, c) DC string collection system and d) series DC collection system; and transmission technology: e) HVAC, f) HVDC and g) DC-linked HVDC.

Finally, the configuration given in Fig. 8(d) illustrates the cascaded AC/DC converter topology to achieve the medium-voltage DC (MVDC) or high-voltage DC (HVDC) levels. Bypass switches are generally required to be connected across the DC link of each AC/DC converter to isolate the WT during system failure or maintenance. This collection system offers several advantages. Firstly, it results in significant cost savings by eliminating a large number of converters, transformers and potentially even the central offshore substation (in the case of HVDC). Secondly, cable and interconnection losses are substantially reduced as fewer conversion stages are required. The feasibility of this collection system with both voltage source converters and current source converters has been investigated in previous studies [54]–[56]. However, if a large number of WTs are bypassed due to various reasons, the entire wind farm may have to shut down, as the HVDC system triggers a lower threshold for transmission.

2) Transmission System: Power transmission systems used in offshore energy applications can be classified into two categories: HVAC and HVDC, which can be further classified as HVDC Line Commutated Converter, HVDC-LCC and HVDC Voltage Source Converter, HVDC-VSC.

HVAC transmission has been widely adopted in offshore transmission systems due to its well-established, stable and mature technology. As shown in Fig 8(e), connecting to an offshore wind farm requires several components, including an AC collection system at the platform, offshore and onshore substations with AC transformers and reactive power compensation and AC subsea cables. The subsea cables typically consist of three individually insulated single-core cables, usually with XLPE insulation, bundled together with a common outer sheath and armour [57].

HVDC transmission is gaining interest in the offshore wind farm industry due to several advantages over HVAC [58], [59], including the ability to transmit over longer distances (over 100 km), lower losses (copper losses), elimination of expensive reactive line compensators and independent control of the phase angle between the source and load, providing stability against disturbances caused by rapid power changes. Additionally, DC lines require fewer cable conductors and can fully utilize the thermal transmission capacity, resulting in lower cable costs. Furthermore, HVDC enables the transmission of power between systems operating at different frequencies while enhancing stability and economics. Table. III provides a technical summary of various comparison elements between HVAC and HVDC transmission systems.

In terms of economic prospects, AC transmission is more economically beneficial for distances below a specific threshold (such as 56 km in [25], 72 km in [60]).

TABLE III COMPARISON BETWEEN HVAV, HVDC-LCC AND HVDC-VSC TRANSMISSION SYSTEMS

Items	HVAV	HVDC-LCC	HVDC-VSC
Trans. Capacity	800 MW	12000 MW	2000 MW
Voltage level (KV)	±400	±1100/±400	±500
Trans. Distances	Shortest	Longest	Medium
Space for substation	Small	Large	Medium
VAR compensation:	Yes	50-60% of rated MW	None
Black-Start Capability	Yes	No	Yes
Filtering Equipment	-	Expensive	Low
Cable types	Three cables	Two bipolar	Two bipolar
Substation Cost	Lowest	Medium	High

This is because the cost of a DC substation is significantly higher than that of an AC substation, while DC cables are cheaper than AC cables. There is a break-even distance point that can be used to determine the preferred transmission technology in a given location. Moreover, as the transmission distance increases, HVDC-VSC becomes the preferred option, although HVDC-LCC is the most economical choice considering factors such as weight, size and control complexity during offshore station start-up.

V. CONCLUSION

This paper provides a comprehensive review of offshore wind energy, focusing on resource assessment and market development. It delves into offshore wind technologies, including turbine generators, foundations, power electronics control systems, and farm configurations, offering thorough discussions on each. The offshore wind industry has experienced significant growth in recent years, driven by the maturity of commercial wind turbine technologies and insights gained from onshore development. PMSG technology is poised to dominate the future offshore wind market due to its unique advantages for large-scale offshore turbines, such as variable speed, high energy efficiency (low energy losses), gearless (direct drive) operation, and high reliability (low operation and maintenance costs). To maximize offshore wind energy potential and address the challenges of utilizing nearshore marine spaces, foundation technologies, particularly floating foundations, are crucial. These technologies enable the development of offshore wind farms in far-shore and deep-water locations, expanding the possibilities for harnessing wind energy. In conclusion, this paper aims to serve as a valuable reference for researchers and industry professionals, supporting the advancement of offshore wind energy.

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