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Offshore Wind Energy Review: The Potential for South Africa

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Abstract

Over the past decades, the energy demand of the world has increased dramatically due to various contributing factors. Environmental impacts, policy, and wind resources impact the size of wind turbines located onshore. Offshore wind technology can play a key role in the decarbonization of coastal cities and assist the global transition towards cleaner electrical generation sources. The offshore wind energy industry has progressed significantly over the past decade due to a multitude of factors in the economic and technical sectors. Policy, regulations, and innovative financing aided the development of the offshore wind industry. Another contributing factor to the increase in deployment of offshore wind power has been the evolution of turbine size for the offshore wind turbine sector. The following study aims to review the key components of the offshore wind industry for a case study of South Africa. The study examines the differences between turbine configurations such as Horizontal Axis Wind Turbine(HAWT) and Vertical Axis Wind Turbine(VAWT)designs of turbines, foundation types, and potential electrical network topologies for South Africa.

Keywords: Offshore Wind, Offshore wind foundations, HVDC, HVAC, South Africa.

1.1 Introduction

Over the past decades, the energy demand of the world has increased dramatically due to various contributing factors, [1]–[5]. According to the British Petroleum (BP) statistical review of global energy supply, the major contributor to energy supply stems from fossil fuel sources (i.e., Coal; Natural Gas, and Oil), [6]. However, there had been a decline in fossil fuel contribution and an increase in renewable energy contributions from 2019 to 2020 as shown in Table 1 below. It was found that the major fossil fuel contribution is natural gas and oil except for the Asia Pacific region which relies heavily on coal for electrical energy generation.

Table 1: Energy Statistics by Fuel

		Fossil	Nuclear	Hydro & Other	Renewables
Total World	**2019**	62.9%	10.4%	16.5%	10.3%
Total World	**2020**	61.3%	10.1%	16.9%	11.7%
% Change		-1.5%	-0.3%	0.4%	1.4%

Major countries, like Japan, the European Union, and China, have since announced ambitious decarbonization plans for the long-term to shift their respective states to a net-zero economy and achieve the respective carbon emission reduction goals. This was seen even through the Covid-19 pandemic which had minimum effect on the renewable energy policy targets or incentives, [10].

The policies which have been developed over the decades have been a key driver for large-scale renewable energy deployment globally as well as cost reductions and innovation in the renewable energy space. Countries across the world have slowly been moving away from feed-in tariffs (FiTs) and feed-in premiums (FIPs) towards more competitive set tariff options (competitive auctions, green certificates, corporate power purchase agreements (PPAs), etc.) for large-scale systems or portfolio based distributed generation projects. It is forecasted that in the next half-decade the policies and regulatory frameworks which enable competitive environments will make up 60% of all global renewable energy expansions, [7].

Figure 1 shows the major contributing policies which support wind deployment across the global markets of wind deployment. The support mechanisms and policies coupled with decreasing materials and other supply costs are attributed to the main key drivers of wind deployment over the next half-decade. Considering all of the wind capacity which is set to come online within the next five years, 40% are supported by FiTs and FIPs which are trailed by 35% which are supported by competitive auctions. Competitive auctions are prevalent in all regions except the United States of America and China, [7].

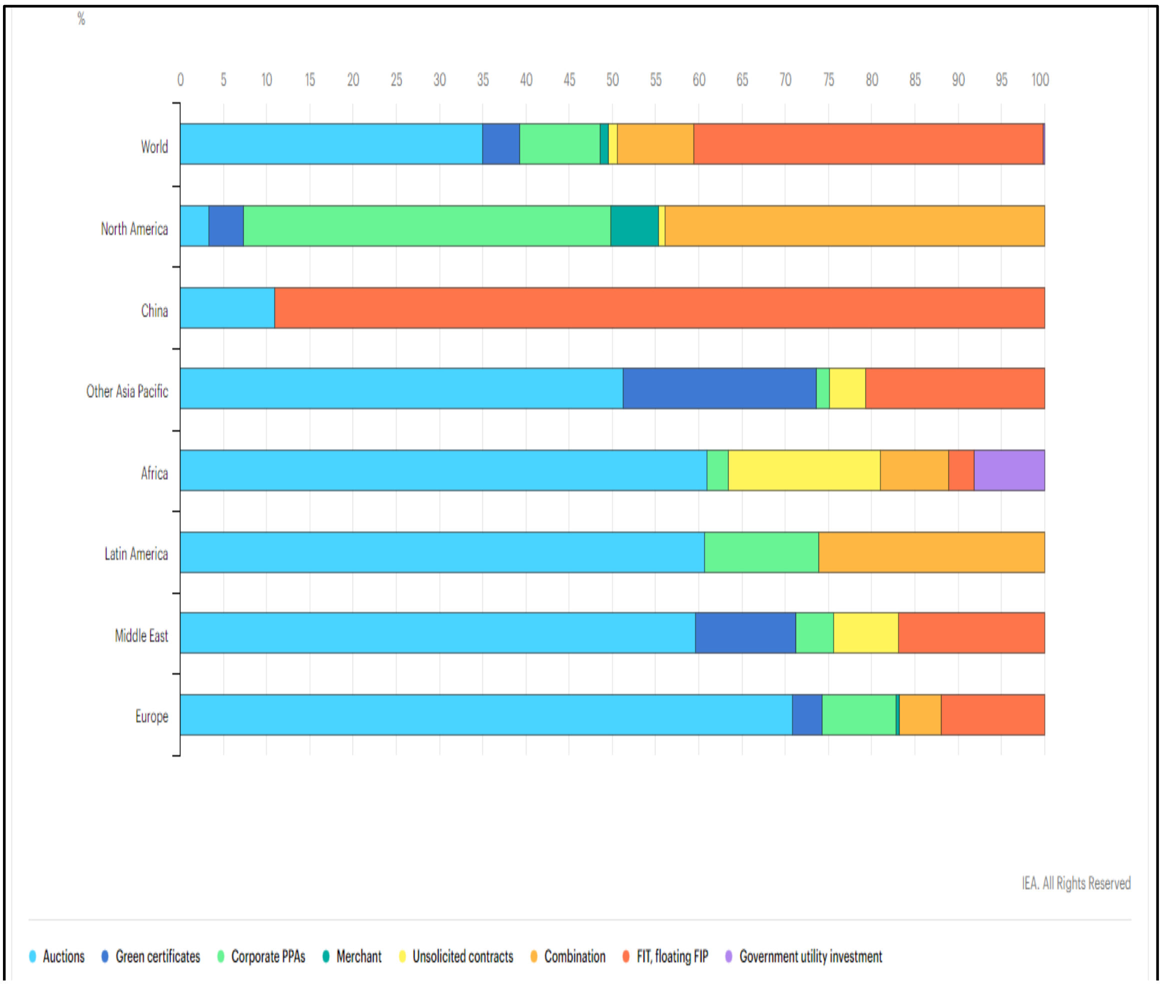

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Figure 1: Supporting Policy Schemes for Wind Energy, [8]

1.2 Status of Offshore wind

Offshore wind technology can play a key role in the decarbonization of coastal cities and assist the global transition toward cleaner electrical generation sources,[6], [9]. Figure 2 shows a graphical representation of the statistics of onshore and offshore wind technology installed capacity from the year 2000 till the year 2020, [10]. The figure accounts for the global installed capacity over the two decades and it can be seen that the offshore capacity is slowly increasing and a steady rate.

This may be due to various factors such as an increase in energy yield in offshore sites as well as larger turbine capacities that can be deployed offshore which are not suitable for onshore integration, [9], [11]– [13]. Recent trends have also shown that deployments are increasingly moving further offshore into deeper water depths forcing innovation in floating platform designs, [14]– [18]. In addition to these factors the offshore wind farms have minimal noise and visual negative impacts, however, considerations concerning marine ecosystems are still required when deploying these solutions, [17], [19]–[21].

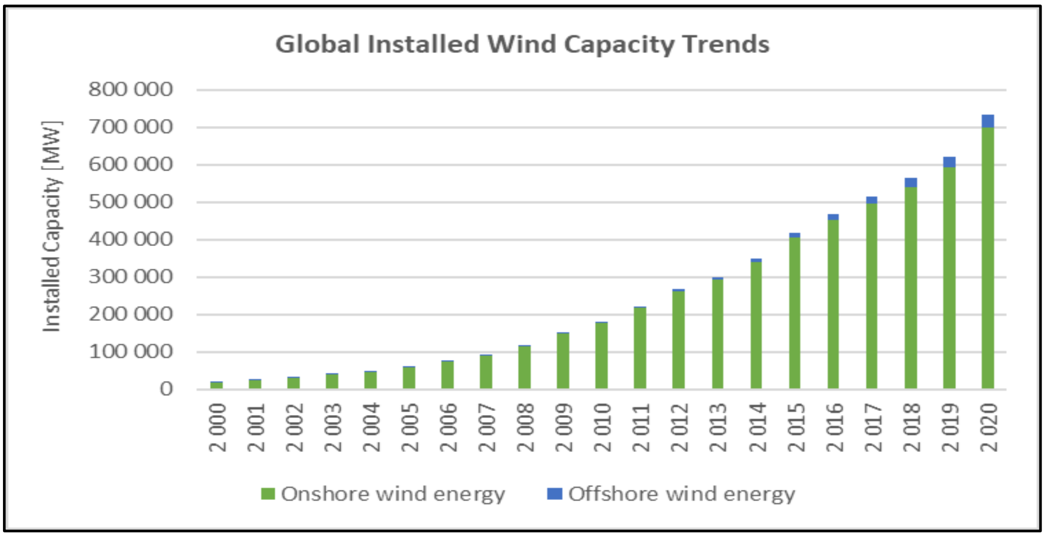

Figure 2: Onshore & Offshore Wind Installed Capacity 2021, [10]

H. Diaz and C. Guedes Soares analysed data from [22] which is shown in Table 2**Error! Reference source not found.** indicating the major regions which have dominated the installation of offshore wind turbines. It can be seen both onshore and offshore that Asian and European markets have dominated the wind sector with the most installed capacity. The data depicts the dominance of the European and Asian markets in the aggressive installation of offshore wind farms. In the European sector, it was found that the United Kingdom (30 wind farms), Germany (19 wind farms), Denmark (13 wind farms), and the Netherlands (6 wind farms) have the most installed offshore capacity. In the Asian market, the leaders are China (21 wind farms) and Vietnam (2 wind farms), [17].

Table 2: Installed Offshore wind Capacity, [17]

Region	***Country***	***Installed Capacity [MW]***	***No. of Turbines***
Europe	Belgium	871.2	231
	Finland	84.4	18
	Denmark	1273.1	510
	Germany	5342.3	1167
	Ireland	25.2	7
	Netherlands	1117.8	365
	Sweden	191.2	79
	UK	7347.8	1796
Asia	China	2409.9	676
	Japan	41.3	22
	South Korea	35	15
	Taiwan	8	2
	Vietnam	183.2	102
America	United States	30	5

A contributing factor to the increase in deployment of offshore wind power has been the evolution of turbine size for the offshore wind turbine sector. Environmental impacts, policy, and wind resources impact the size of wind turbines located onshore. Offshore wind energy about onshore wind energy does have many advantages concerning wind energy production, [23]–[25]. Larger turbines may be deployed offshore due to the lower impacts of terrain on the wind resource which normally translates to higher and more constant wind speeds as well as higher capacity factors, [25]–[28]. Figure 3 depicts the evolution of wind turbine size over the last three decades. The increase in turbine capacity usually is a result of an increase in rotor diameter. The benefits of larger rotor diameters can result in more energy being captured as well as a more consistent output over the year, [13], [29].

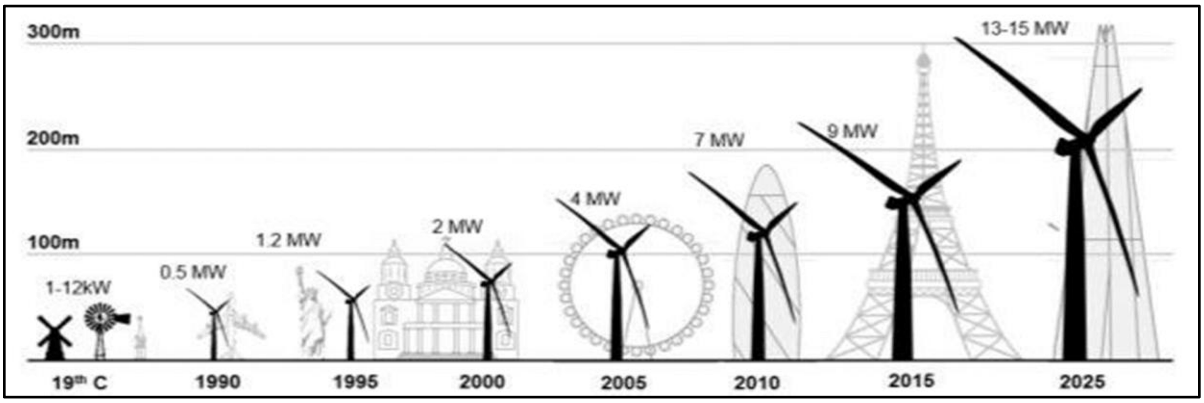

Figure 3: Evolution of wind turbine sizes, [30]

As mentioned in Table 2, Europe and Asia dominate the offshore wind industry currently with an installed capacity of 24.9 GW and 9.4 GW respectively, [10]. Figure 4 shows the trend of installation from the year 2000 to 2020 with Europe depicted in blue and Asia (predominantly China) highlighted in red. China consists of 8.99 GW of offshore wind capacity which constitutes 95.4% of Asia's offshore wind installed capacity, [10]. The figure shows an increasing trend of offshore wind energy deployment in the two major regions over the last ten years. It should be noted that the increases in turbine capacity, subsequently rotor diameter, have led to large wind farms being developed within the regions as seen in the figure.

Figure 4: Average global offshore wind farm capacity and turbine size 2000 – 2020, [13]

It can be seen that the offshore wind energy industry has progressed significantly over the past decade due to a multitude of factors in the economic and technical sectors. Policy, regulations, and innovative financing aided the development of the offshore wind industry. This will continue as energy markets adapt and learn from one region to another but there are still some hurdles to overcome over the coming years, [31]–[33]. However, further decreases in costs are predicted as well as technology to allow for deeper sea deployment to harness more abundant wind resources, [34]–[36].

1.3 Types of Offshore wind Turbines

There are two main types of wind turbines which are grouped as Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) and are recognized based on the axis of rotation of the turbine blades, [37]. The offshore wind industry adopted the HAWT type systems first due to years of existing research and the success of onshore HAWT systems, however, this was assumed and did not consider the variance in offshore environmental conditions, [38], [39].

Wind turbines are subject to a theoretical limit first identified by Joukowsky, Betz, and Prandtl during the early 1900s which defined the flow regime around an airfoil utilizing and integrating various mathematical models of the time, [40], [41]. Researchers use this in wind turbine design as a theoretical limit to which the turbine can extract energy from the wind resource. Airfoils are geometrical shapes that can either be symmetrical or asymmetrical to create a local pressure variance to create lift, much similar to that of an airplane wing, [42]–[44]. The design of the airfoil is of importance to maximize the power output from the wind turbine, [45].

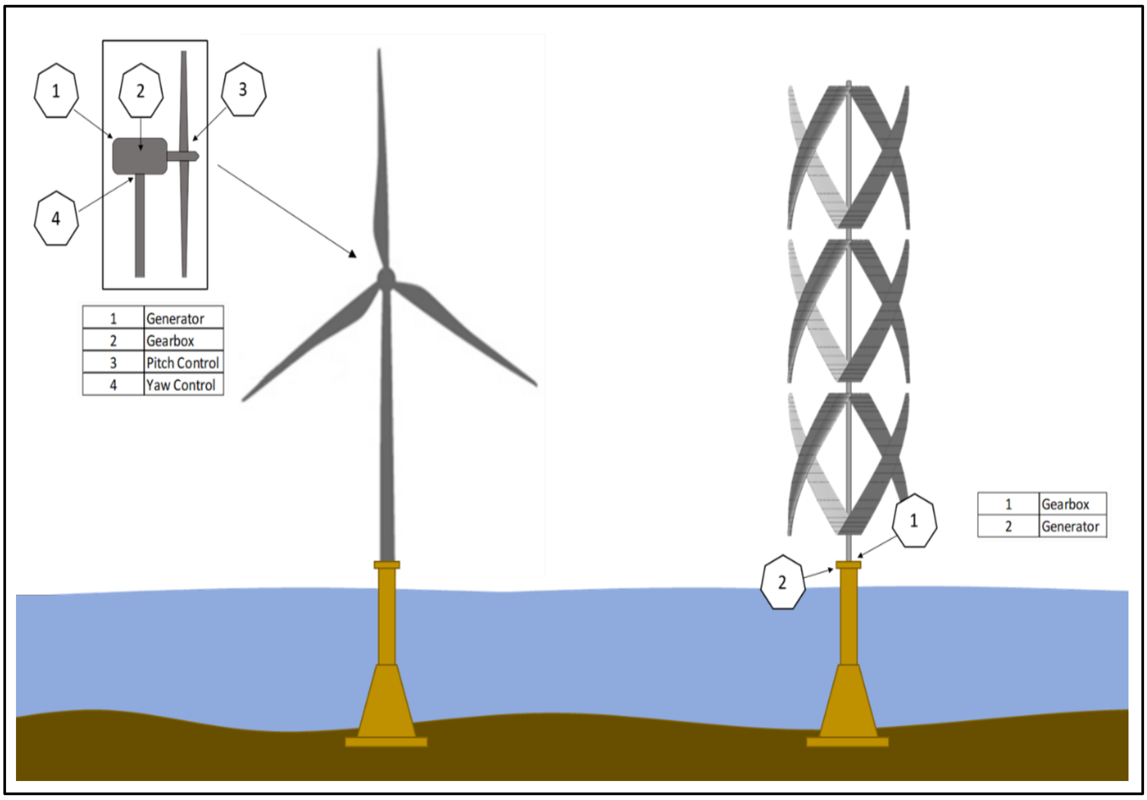

Figure 5: Comparison of HAWT and VAWT systems,

Research from [46] had initially indicated the investigations of VAWTs were low due to fatigue constraints, however, due to the need for systems to be deployed further offshore research has shown that VAWT systems are at an advantage over that of HAWTs, [38]. Researchers from Sandia laboratories have investigated the difference between HAWTs and VAWTs for deep offshore applications and some of the findings are shown in Figure 5. Results from the researchers show that the center of mass of the offshore VAWTs, compared to that of traditional HAWTs is lower which had led to a decrease in substructure costs, [47].

1.4 Offshore Wind Resource

The localised wind characteristics are required for the development of offshore wind farms, [48]. Due to the lack of existing offshore meteorological stations, synthetic data such as MERRA and MERRA-2 are used internationally as a trusted source of data for the initial feasibility investigation of the wind farm development. Various studies have been conducted on the validity of the utilisation of the MERRA datasets for onshore and offshore wind farms.

Olauson et al. had initially modelled the wind power potential in Sweden by using the MERRA-2 datasets, [49]. Staffell et al. were amongst the initial researchers that have used MERRA-2 and validated its use for the purpose of wind power generation for 23 European countries during 2016, [50]. Cali et al. had investigated and analysed the potential site locations for offshore wind farms in Turkey by using the MERRA dataset in 2018 with good correlation to the LiDAR measurement campaign, [51]. Hassoine et al. had used the MERRA-2 dataset to evaluate the optimal placement of the wind turbines for a large offshore wind farm and had shown that the dataset was a reliable source of information for the energy prediction of the wind farm, [52]. The studies provide favourable conclusions on the use of the synthetic datasets for use of energy prediction of offshore wind farms.

1.5 Offshore wind Turbine Foundations

Offshore wind turbines gradually developed from the more known onshore-based turbines towards offshore locations for higher wind resources. A similar evolution had occurred with the foundations of these turbines as the systems progressed further from the shoreline. The depth in which the offshore wind farm system will be deployed is of importance when choosing a suitable foundation system because the typical cost of implementing the system increases significantly in proportion to depth, [53]. The sea depth may be classified into three regions: Shallow water depth (0 m – 30 m); transitional depth (30 m – 50 m) and deep-water depth (50 m and greater), [54]. Offshore foundations for fixed systems are broken into six types of fixed foundations, shown in Figure 6, which are typically implemented in shallow and transitional depths, [54]– [56].

1.5.1 Gravity-Based Foundations

The gravity-based foundation systems were the first foundations to be used as wind turbines migrated from onshore to offshore. The systems are designed based on the self-weight of the turbine to be sufficiently able to resist the offshore forces and moments to allow for stability, [57]. The researchers from [58] also give a large review of the evolution of gravity-based foundation systems. This type of foundation is normally suited for shallow water depths, with the deepest wind farm being in Blyth (UK) in a water depth of 35.5 m, [17], [59].

A comprehensive construction procedure was described in studies conducted by researchers in [59]. One of the deficiencies of the gravity-based foundation system is that the foundation requires identification of suitable bearing soil and leveling of the seabed soil before installation and the use of considerable scour protection around the substructure. The most recent generation of gravity-based foundations also requires a large onshore production and storage area including the required heavy lifting machinery to hoist the substructures for transportation and site installation, [56], [58], [60].

1.5.2 Monopile Foundations

Monopile foundations utilize a single large-diameter steel substructure that is anchored sufficiently in the seabed. The foundation is simple in design and manufacturing traditionally consists of joining circular steel sections onshore and more than one substructure can be transported on a single vessel. Due to the simplicity of the design, fabrication, transportation, and installation of the foundation; the monopile system has become the most common type of substructure which is being utilized in current offshore fixed base wind turbine farms. Connected to the substructure is another transitional cylinder that carries secondary structures such as access ladders, work platforms, and boat landings. This type of foundation requires no prior preparation of the seabed and less scour protection, [56].

Monopile foundations are the most commonly used foundation methods for offshore wind farms in the European region and 63% of the operational offshore wind farms consist of these foundation systems as of 2018. Diaz and Soares also indicate that America utilizes this foundation method 100% of the time and Asia roughly 43%, however, it should be noted that this type of foundation method is best suited for shallow water depths, [17].

1.5.3 Suction Bucket Foundations

Suction bucket foundations or suction caisson foundations are sometimes divided into single and multiple designs, [57]. These systems are becoming increasingly used in offshore applications due to the convenience of transport and lower installation costs in comparison to the previous two foundation methods, [17]. The foundation represents an upside-down bucket that is gradually lowered into the soft seabed. The water is then pumped out creating a negative pressure which aids the mechanism to sink deeper into the seabed without too much external force being applied, [17], [57].

1.5.4 Tripod Foundations

The tripod foundation uses a central steel tube structure on top of a three-legged steel structure which is used to translate the loading of the wind turbine to the foundation. In comparison to that monopile foundations, Tripod foundations may be more stable in extreme weather conditions, [61], [17]. Oh, K.Y. et. Al. indicates that tripod foundations are more suited for transitional water depths as they provide the required bearing capacity, which is needed for such systems, [53].

1.5.5 Lattice Jacket Foundations

The jacket foundation systems use a steel lattice jacket structure to support the top bearing load of a wind turbine. The lattice structure reduces the cross-sectional area of the foundations to reduce the impact of wave loading on the structure, [62], [63]. These types of structures are suitable for transitional water depths between 20 m and 50 m, [17], [62], [63]. This is the second most frequently used type of foundation structure for offshore wind turbines, [63].

1.5.6 High Rise Pile Cap (HRPC)

The response of the offshore structure is important when designing offshore wind farms. The soil properties of which fixed bottom offshore wind turbine structures are installed are also important concerning Poison's ratio; the shear modulus as well as the shear strength of the seabed soil, [53]. The HRPC system comprises a concrete top structure bearing the load and a configuration of steel piping that extends outwards as it descends into the depths of the [53] ocean, [17]. This type of offshore wind foundation is predominantly located in Asia with all of Vietnam's offshore fleet utilizing these foundations, [64].

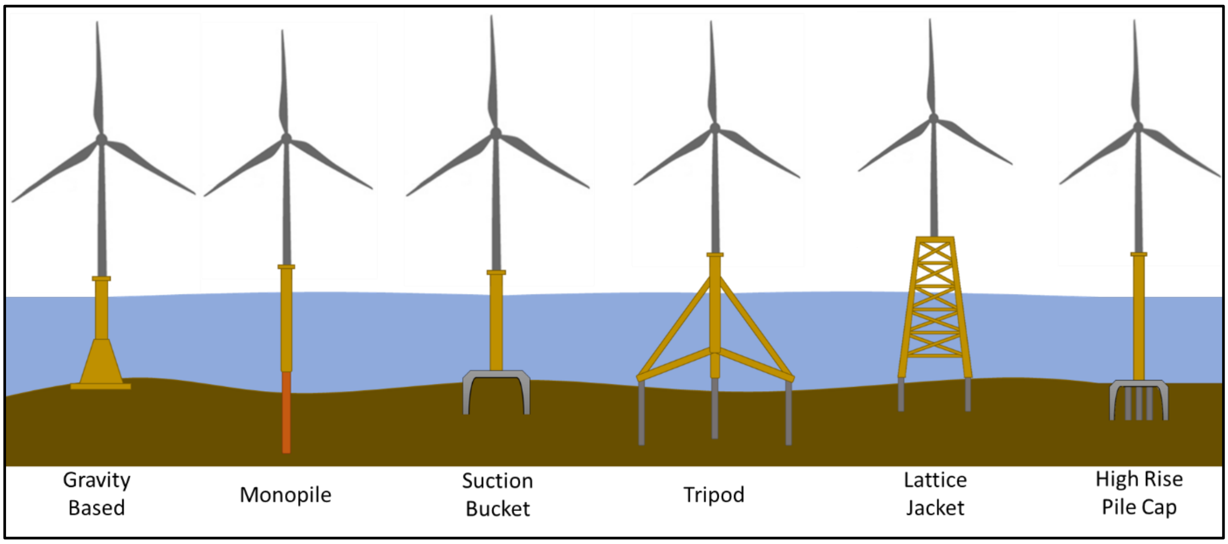

Figure 6: Fixed offshore foundations

The above foundations are suitable for shallow and transitional water depths and would be too costly to be developed for deeper waters due to the turbine requirements which would be higher than the highest wave height in the desired location, [57].

1.6 Floating Offshore Wind Platforms

Floating platforms are being investigated for deep water applications with water depths of greater than 100 m as some regions do not have suitable continental shelves for fixed bottom foundations as highlighted above. The developments are influenced by the oil and gas industry as it has made significant advancements for offshore platforms, however, there are some differences due to different aerodynamic and hydrodynamic loading forces of wind turbines on the platform structure.

Figure 7 illustrates the different types of floating offshore foundations available on the commercial market. The Dutch tri-floater consists of a semi-submersible tripod structure which achieves static stability by exploiting the buoyancy force mainly, which requires a large waterplane area. The spar buoy consists of a monopile structure that occupies a low waterplane area, which is ballasted with water or a solid ballast. This maintains the center of gravity below the center of buoyancy. Spar buoy floaters are traditionally stable due to the large draught. The tension leg platform (TLP) system consists of a submersible foundation that has a large buoyancy which is anchored via tension mooring lines. This creates the require restoring moment needed for stabilising the turbine during operation, [65].

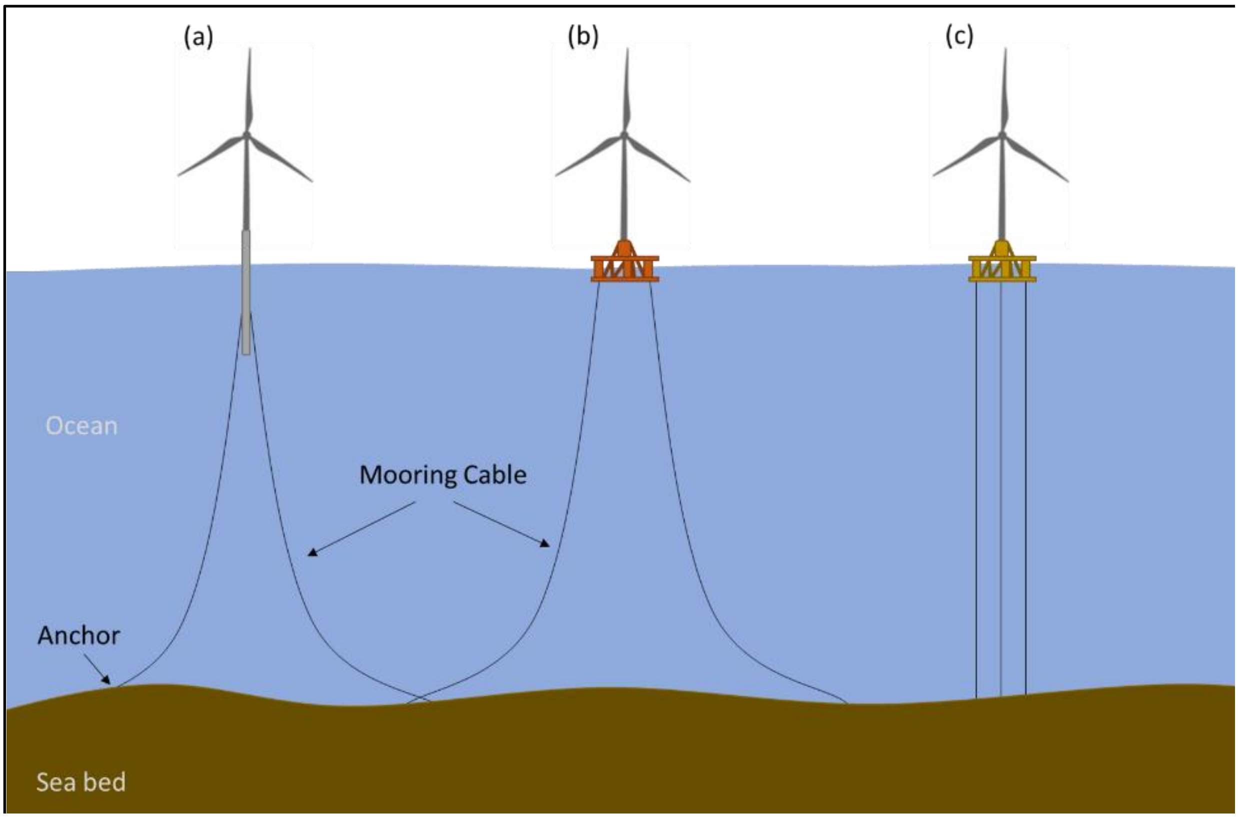

Figure 7: Floating offshore foundations: (a) Spar-Buoy; (b) Semi-submersible; (c) Tension leg

All these types of foundations utilize mooring cables to the ocean floor with large mooring cables which are anchored to the sea floor. Some mooring lines are manufactured out of steel, some use a hybrid polyester or nylon line which may be taut or have slack allowing for natural movement in the ocean conditions, [66]. Figure 8 shows the different configurations of mooring lines that are used for floating offshore wind turbines. Figure 8 (a) shows a steel catenary configuration consisting of steel components, Figure 8 (b) is a taut configuration consisting of fibre and steel components and Figure 8 (c) is a hybrid configuration using counterweights and a buoy consisting of steel and fibre components. The steel components are usually steel wires or steel chains and the fibre components are usually polyesters or nylon fibres, [66].

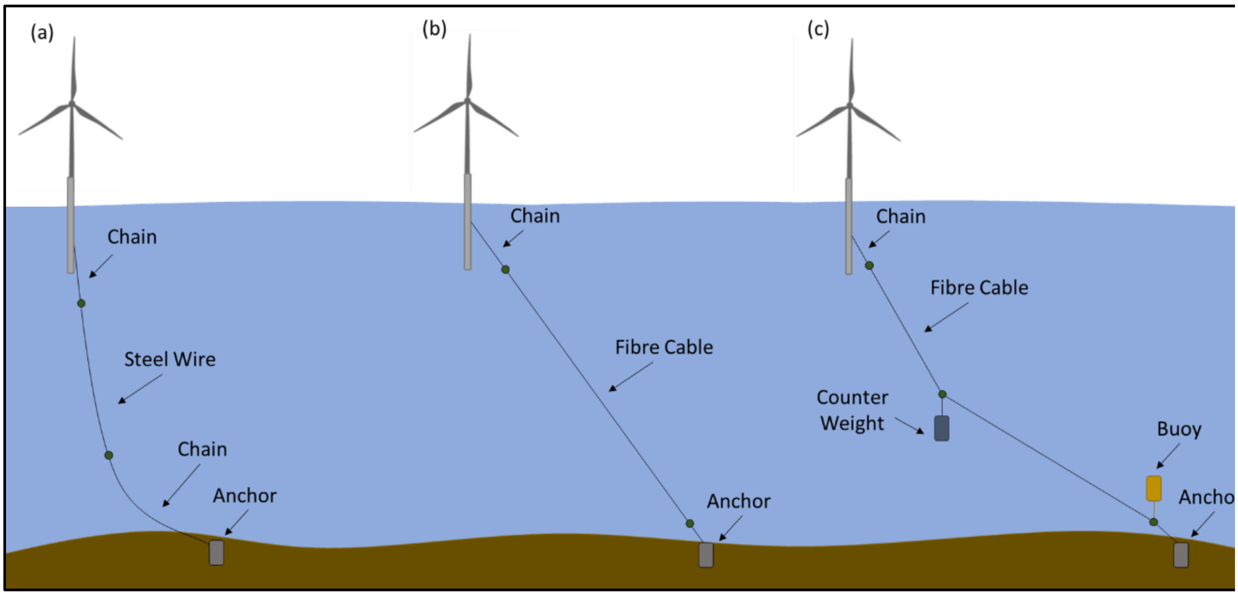

Figure 8: Mooring Line Configurations: (a) Catenary, (b) taut, (c) hybrid

For floating wind turbines, the cost and the stability of the systems as well as the scale of the farm are required to achieve a financially suitable solution for power generation in deep waters. As shown above, various mooring systems may be utilized for the tethering of the floating structure for stability, however, suitable anchors are also required for the entire system. There are traditional gravity-based anchors, anchor piles which are anchors that are piled into the seabed first, suction embedded anchors utilizing negative pressure with an anchor at the base of the system, dynamically installed torpedo anchors which are driven into the seabed, and drag embedded anchors which are also driven into the seabed and uses drag forces to maintain the stability of the floating structure, [57], [67], [68]. These are some of the many anchors which are used for floating applications within the oil and gas and floating wind turbine industry.

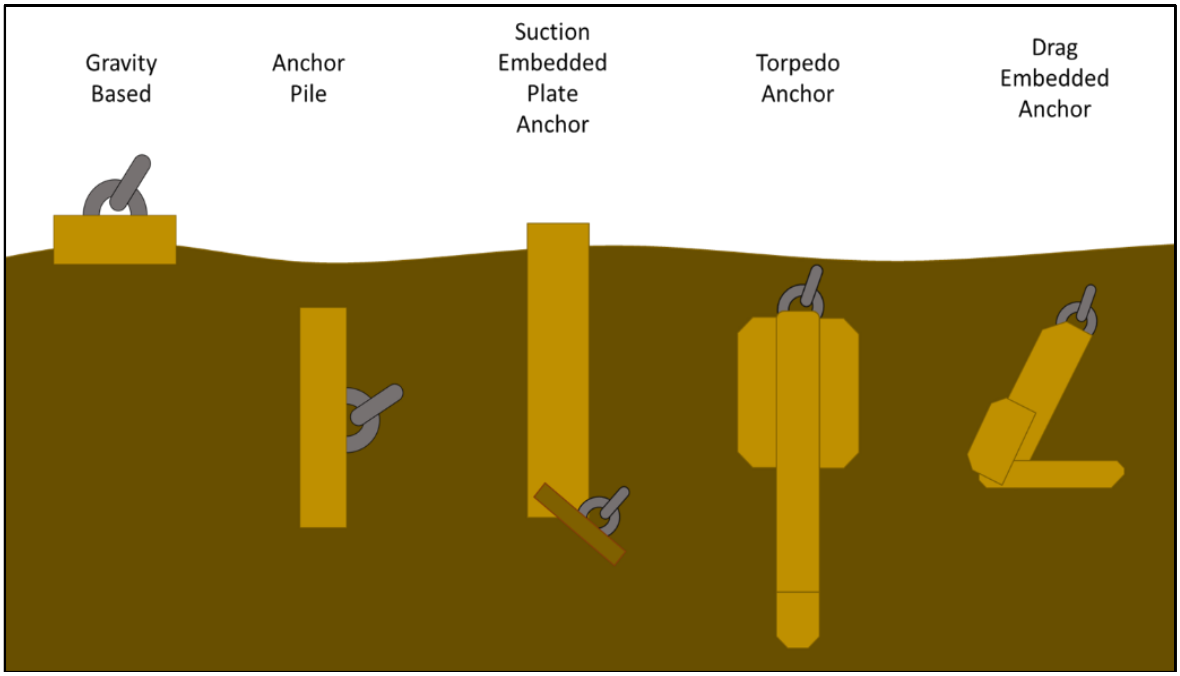

Figure 9: Types of Anchors for Floating Systems

1.7 Offshore Wind Energy Grid Integration Systems

The following section of the study highlights the different potential electrical collector components, systems, and configurations for offshore wind turbines to date. These types of systems are essential for evacuating the electrical power generation from the offshore site to onshore locations where it may be utilized within the respective electric grid.

Two main types of electrical transmission types exist for evacuation, both for onshore and offshore applications, of power generation. The following study aims to highlight a high-level overview of the offshore high voltage direct current (HVDC) and high voltage alternating current (HVAC) network architectures.

The individual wind turbines are interconnected via an internal reticulation network at lower alternating current (AC) voltages because the electrical output of each wind turbine is highly variable. The most common generator type of wind turbines, for offshore applications, is the doubly fed induction generator (DFIG) due to its ability to operate under variable speeds, lower costs and losses in comparison to other generator types, [69]. The stator of the offshore wind turbine generators is usually connected to a local rectifier which converts the power output to direct current (DC) and inverts the power back to AC at a stable network frequency within the local reticulation network, [70]. This configuration can be seen in Figure 10 below.

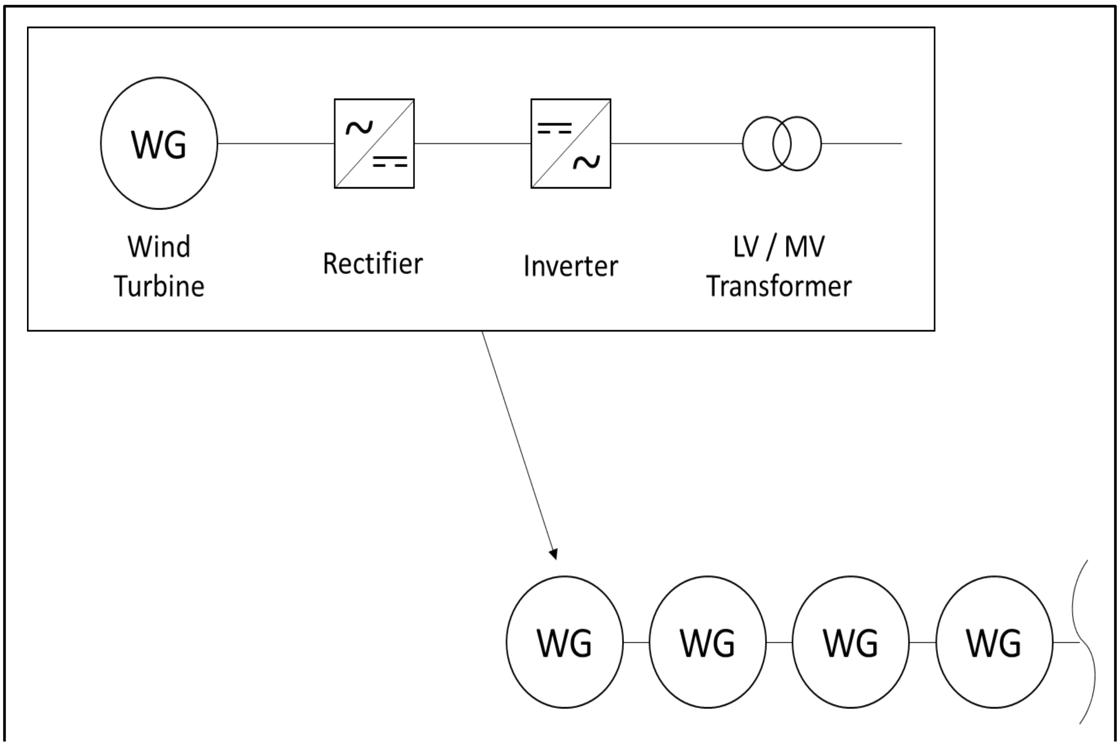

Figure 10: Wind Turbine Reticulation Network Architecture

1.7.1 HVAC

The HVAC system is the most traditional system being utilized for many years now for onshore applications as it allows for efficient transiting of electrical power from power generators (coal-fired power stations, nuclear stations, solar power stations, onshore wind power stations, etc.). Due to the mature nature of the system, connection to the onshore transmission grid may be achieved via traditional step-up transformers reducing the need for power electronic converters, [70]. The power is then transmitted to shore via subsea cables and collected at an onshore substation for grid integration as shown in Figure 11.

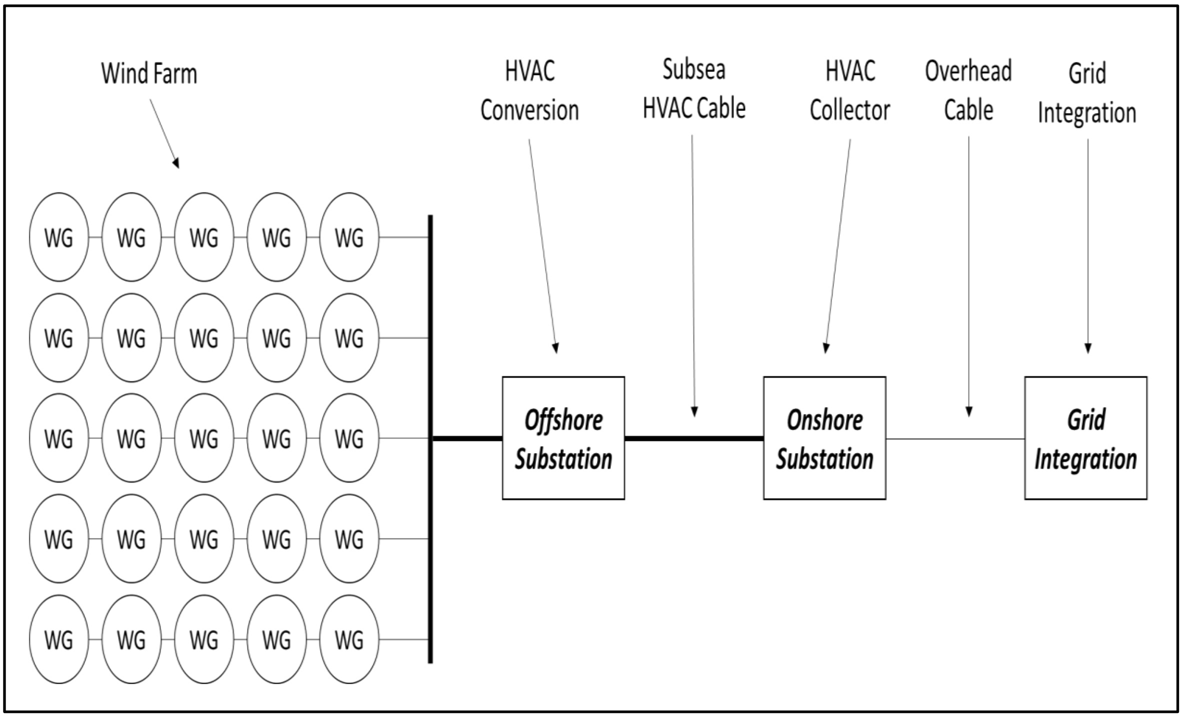

Figure 11: HVAC Grid Integration

The AC collection system works similarly to that of traditional AC grids onshore using an HVAC transmission network. At the point of the AC offshore substation, the power from the wind farm is collected and passes through a step-up transformer. The power is transmitted via HVAC subsea cables to an onshore substation that collects and steps down the power to the same frequency and voltage of the electrical grid for integration.

1.7.2 HVDC

The HVDC system is a transmission method for evacuating power from the localized wind turbine farm to the onshore grid integration point. As offshore wind farms migrate further from onshore connection points, the HVDC transmission method becomes an attractive investment option, [71]. At an offshore substation, the AC collector uses a traditional step-up transformer, to step up the voltage, which is then converted to HVDC for power transmission to shore via subsea cables as shown in Figure 12.

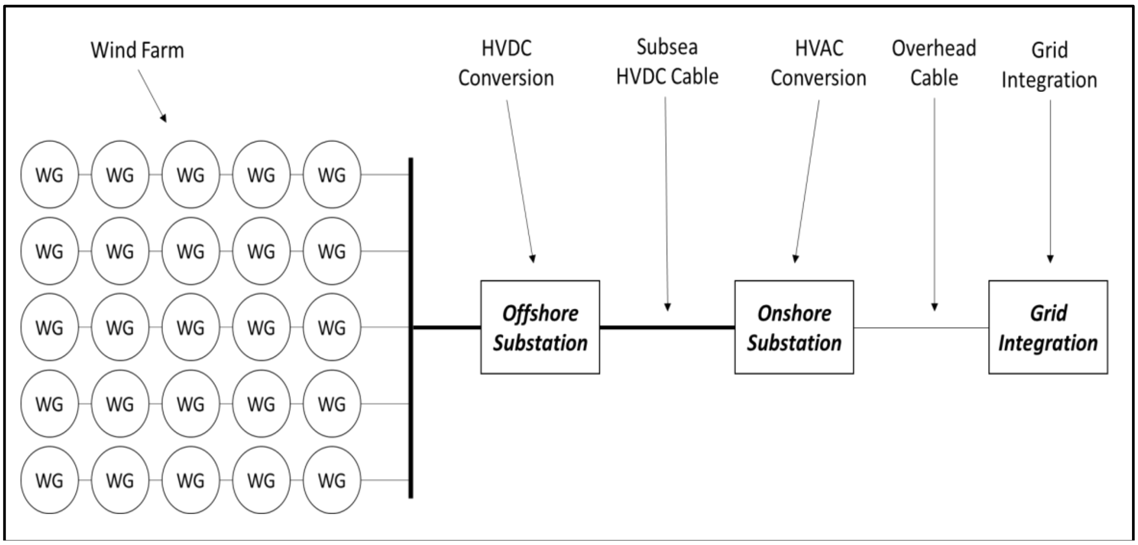

Figure 12: HVDC Grid Integration

The HVDC network architecture utilizes a step-up AC transformer at the offshore substation collector which then feeds into a controlled rectifier that transmits the HVDC power via subsea cable to an onshore substation collector. At this point, the HDVC passes through an inverter which is then collected into an AC step-down transformer which is integrated into the electrical grid.

There are two main types of HVDC transmission technology, the first which is the line commutated converter (LCC) and the second being voltage source converter (VSC). The LCC requires a compensator to support the voltage and reactive power that integrates to the offshore electrical common bus bar. The VSC though, does not need the reactive power compensation and has the added benefit ofblack-start capability, meaning it does not need conventional generation units to retrieve the electrical system, [72].

1.8 Offshore Wind Potential – South Africa

South Africa has undergone significant changes concerning renewable energy deployment in the country. The need for South Africa's energy diversification was conceived in the Department of Minerals and Energy (now Department of Mineral Resources and Energy – DMRE) White paper of 1998 which highlighted the need for primary energy diversification under objective 5 of the paper, [73]. This was further followed by the 2003 update to the paper which extended the diversification to cleaner energy generation in line with international commitments such as the Paris Accord, [74].

The Renewable Energy Independent Power Producer Procurement Program (REIPPPP) of South Africa, launched in 2011, has received international recognition for the program's success and lessons learned as a mechanism to stimulate private-public participation in the renewable sector, [75], [76]. Figure 13 depicts a map of the successful renewable energy plants from bid windows 1-4 of the REIPPP program, [77]. Concerning wind energy, the figure shows that the eastern and western cape regions have the most installed wind energy in the country.

The REIPPPP and the Integrated Resource Plan (IRP) 2019 [78] do not yet accommodate offshore wind energy for South Africa yet Cunden, K and Inambao, F.L. had investigated the offshore wind resource potential for South Africa in [28] deep-sea locations. This was to understand the potential of floating offshore wind turbines and the benefits for coastal region energy supply.

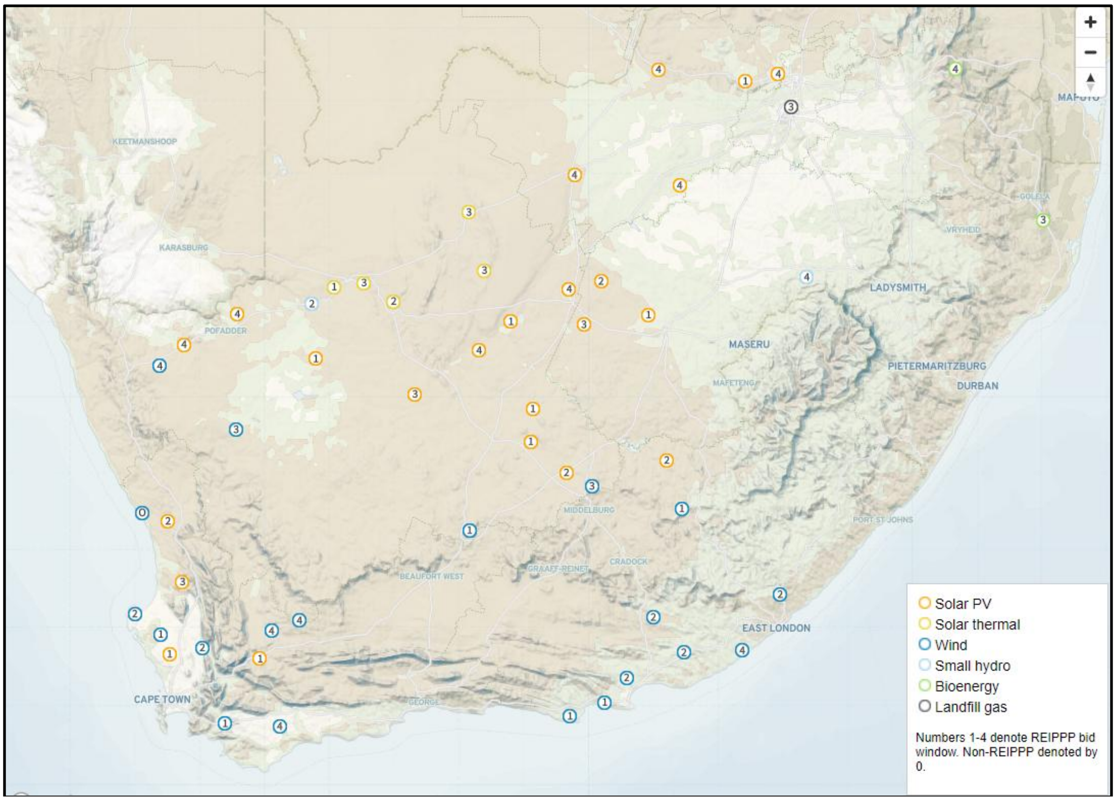

Figure 13: South African REIPPPP Technology Map, [77]

The study had found that there is significant potential for the South African coastline along the eastern and western coasts shown as potential site locations in Figure 14. The ocean depth, of sites that were located 200 km to 500 km from shore, was found to be more than 2 km deep in some region which call for the need for floating offshore wind turbines. The deep-water regions are due to the steep continental shelf which is found around South Africa. Studies conducted by researchers of [79] and [70] have shown that HVDC may be viable for grid integration of far offshore wind farms due to the advantages of HVDC compared to HVAC concerning the distance to shore.

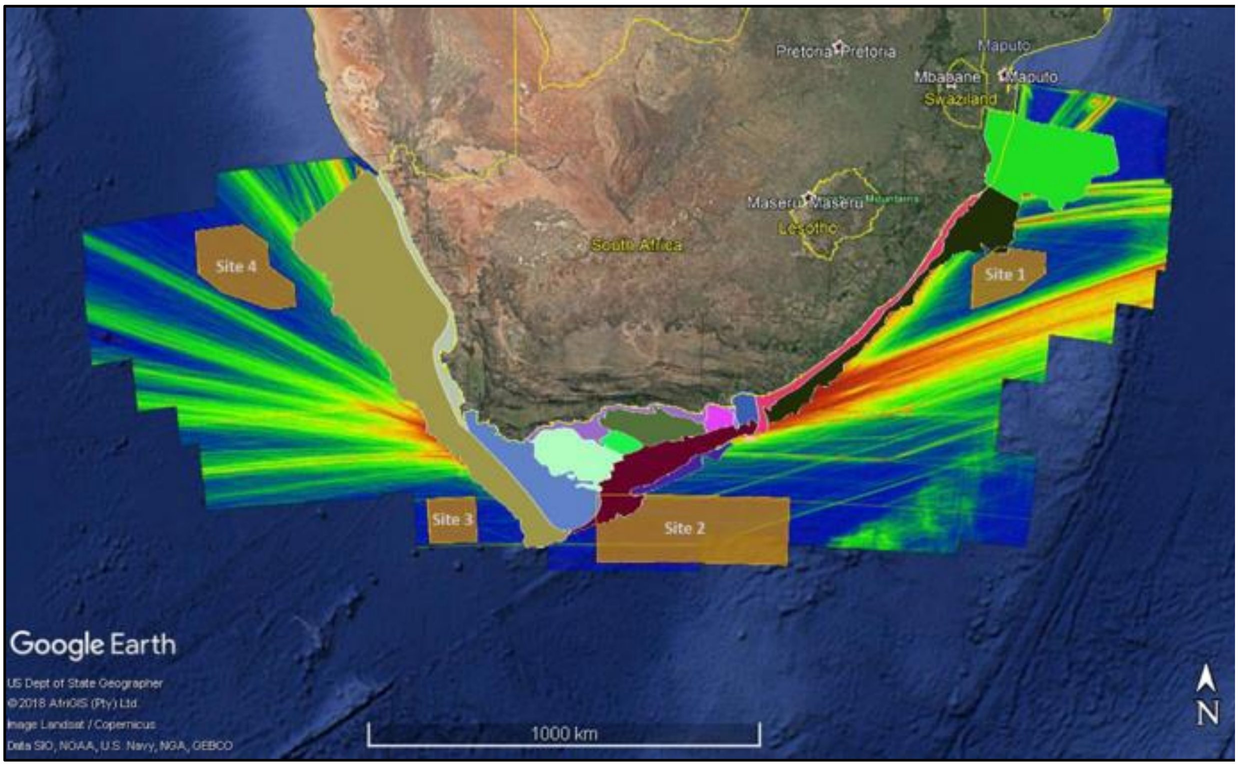

Figure 14: Identified Potential Site Locations, [28]

The site locations shown in Figure 14 have power densities ranging from 591 W/m^2 to a maximum of 1201 W/m^2 between hub height ranges of 100 m to 200 m, [28]. However, due to the current needs of the state, options that are roughly 100 km from the onshore connection may also be a suitable option for an offshore wind farm development. This would require permit clearance for the oil and gas blocks, clearance protocols for major shipping routes, existing fishing rights and environmental permitting required to name a few, [80], [81].

The turbines may lay along the coastal regions which can be coupled with the appropriate floating wind platforms as shown in Figure 7 and anchored to the ocean floor with a mooring system as shown in Figure 8 may assist in developing large-scale floating offshore wind farms. Choice of the best-suited anchor is required as shown in Figure 9 above. The study of the soil structure at various anchor levels is required to ensure the wind farm is harnessed to the seabed during rough sea conditions. This also requires a complex hydrodynamic study of the oceanic forces, induced resonance, and acoustic vibrations on the mounting structure and rotating body.

1.9 Conclusion

The following study aimed to review the key components of the offshore wind industry for a case study of South Africa. The study examined the differences between turbine configurations such as HAWT and VAWT designs turbines. The types of foundations were also examined for an offshore application for fixed and floating offshore wind turbines and the requirements for each of the configurations. The power evacuation network architecture was also investigated and comparisons of HVAC to HVDC were conducted. Studies conducted by [28] show the offshore wind resource potential for South Africa as well as potential sites along the eastern and western coastline of the country.

1.10 Future Work

Future geotechnical research requires to be conducted per potential site to understand the grain structure, soil composition, and ocean hydrodynamics to design a suitable offshore platform and mooring system for the wind farm. The examination also is required of the onshore grid connection points and the availability of capacity of the regional network for grid integration of the offshore wind farm.

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