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Assessment of the locational potential of floating offshore wind energy in South Africa

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Abstract

Expanding floating wind into new markets could support emission reduction targets in several national contexts. It furthers the need for adequate assessments to gain a full understanding of the technology's potential in future markets. South Africa is a prime case study as it has seen limited industry and policy developments despite its huge technical potential for floating offshore wind (FOW). This paper assessed the locational potential of floating wind in South Africa through a three-phased approach that evaluated the key technical drivers/barriers of the technology, conducted a Geographic Information System analysis (GIS) using ArcMap 10.8 to exclude unsuitable sites based on a predetermined exclusion criteria (including marine protected zones, underwater cables, major oil and gas deposits, etc.), and estimated the total harvestable capacity in the feasible sites. The study found that 2% (246,105.4 km^2) of South Africa's entire Exclusive Economic Zone (EEZ) is suitable for hosting floating wind turbines, with a potential to generate a maximum of 142.61 GW of floating wind power. Although the Western Cape province holds the highest potential (80.52 GW) for floating wind in the country, the Eastern Cape region, with a locational potential of 20.04 GW, is considered most suitable for early-stage developments due to the availability of grid connection points, limited marine traffic, and proximity to appropriate port facilities. Future work can conduct techno-economic assessments to evaluate the technical and economic implications of developing floating wind in distinct sites in the country's EEZ.

Keywords Floating wind, Offshore wind, Technical potential, Locational potential, GIS, South Africa

Introduction

Floating offshore wind turbines (FOWT) can unlock greater wind power generation in deeper and more distant waters, due to the presence of stronger and more stable mean wind speeds (Hannon et al., 2019). As opposed to bottom-fixed structures, where foundations like jackets, gravity-based structures and monopiles are utilised for turbine-tower mounting (IRENA, 2016), FOWT utilises floaters (such as tension-leg platform [TLP], semi-submersible, and spar-buoy), along with a station-keeping system (including moorings and anchors), for turbine mounting in water depths greater than 50 m (EWEA, 2013). Amidst the numerous floater typologies currently under development, the major floating foundations include tension-leg platform (TLP), barge, semi-submersible, and spar (as displayed in Fig. 1) (Carbon Trust, 2015). The technology could facilitate better capacity factors and play a key role in the energy transition, as 80% of global offshore wind resources are in deeper waters (i.e. in water depths greater than fifty metres) (Wind Europe, 2017). In recent times, there has been an increased level of activity in the floating wind market, as the sector heads for full commercialisation around 2030 (GWEC, 2019). With more than 100 MW of capacity currently installed, the commercialisation of this technology will see it play a major part in the global energy mix with a projected capacity of 250 GW (2% of global power supply) by 2050 (DNV, 2020).

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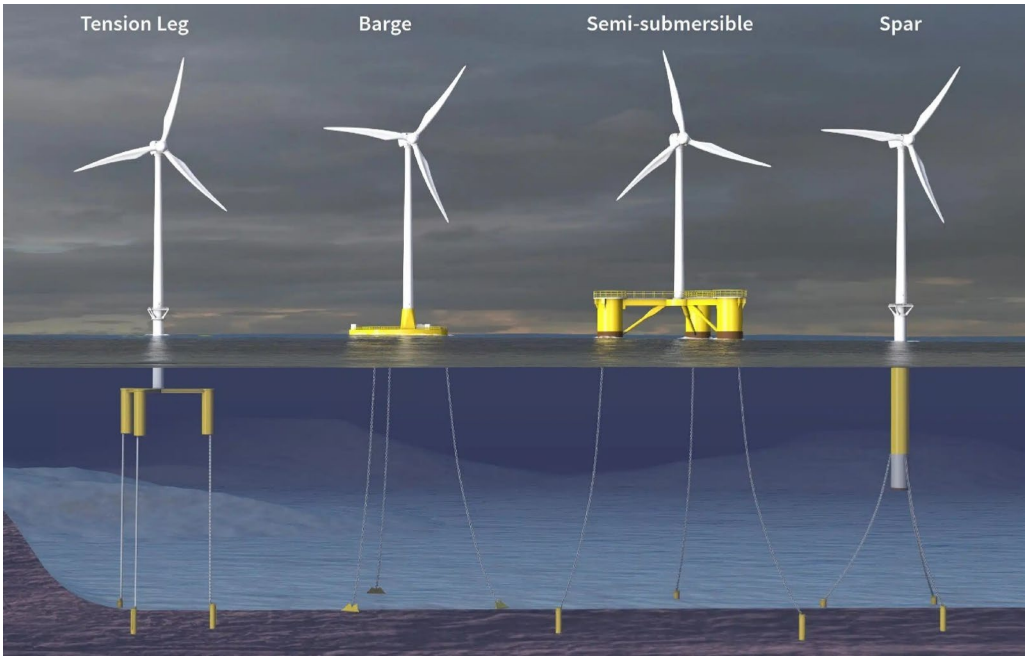

Fig. 1 Major floating foundations (Source: Acteon, 2024)

Much of the movements in the floating wind industry so far has been in Europe, with the UK and Norway leading in both deployment capacity and supply chain activities. The first pilot scale floating wind array, 30 MW Hywind Scotland Pilot Park, was commissioned by Equinor (Norway) off the North-East of Scotland in 2017. This project recorded a capacity factor of 56% in its first two years of operation (Equinor, 2019), thereby further validating the technical and commercial viability of FOWT. Countries or regions with suitable offshore wind sites limited to deeper waters and possessing capable maritime supply chains are considered key future markets in floating wind. They include Japan, South Korea, and the USA, who are expected to deploy 11 GW, 10 GW, and 9.8 GW of floating wind by 2040, respectively (Carbon Trust, 2020). Moreover, a study by ESMAP (2019), sponsored by the World Bank, also found huge technical potential for floating wind in the African continent, with South Africa and Morocco having possible deployment capacities of 589 GW and 178 GW, respectively—which are significantly higher than their technical potentials for bottom-fixed offshore wind (57 GW in South Africa and 22 GW in Morocco). With no offshore wind deployment till date (IRENA, 2019), the viability of floating wind in these countries are in question.

Feasibility studies for floating offshore wind (FOW) development in future markets has received limited research attention. The Global Wind Energy Council (GWEC, 2022a) produced a report which assessed the potential for development in future floating wind markets. They ranked these markets based on technical, supply chain, and policy factors and provided snapshots of the drivers and constraints present in the highest-ranked countries, such as Ireland, Philippines, and USA (California). There were no inclusions of the optimum zones for floating wind development in this study. In Umoh and Lemon's (2020) work, the drivers and barriers associated with floating wind deployment in South Africa were assessed through a conceptual framework that evaluated the technical, economic, political, and social factors which could facilitate or hinder the development of the technology. The study relied on qualitative data and did not fully address key parameters in FOW development, including site conditions, port capability, and grid capacity. ESMAP's (2019) study assessed the technical potential of offshore wind development in emerging markets, including South Africa, Brazil, India, and Turkey. The study developed a framework for offshore wind feasibility studies that highlighted the importance of technical, locational, economic, and actual deployment assessments for bottom-fixed and floating offshore wind technologies; nevertheless, the scope of the paper was limited to analysing the technical potential of offshore wind in these emerging markets. Karamanski and Erfort's (2023) work is closely related to the focus of the current paper, as they assessed offshore wind potential in South Africa's coast via a methodology that considered the supply profile of existing onshore wind farms along with electricity demand in the country. The authors then evaluated the potential for offshore wind to meet current supply shortages by calculating the technical potential using a Vestas V164-9.5 MW turbine. Taking into account wake effects, electrical, and other losses, they found possible generation capacities of 64 GW and 764 GW for bottom-fixed and floating wind, respectively; however, the technical constraints associated with turbine siting and detailed analysis of the regional potentials for floating offshore wind power generation in the South Africa were not considered.

South Africa has a 589 GW technical potential for floating offshore wind technology, which is significantly larger than its 57 GW technical potential for bottom-fixed offshore wind (ESMAP, 2019). The case for floating offshore wind energy development in South Africa is validated by the country's ageing coal-fired power plants and associated energy crisis (Bloomberg, 2022; National Planning Committee RSA, 2012). To address this issue, the government in the Republic of South Africa established the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) in 2011, which has facilitated the procurement of 6422 MW of renewable energy projects to date (Department of Mineral Resources & Energy RSA, 2019). This indicates a healthy appetite for renewable energy deployment, which could spur greater activity in the country's floating wind market soon (Umoh & Lemon, 2020). More research can advise industry and policymakers on the technical and economic feasibility of FOWT in South Africa. Knowledge of technical factors, such as grid infrastructure, port capability, and site conditions can help determine the techno-economic feasibility of the technology in distinct locations (GWEC, 2022a). For instance, the availability and lack of suitable grid connection points in various locations enabled or stifled the development of early-stage floating wind projects in the UK (Carbon Trust and ORE Catapult, 2017). Ports also play a crucial role in the manufacturing, assembly, installation, and operations and maintenance (O&M) of floating wind components (Wind Europe, 2020), indicating that they must be developed strategically to facilitate the build-out of offshore wind farms (The Crown Estate Scotland, 2020). Similarly, site conditions ascertain what locations could best host floating wind turbines due to varying factors including seabed structure, water depth, and wind speed, which invariably affect the costs associated with developing a project (Carbon BVG Associates, 2019; Trust, 2015).

Although beyond the scope of this work, understanding the financial implications of developing floating wind projects can stimulate market activity and improve investor confidence. Available cost models in the literature can be modified or applied directly to potential sites in future markets to calculate the relevant financial metrics in floating wind development. For example, Castro-Santos et al. (2016) developed a methodology to calculate the internal rate of return (IRR), net present value (NPV), and levelized cost of electricity (LCOE) of floating wind in the Galician region of Spain using the three major floating foundations. Following a technical analysis of the wind farm via a GIS software, the study concluded that the area situated between the Ría de Pontevedra and the Ría de Ribadeo was most suitable for floating wind development, with the possibility of achieving an LCOE value of €75.11/MWh on a semisubmersible floating foundation. Ioannou et al.'s (2018) work can be considered an improvement on the previous study as it provided a more detailed breakdown of the capital expenditure (CAPEX), operational expenditure (OPEX), and decommissioning expenditure (DECEX) modules as well as applied the model from an investor perspective to reveal the implications of investing in FOW projects at different stages of its life cycle.

Other studies have sought to improve upon existing models by optimising cost criteria with models from both bottom-fixed and floating wind technologies (Maienza et al., 2020) and developing cost assumptions with respect to literature and installed floating wind projects in Europe (Rinaldi et al., 2021; Diaz and Soares, 2023). A lack of agreement on the most cost-effective floating platform and the novelty of the technology implies the need for continuous refinement of existing cost models, especially considering that some floater typologies (such as TLPs) are yet to achieve higher technology readiness levels (Leimeister et al., 2018). It is worth noting that three turbines using SBM Offshore's TLP design were installed in the South of France in October 2023, indicating a huge step towards the commercialisation of this floater typology (SBM Offshore, 2023). However, adequate operational data are required to fully understand its technical characteristics and performance.

The identification of suitable zones for deployment represents a crucial first step in the initial stages of developing any floating wind project. It allows for the collection and analyses of information from regulatory bodies, marine spatial planning, maritime lease agreements, and other relevant sources (Diaz and Soares, 2020). This contributes to the sustainable and strategic development of this technology, which considers key stakeholders in proposed exploration zones. For instance, Taoufik and Fekri's (2021) work considered six exclusion criteria (including submarine cables, shipping routes, bird migratory routes, and blue flag beaches) in relation to the technical and socio-economic factors of offshore wind development in Morocco. In the Philippines, local ferry routes, typhoon paths, and areas prone to earthquakes, were excluded from offshore wind considerations to reflect the specific constraints present in the case study context (Maandall et al., 2021). This implies that conducting such feasibility assessments could provide a clearer picture of the locational potential of FOWT in countries with significant technical potential for the technology. Therefore, the principal aim of this paper is to study the main exclusion criteria for prospective FOW deployment in South Africa. The significant contributions of this study include: (i) development of a new methodology for assessing the locational potential of FOW in new markets using ArcGIS and proposed exclusion criteria; (ii) providing an in-depth analysis of the most relevant technical aspects of FOW development in South Africa; (iii) conducting an advanced GIS analysis to exclude non-feasible zones from current considerations in FOW development in South Africa; and (iv) estimating the locational potential of FOWT based on the results of the GIS analysis. The outcomes of this study would be of great benefit to industry and policymakers as it will outline a systematic approach for a streamlined and sustainable development of FOW farms in South Africa and future markets.

The remaining sections of this paper are organised as follows: Sect. "Materials and methods" discusses the material and methods; Sect. "Case study: South Africa" provides a technical analysis of the major drivers and barriers of floating wind with respect to the study area; Sect. "Exclusion criteria" performs a site exclusion analysis; Sect. "Locational potential" is concerned with the locational potential of floating wind in South Africa; Sect. "Discussions" discusses the main findings; and Sect. "Conclusions" concludes.

Materials and methods

Content analysis

This work adopts GWEC's (2022a) framework for assessing the major drivers and barriers of FOW development. The report asserted that site conditions, policy environment, support regime, permitting regime, supply chain and infrastructure (ports), and transmission grid were key drivers and constraints to the build-out of floating wind in follower markets (GWEC, 2022a). The approach was modified to limit data collection and analysis to the technical factors of FOW deployment, including site conditions, port capability, and transmission grid. A focus on the technical factors represents the current state of development of FOWT in future markets, which is characterised by limited market and policy developments. The approach sought to evaluate these technical factors in greater detail, when compared to similar studies in the case study context (Rae & Erfort, 2020; Umoh & Lemon, 2020), in order to improve understanding on the actual deployment potential of floating wind in South Africa. Data were obtained from the wider FOW literature and relevant national agencies to ensure that analyses were representative of the current and future developments in the floating wind sector as well as relevant to the study area. The key technical drivers and barriers of floating wind development considered in this work are as follows:

Site conditions. Factors including wind speeds, bathymetry, geotechnical, and metocean conditions indicate the technical potential of offshore areas.

Port capability. Port capabilities, local industrial capacities, and possible synergies from related sectors can influence site selection in FOW development.

Grid infrastructure. Grid capabilities and build-out plans that could determine the feasibility of potential sites.

Site exclusion

This stage entails an analysis of literature and secondary data to determine the technical, socio-economic, and environmental constraints relevant to FOWT in the study area. Wind speed is a critical component of floating wind development (Carbon Trust, 2015) and considering that current wind turbines are planted with hub heights greater than 100 m (IRENA, 2019), it is difficult to anticipate future deployments at lower hub heights. Moreover, sites above 6 m/s are commercially viable for offshore wind development (ESMAP, 2019). Floating platforms, including semisubmersibles, spars, and TLPs, can be installed in water depths between 50 and 1000 m (Carbon Trust, 2015). In the context of environmental sustainability, factors including marine protected areas and bird migratory routes must be considered to promote sustainable development of floating offshore wind farms (Taoufik & Fekri, 2021; van and Fthenakis, 2011). Oil and gas development zones and underwater cables are other key technical factors that have been defined as constraints to offshore wind development by extant research (Diaz and Soares, 2020; Maandal et al., 2021). In addition, the Exclusive Economic Ezone (EEZ) of desired national contexts should be regarded as the study area, as sovereign states have control over resources in this zone. ArcMap 10.8 can be used to enable visualisation of the study area. This software enables the representation and analysis of geographic information in the form of layers and other elements in a map, which provides a robust platform for evaluating the exclusion criteria of a study area.

Wind generation

To determine the locational potential of FOWT, it is necessary to calculate the actual energy available in the feasible sites. This implies calculating the wind power density of the identified locations and evaluating the total harvestable capacity with respect to each province and/or for the entire EEZ.

To compute the wind power density (WPD) that measures the moving power of wind, theoretical literature (Francis et al., 2012) uses the following formula:

$$WPD = 0.5\rho V^3 A, \tag{1}$$

where ρ is the constant air density value (1.225 kg/m^3), V is the average wind speed, and A is the swept area of the turbine (Francis et al., 2012).

To estimate the possible generation capacity, this work considered the current project data of floating wind farms from 4C Offshore (2023). 4C Offshore is the leading market intelligence organisation targeting global offshore renewable energy markets. Their Global Offshore Wind Farm Database and Intelligence service provides data on offshore wind projects all over the world. Information including the turbine swept area, power curve, site area, and average area per wind turbine were sourced and contributed to approximating the locational potential of FOWT. The possible impacts of moorings and anchors on turbine spacing were also considered, as floating wind turbines are expected to have extended footprints when compared to bottom-fixed offshore wind technology (Carbon Trust and ORE Catapult, 2017). Besides, the relatively larger area per wind turbine (5.3 km^2/turbine) in semisubmersible floating wind farms when compared to spars (3.3 km^2/turbine) (4C Offshore, 2023), can be explained by the lesser turbine footprint in spars when compared with semisubmersibles (Carbon Trust and ORE Catapult, 2023). Consequently, Vestas's (2023) V164-8.0 MW turbine, which has a 164 m rotor diameter and a swept area of 21,124 m, was selected for analyses in this work. The locational potential was derived using the formula below (Myhr et al., 2014; Nie & Li, 2018):

$$WP_{loc} = \frac{A_S}{A_T} * WPD * \frac{16}{27} * (1 - L), \tag{2}$$

where A_S is the geographical area available for floating wind deployment; A_T is the average area per wind turbine: WPD is the wind power density; 16/27 is the Betz limit; and L represents losses, including electrical array losses, aerodynamic losses, wind farm availability and other losses—modelled as 18% (Myhr et al., 2014). The methodology is summarised in Fig. 2.

Case study: South Africa

South Africa's onshore wind energy market has seen steady growth since the installation of the Darling Wind Farm in the Western Cape region of the country in 2008. The 5.2 MW rated wind farm generates an average of 8.6 GWh annually and helps power about

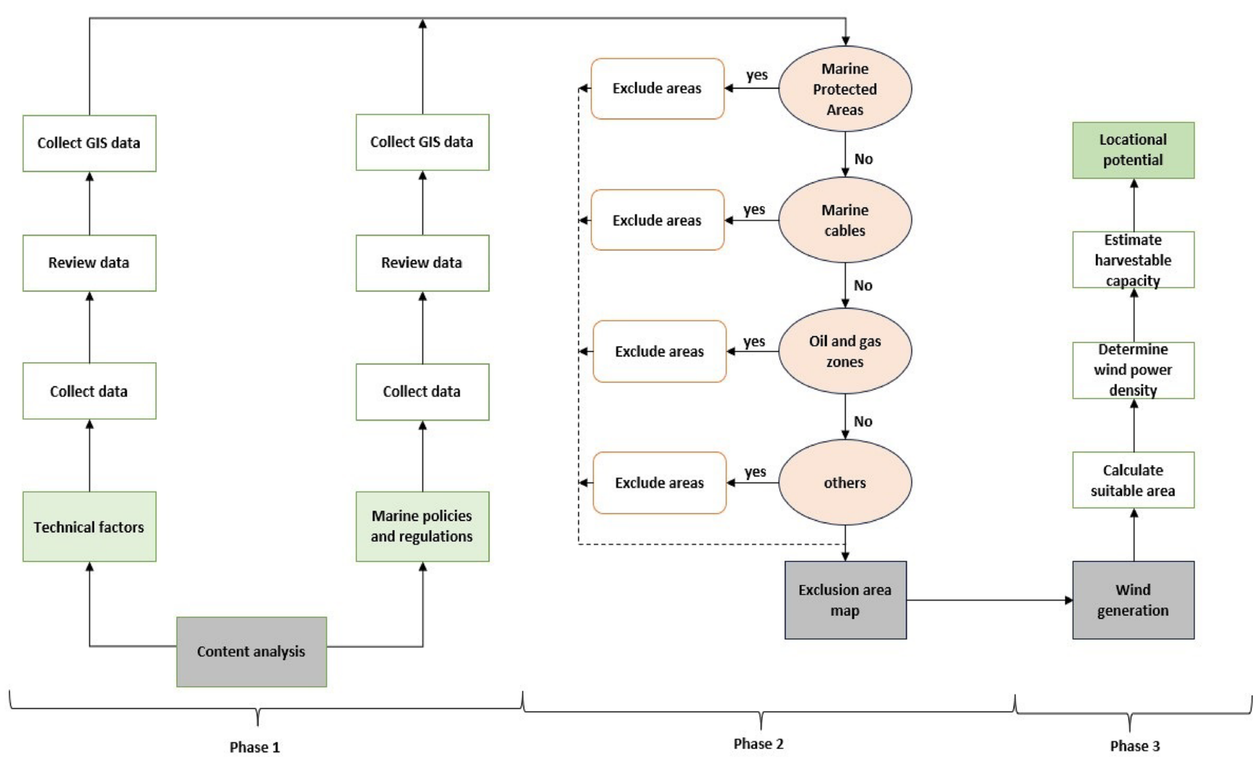

Fig. 2 Methodological approach

700 households in South Africa (Kruger Africa, 2008). The total onshore wind capacity in South Africa currently stands at 2495 MW as of the end of 2020, following the installation of 515 MW of new capacity in that year (GWEC, 2020). This growth can be attributed to the government's Integrated Resource Plan (IRP), which was launched in March 2011 as an electricity infrastructure development plan aimed at developing 39,730 MW of new capacity and reducing its energy sector's GHG emissions (Department of Mineral Resources & Energy RSA, 2019). The plan facilitated the REIPPPP, which has enabled the procurement of 6422 MW of renewable energy projects (Department of Mineral Resources & Energy RSA, 2019). Over 50% (3357 MW) of this capacity have been procured for onshore wind projects (Department of Mineral Resources & Energy RSA, 2021). Despite the recent increases in installed onshore wind capacity Africa, as spearheaded by South Africa, the region is said to be exploiting only 0.01% of its wind energy potential (GWEC, 2022b). South Africa could take advantage of its vast wind resources to tackle its energy crisis, meet its GHG emission reduction targets, and establish itself as a global hub for wind development.

Limited research has assessed the feasibility of offshore wind (bottom-fixed and floating) in South Africa despite the potent wind resources in its offshore wind region. A study by Rae and Erfort (2020) found offshore wind potentials of 44.52 TWh and 2387.08 TWh in water depths below 50 m and between 50 and 1000 m, respectively, in South Africa's offshore EEZ. The abundance of wind energy in deeper waters implies that deploying floating platforms could maximise the technical potential of offshore wind in the region. Elsner (2019) furthered that huge technical potential for offshore wind development in deeper waters calls for an integrated deployment approach amongst coastal states in the southern African region. Such endeavours require multidisciplinary studies that assess the major factors associated with the development of the technology. Moreover, the levelized cost of floating wind-generated energy, which is currently double the cost of bottom-fixed (Wind Europe, 2017), could deter investors, industry actors, and policymakers from current and future floating wind development efforts.

Site conditions

Marine region characteristics such as wind speeds and water depths are major determinants of site choice and platform selection in FOW development (Carbon Trust, 2015). Sites with mean wind speeds over 6 m/s and water depths between 50 and 1000 m are considered technically feasible zones for the deployment of floating foundations (The Crown Estate Scotland, 2020). Figure 3 shows the area with technical potential for FOW development in South Africa with mean wind speeds at 100 m hub height ranging from 6 to 12 m/s and water depths between 50 and 1000 m. Wind speed data, as obtained from the Global Wind Atlas (2022), are based on a long-term reference data (2008–2017) of ERA5 (a climate dataset developed through the Copernicus Climate Change Service) reanalysis data. Data showing water depths were sourced from the General Bathymetry Chart of the Oceans' (GEBCO) (2022) gridded bathymetry data. The resulting area has a total size of 335,673.8 km^2, which is over 5% of the country's EEZ. Nevertheless, the suitability of various floater typologies varies with respect to water depth. Spar buoys require water depth above 100 m; semi-submersibles can be utilised in water depths as low as 50 m; TLPs are appropriate for water depths greater than 60 m (IRENA, 2016).

An assessment of the geotechnical conditions of potential development zones is also necessary to inform developers on choice of anchors for floating platforms (Carbon Trust, 2020). Geotechnical surveys, which investigate the soil composition of offshore sites, usually begin at least five years before the commissioning of a wind farm and costs around £2.5 million for a 1 GW rated wind farm (BVG Associates, 2019). Its prohibitive cost implies that early-stage development could benefit from readymade geotechnical datasets from suppliers such as Fugro, Horizon, and G-tec. Current specifications for anchor deployment were discussed in Carbon Trust's (2015) work. They stated that drag-embedded anchors and suction piles were more appropriate for soft soils, while gravity anchors and driven piles were preferred for tougher soil conditions. Anchors may lead to heightened sedimentation (due to scour) and could trigger stressors to deep-sea benthic communities (DNV, 2020). This implies that early projects should be sited in less environmentally sensitive areas to mitigate the impacts of FOWT on marine habitats.

Met-ocean conditions can influence the design of floating platforms, installation activities, and O&M planning. Greater extreme wave heights indicate the need for conservative substructure design as floating platforms would require the optimal weight to counteract wave loading in these areas. Although the potential for improved component design and the integration of wave cancelling functionality in wind turbine controllers have been discussed in Lemmer et al.'s (2020) paper, their implication for FOW deployment is increased CAPEX and LCOE costs, which are undesirable in early-stage technology demonstrations. Besides, project cost overruns due to the inaccessibility of floating wind sites could negate the technical and commercial viability of this technology in future markets. Carbon Trust (2015) provided wave

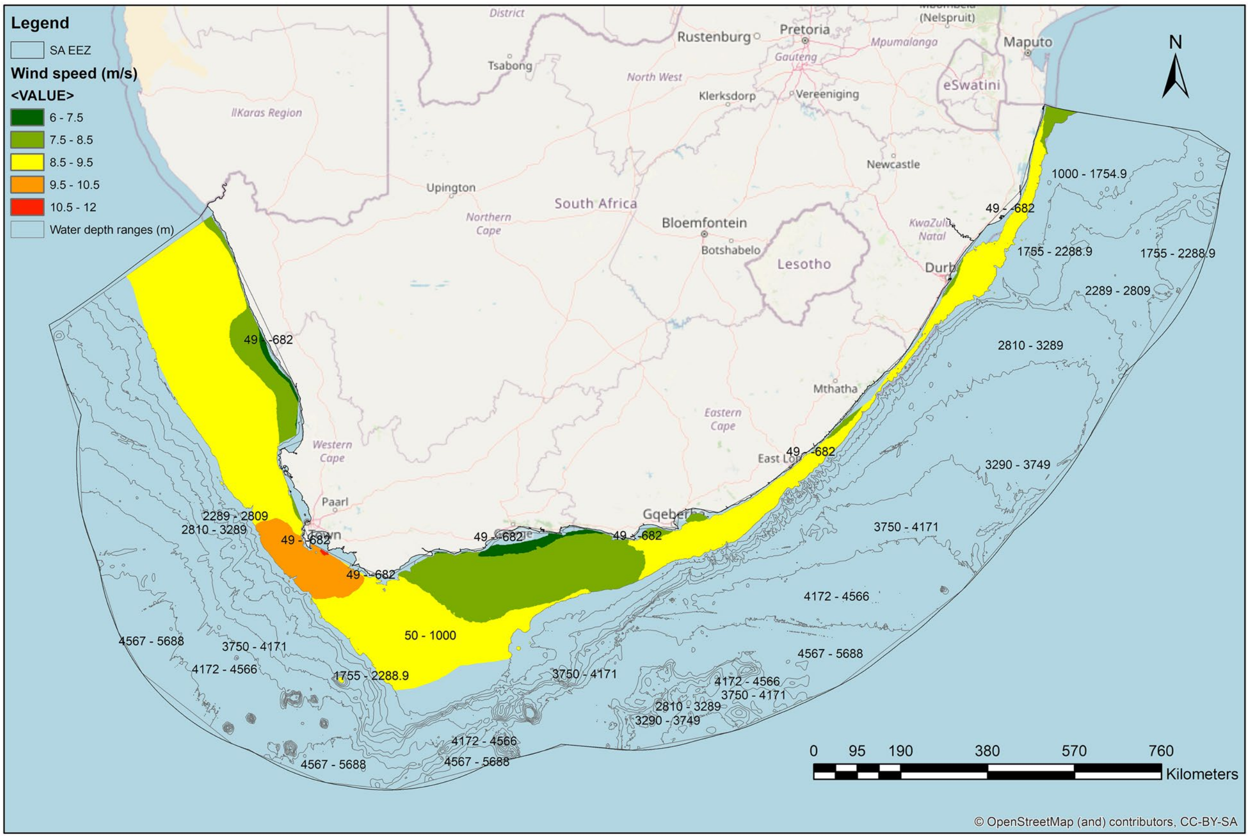

Fig. 3 Technically feasible zones for FOW development in SA (data sources: GEBCO, 2022; Global Wind Atlas, 2022)

height recommendations for various platform types. For example, installation activities for TLPs should be limited to wave heights of around 1.5 m, while semisubmersible platforms can be installed in wave heights of up to 2 m. The ERA5 climate dataset which has been developed through the Copernicus Climate Change Service (2018) provides historical data of significant wave heights in some offshore sites in South Africa. An assessment of such data could enable a better planning of installation and O&M activities in these zones.

Port capability

In offshore wind development, factors such as quay load-bearing capacity, port depth, proximity to site, quay length, and potential for expansion are crucial to optimum site selection in relation to installation, and O&M activities (Ozturk and Karipoglu, 2021). Port requirements for installation generally include a minimum of 8 hectares appropriate for laydown and pre-assembly of components; water access capable of receiving vessels with a 140 m length, 45 m beam, and 6 m draft, and without tidal or other entry restrictions; and overhead clearance of 100 m and above (Carbon Trust, 2015). Wind farm developers will usually secure long-term leases for quayside services with port owners to ensure a suitable base for O&M activities (Carbon Trust, 2015). The Crown Estate Scotland (2020) conducted a port capability assessment for FOW deployment in Scotland. Although the specific port requirements for this novel technology is uncertain, they concluded that proximity to site as well as extra specialist port facilities are of great significance with respect to future floating wind endeavours in the country. For instance, semisubmersible floaters would require 20 to 25 m water depth for turbine mounting at quayside, while spars may require an 80–90 m water depth or availability of a sheltered locations offshore for horizontal float-out installation operations (The Crown Estate Scotland, 2020). The additional port requirements for floating wind development entails the need for adequate collaboration between key stakeholders, including wind farm owners, regional policymakers, and port operator, to map out strategies to ensure a sustainable and cost-effective approach to building out FOW farms in South Africa.

Figure 4 displays the major ports in South Africa and their respective sizes. The largest port, Port of Durban, represents the busiest port both in South African and sub-Saharan Africa (National Ports Authority, 2022).

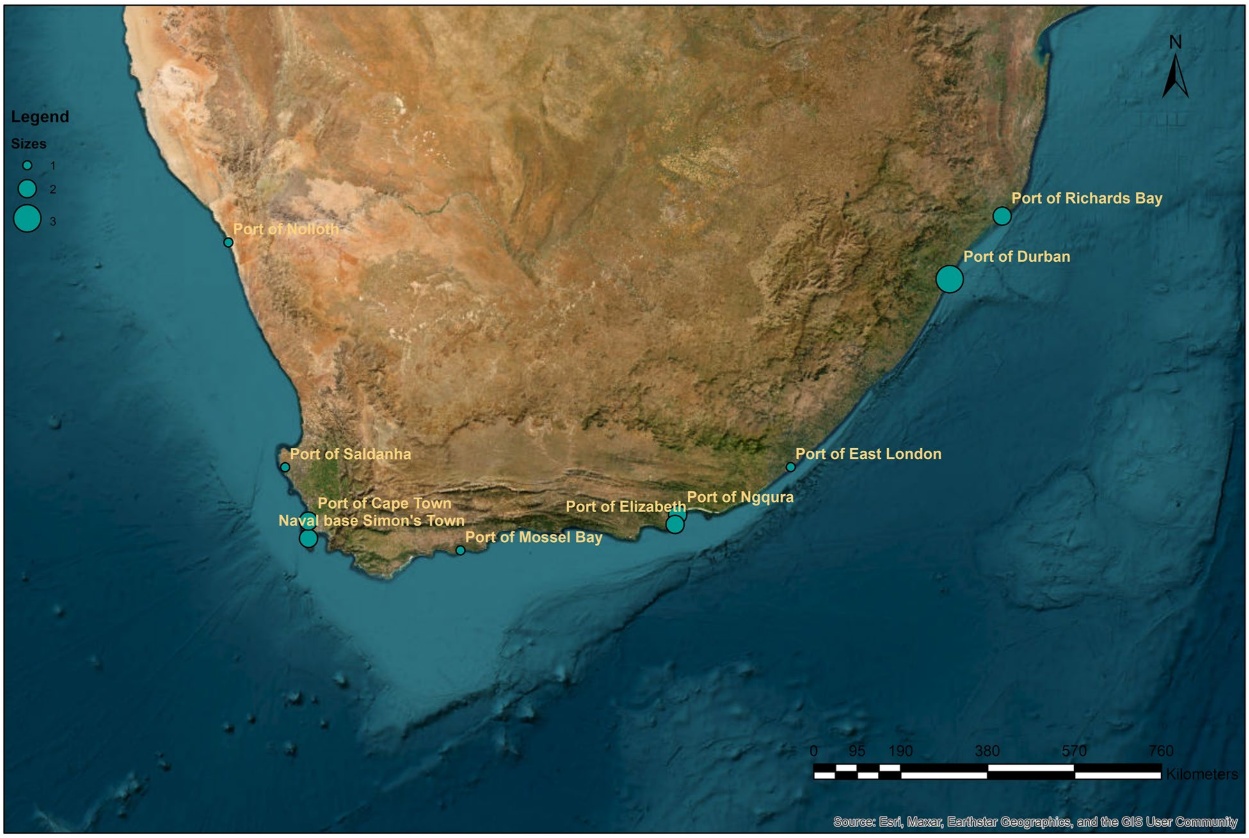

Fig. 4 Ports in South Africa (data source: World Port Source, 2022). Sizes: 1 = small; 2 = medium; 3 = large

It is equipped with 8 tugboats, 2 pilot boats, 2 pilot boats, 2 pilot helicopters, 1 floating dock, and 1 passenger vessel; nevertheless, the bulk of its services are concentrated on container haulage and storage (National Port Authority, 2022). The Prince Edward Dry Dock (350.52 m × 33.53 m × 12.5 m), which is situated in the Port of Durban, has seven cranes with capacities ranging from 4 to 50 t and a quay depth of 8 m (National Ports Authority, 2022). Although the region boasts of excellent wind resources (as seen in Fig. 2), the Port of Durban specifications may be unsuitable as a marshalling and installation base for early stage floating wind projects due to its limited dry dock width, shallow draft, and its low crane lifting capacity. For instance, turbines mounted on the semisubmersible floating foundations may require a port area with 90 m and draft of up to 14 m (Crowle & Thies, 2022). Similarly, crane lifting capacity requirement is 550 tonnes for all foundation types (Carbon Trust and ORE Catapult, 2017). As large port size does not necessarily translate to port suitability, a timely and extensive engagement with port suppliers is essential to understanding the suitability of the existing ports for specific floating wind projects or the extent of upgrades required to accommodate construction, marshalling, or O&M activities.

On the other hand, the Cape Town region has the most potent wind resources in South Africa's EEZ (see Fig. 3) as well as potentially suitable ports for the installation and maintenance of turbines mounted on all existing floater typologies (Umoh & Lemon, 2020). The multipurpose Duncan Dry Dock (1800 m × 600 m), located in the Victoria basin of the Port of Cape Town, has a 180-m-wide entrance and 12.9 m depth, which could facilitate the mating of turbines to floating substructures before they are transported to potential offshore sites (Umoh & Lemon, 2020; World Port Source, 2022). In addition, its 253 hectares of laydown area and appropriate quay lengths (World Port Source, 2022) indicates adequate port area for the storage and assembly of commercial scale wind farm components such as tower, nacelle, blades, and substructures. Moreover, the Nor-Sea Stordbase, which facilitated the storage and assembly of five Hywind spar floating units boasts of a 10-hectare base area and 120 m quay lengths (Norsea Group, 2023).

The coast of Cape Town's high shipping traffic (see Fig. 5) implies a reduced suitability for turbine sitting in the area due to an increased risks of collision with marine

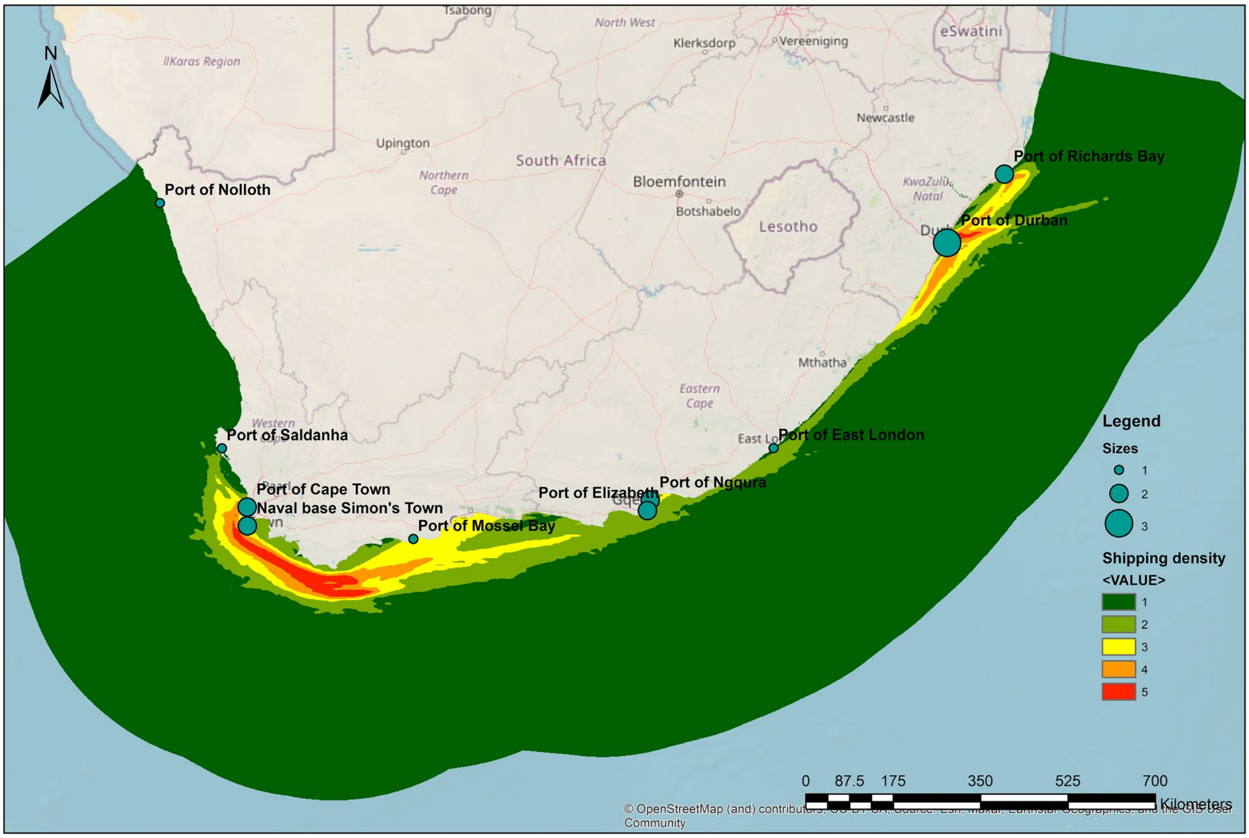

Fig. 5 Shipping density in South Africa's Exclusive Economic Zone (data source: Halpern et al., 2013) Port sizes: 1 = small, 2 = medium, 3 = large; shipping density range: low (1)–high (5)

traffic. Navigational safety is key priority in the context of sustainable site selection in offshore wind development (Rawson & Rogers, 2015). The deployment of offshore wind farms in sites with frequent passenger or cargo vessel traffic could trigger conflicts amongst relevant marine users (Vagiona & Kamilakis, 2018). This makes sites and ports with less marine traffic preferable for turbine sitting and project development activities. Industry and policymakers could further assess the potential for expansion of the Port of Ngqura, due to comparatively limited marine traffic (see Fig. 5) and suitable facilities. The port has an entrance channel of 300 m width, total land area of 1307.77 hectares, and quay depth of 18 m (National Ports Authority, 2023). Development plans currently include the establishment of a ship repair facility and an energy hub, to take advantage of its vast available land area and complement the energy sector development which is underway in the Coega Special Economic Zone (National Ports Authority, 2023).

The existing port or supply chain capabilities in South Africa can be evaluated by exploring potential synergies with the country's burgeoning offshore oil and gas and related sectors. For instance, Scotland's position as a global leader in FOWT has been facilitated by its long-standing experience in the North Sea oil and gas industry (The Crown Estate Scotland, 2020). The transition from fixed to floating foundations for deep water oil and gas exploration in the 1970s prompted the design, construction, and installation of the platform, moorings, and anchors, which have been adapted for use in the offshore wind sector (Carbon Trust, 2015). Although the Hywind and Kincardine floating wind turbines were manufactured and preassembled overseas, the projects have benefitted from the UK's existing supply chain capabilities in installation, operations, and maintenance services (Hannon et al., 2019).

A report by ORE Catapult (2021) has also highlighted how the UK could deploy floating wind to power its oil and gas platforms for decarbonisation and supply chain development purposes. The relevance of the UK case study to South Africa is the huge possibilities within the joint development of the country's offshore oil and gas and floating wind sectors, which could facilitate the upgrade of port facilities with respect to the needs of both sectors. Data from the Petroleum Agency SA (2023) indicate high offshore oil and gas activities in South Africa's

EEZ, with most areas currently under application for exploration or having obtained exploration rights. It reinforces the nascent state of these sectors and the potential for collaboration between oil and gas players and floating wind developers. The Ports of Saldanha, Ngqura, and Richard's Bay, which were identified as viable for facilitating a zero-carbon South African shipping sector (Ricardo, 2022), could be upgraded to meet the installation, operations, and maintenance activities of South African floating wind farms. Synergies between the floating wind industry and shipping sector also exist in that the desired adoption of zero-carbon fuels in the country's shipping sector could drive investments in renewable electricity to meet the local and global demand of green fuels (Ricardo, 2023), such as floating wind-generated green hydrogen.

Table 1 summarises the capabilities of the ports in South Africa. They have been qualitative evaluated using data provided by National Ports Authority (2022, 2023) and World Port Source (2022).

Transmission grid

The availability of suitable grid connection points was key to the selection of the Buchan Deep region as host of the Hywind Scotland floating wind farm (Carbon Trust and ORE Catapult, 2017). This can be seen in the extant literature, where sufficient grid capacity and proximity to grid connection points have been noted as key factors in FOW development (Diaz and Soares, 2020; Maandal et al., 2021). For instance, due to economic and logistical reasons, Diaz and Soares (2020) limited the areas under consideration for FOW development in the European Atlantic Coast to sites within 200 km from the local electricity grid. Similarly, sites with distances greater than 120 km were excluded from consideration due to high uncertainties associated with transmission costs in the Philippines (Maandal et al., 2021). It follows that high priority must be assigned to current grid capabilities and future development plans in the study area. Eskom's (2021) recent Generation Connection Capacity Assessment report revealed a total available connection capacity of 30 GW in South Africa's grid, with its coastal regions (Northern Cape, Western Cape, Eastern Cape, and Kwazulu-Natal) having an available connection capability of around 8.5 GW.

Plans are underway to expand the grid network to accommodate the 9.8 GW and 17 GW of generation capacity expected to be connected by 2025 and between 2026 and 2030, respectively (Eskom, 2021). Although there was no mention of floating or bottom-fixed offshore wind in this report, the Transmission Development Plan revealed an inclination towards renewable integration as well as capital constraints in relation to current and future grid expansion proposals (Eskom, 2022). Eskom (2021) further reported the current supply area capacity of the provinces in South Africa. The total generation connection capacity in the coastal regions are as follows: Northern Cape: 0 MW; Western Cape: 1100 MW; Eastern Cape: 1740 MW; Kwazulu Natal: 5640 MW.

Northern Cape

The Northern Cape zone currently has no generation connection capacity (Eskom, 2021). This is a common trend in the Greater Cape region (consisting of Northern Cape, Eastern cape, and Western Cape networks), as they require significant upgrades to accommodate substantial added generation capacity (Eskom, 2022). With a number of onshore wind and solar projects in the pipeline procured under the REIPPPP, the Northern Cape province has a total of 3.8 GW committed capacity, which significantly exceeds the local peak load (Eskom, 2021). The current transmission network consists of 220 kV and 400 kV lines, which enable power transfer to Kimberley and Upington, where economic activity is concentrated in the province (Eskom, 2021). Current transmission project plans include the strengthening of existing lines and construction of new substations and new transmission lines to facilitate the integration of procured renewable power plants in the province (Eskom, 2022).

Western Cape

The transmission infrastructure in the Western Cape province is made up of 400 kV and 765 kV assets and an available connection capacity of 1.1 GW (Eskom, 2022). The REIPPPP has contributed significantly to the procurement of around 1.5 GW of Independent Power Projects in this province, which has seen the commissioning of 589 MW of wind and solar energy projects (Eskom, 2021). With power demand in its three customer load networks (Peninsula, Outeniqua, and West Coast)

Table 1 Summary of port capabilities

Port	Capability	Remark
Port of Durban	Low	Limited dry dock width, shallow draft, high vessel traffic
Port of Cape Town	Medium	Suitable depth and dock entrance, sufficient laydown area, but high vessel traffic
Port of Ngqura	High	Relatively low vessel traffic, large port laydown area, suitable quay depth, prime for expansions

expected to increase by 24% in the coming decade, major reinforcement plans were initiated to guarantee supply of the projected load as well as enable integration of additional generation capacity (Eskom, 2021). For instance, the Komsberg Substation was commissioned in 2021 to accommodate the procured 6.6 GW of new wind and solar PV generation in the province. There are also plans to establish two 765 kV lines to connect the Mercury and Sterrekus substations by 2031 (Eskom, 2021). Thus, floating wind farms may be connected through the planned 765 kV line in Cape Town, which passes through the Sterrekus, Kappa, and Gamma Substations. This can facilitate power transmission to Northeast region of the country, where power demand is huge (ESMAP, 2019). Besides, the Cape Town region experiences the strongest average wind speeds ranging from 9.5 m/s to 12 m/s (see Fig. 2).

Eastern Cape

The development of floating wind in the Eastern Cape coast can benefit from the substantial substation transformation and transfer capacity in the area (Eskom, 2021). Potential FOW farms can connect to the electricity grid via the Grassridge and Dedisa stations due to their proximity to the technically suitable areas for floating wind development as well as their sufficient connection and transfer capacities. The planned reinforcement of the coastal grid in relation to the construction of a 765 kV line, which connects the Grassridge substation to the Gamma substation in Western Cape, would provide additional transfer capacity when it comes online in 2024 (Eskom, 2022). Due to its potent wind resources and associated procurement of 1.5 GW of wind energy projects in the Eastern Cape province since the introduction of the REIPPPP, this region may require further strengthening to facilitate the integration of new capacity from independent power producers in the period 2022 to 2031 (Eskom, 2022).

Kwazulu-Natal

The Kwazulu-Natal grid consists of four customer load networks, including Newcastle, Pinetown, Ladysmith, and Newcastle, which currently have 5640 MW of generation connection capacity (Eskom, 2021, 2022). The proximity of 275 kV and 400 kV connection points in the Durban and Richard's Bay offshore regions of South Africa can enable the transfer of floating wind power to load centres in the Northeast region of the country (ESMAP, 2019) as well as facilitate industrial and commercial activities in the Pinetown and Empangeni local areas—the two major load centres in the network, which are expected to experience significant load growth in the period 2022 to 2031 (Eskom, 2022). Much of this increase could be attributed to the commissioning of the Richard's Bay Industrial Development Zone, which is poised to attract investors in the ICT, marine, renewable energy, and manufacturing sectors (Provincial Government of South Africa, 2022; RBIZ, 2022). Besides, GenesisHexicon, a floating wind joint venture in South Africa, have identified a site off the coast of Richard's Bay for the development of an 800 MW floating wind farm (Hexicon Group, 2022). Major network reinforcements have been planned and proposed to accommodate the integration of new generation capacity, such as the large-scale gas-to-power plants in Richard's Bay (Eskom, 2022).

Table 2 summarises the availability of grid connections in South Africa, which have been assessed qualitatively with respect to data published by Eskom (2021, 2022).

Exclusion criteria

Data and approach

Section "Site conditions" excluded sites with water depths less than 50 m and above 1000 m and with average wind speeds below 6 m/s, which represent zones technically feasible for floating wind deployment (Carbon Trust, 2015). Other exclusion criteria included technical and environmental factors which could impact the development of the technology in South Africa. They were selected by assessing the relevant floating wind literature and marine-related policies and regulations in the case study context.

Data were obtained from various reputable sources as displayed in Table 3. They were collected in varying formats (such as raster, shapefile, data points) varying formats (such as raster, shapefile, data points) with respect

Table 2 Summary of grid availability

Zone	Availability	Remark
Northern Cape	Low	Grid constraints due to a lack of generation connection capacity and need for substantial network reinforcements
Western Cape	Medium	Requires reinforcement of its transmission network to accommodate procured and future generation capacity
Eastern Cape	High	Availability of grid connection points in the Grassridge and Dedisa substations
Kwazulu-Natal	High	275 kV and 400 kV connection points in Durban and Richard's Bay. Current network reinforcements may offer more connection options

Table 3 Exclusion criteria

Component	Criteria	Source	Format
Wind speed @ 100 m	< 6 m/s	Global Wind Atlas	Raster
Water depth	< 50 m and > 1000 m	GEBCO	Raster
Exclusive Economic Zone	Study area	Marine Regions	Shapefile
Marine protected zones	3 km buffer	UNEP-WCMC and IUCN	Shapefile
Underwater cables	3 km buffer	Koordinates	Shapefile
Oil and gas fields	5 km buffer	Petrodata	Shapefile
Bird migratory routes	1 km buffer	Birdlife International	Shapefile
Blue flag beaches	2 km buffer	Department of Forestry, Fisheries and the Environment	Data points

Table 4 Other data sources

Component	Source	Format
South African Ports	World Port Source	GPS coordinates
Shipping density	Halpern et al	Shapefile
Africa transmission grid	World Bank Group	GeoJSON

to their availability on secondary data repositories. Layers were manually included on ArcMap 10.8 using the WGS 1984 Geographic Coordinate System, which was used as the basis of this work. The lack of access to data from primary sources such as the South African Maritime Safety Authority, South Africa Weather Service and Petroleum Agency SA, also informed the use of secondary documentation. Moreover, similar studies have utilised data from the sources in Tables 3 and 4 (Diaz and Soares, 2021; Taoufik & Fekri, 2021). Data analysis was conducted using the ArcGIS ArcMap software.

GIS analyses were conducted on ArcMap 10.8 to exclude unsuitable areas for floating wind development in SA based on technical, socio-economic, and environmental constraints. All layers were converted to raster format and same cell size to ensure consistency of results. The BUFFER function was deployed to create buffers around some exclusion criteria. For instance, offshore wind farms should be installed at least 5 km away from the radius of oil and gas installations (Maandal et al., 2021). The RECLASSIFY tool was deployed to designate the unsuitable areas as “0”, while the suitable areas were assigned “1”. Based on Boolean logic, the AND, CON, and SETNULL tools were utilised to permanently exclude unsuitable areas using the RASTER CALCULATOR function. Furthermore, provincial offshore zones in the case study were digitised using the CREATE FEATURES tool and with respect to the inland boundaries on OpenStreetMap (within the ArcGIS ArcMap software). The CLIP data management function was then used to segment relevant raster layers for further analysis.

Marine protected areas

The National Environmental Management Protected Areas Act 2003 (South African Government, 2003) was instituted to protect and conserve ecologically viable areas which represent South Africa’s biological diversity and its natural landscapes and seascapes. Therefore, excluding protected areas from sites considered for floating wind development could ensure the environmental sustainability of these projects in the country. Data deployed in this study were obtained from the World Database on Protected Areas collated by the UN Environment World Conservation Monitoring Centre (UNEP-WCMC), in association with actors from government, non-governmental, academic and industry institutions. A 3 km buffer was included to these areas, as consistent with the literature (Maandal et al., 2021). Figure 6 displays the marine protected areas in South Africa’s EEZ along with the 3 km buffer.

Underwater cables and pipelines

The presence of submarine cables and pipelines could constrain the development of FOW farms, especially due to the potential for damage during construction and maintenance activities. Taoufik and Fekri (2021) included a buffer of 500 m to submarine cables in their GIS-based analysis of offshore wind development in Morocco. Similarly, Diaz and Soares (2020) incorporated 500 m and 750 m buffers on each side of power cables and telecommunication cables in their GIS assessment of suitable sites for floating offshore wind farms in the Atlantic continental European coastline. In Maandal et al.’s (2021) assessment of offshore wind development in the Philippines, the authors incorporated 5 km buffers

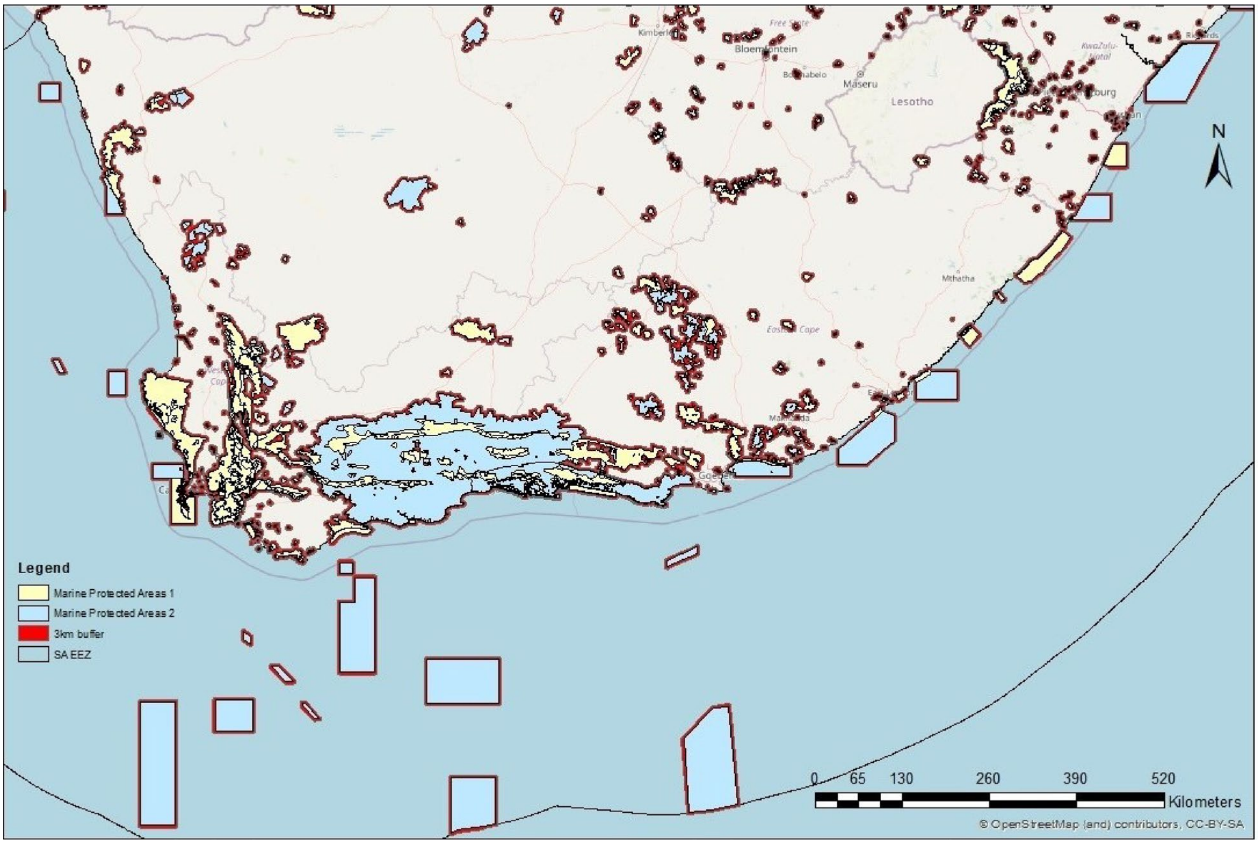

Fig. 6 Marine protected areas in South Africa's EEZ (data source: UNEP-WCMC & IUCN, 2022)

to submerged cables to prevent damage to cables during wind farm development. A conservative approach is relevant to FOWT due to the presence of anchors and mooring lines which imply greater footprint for floating offshore wind farms, when compared to bottom-fixed offshore wind (Carbon Trust and ORE Catapult, 2017). Also, due to the lack of offshore wind experience in South Africa's supply chain, it may be useful to restrict early-stage developments to areas with limited marine constraints to facilitate the sustainable development of these projects. Following an absence of specific marine regulations for submarine cables in South Africa, a 3-km buffer was added for underwater cables and pipelines in this study to represent a conservative approach to site selection as well as to maximise the locational potential of floating wind in South Africa (as displayed in Fig. 7).

Oil and gas deposits

South Africa's burgeoning offshore oil and gas sector has attracted interests from several big players including Shell PLC and Total Energies (Petroleum Agency SA, 2023). A recent notice by the Minister of Mineral Resources has suspended the awarding of new permits for technical co-operation, exploration, and production rights (Department of Mineral resources, 2023). This was intended as a licensing strategy to accelerate current exploration activities, as advised by section 2(d) of the Mineral and Petroleum Resources Development Act 28 of 2002. Nevertheless, the potential for exploration is higher in sites with significant hydrocarbon reserves. PetroData (2009) provides GIS data of oil and gas fields around the world. A 5-km buffer was included the major oil and gas zones in South Africa's EEZ (as shown in Fig. 8) to mitigate future conflicts with stakeholders from the oil and gas sectors and support licensing and permitting in early floating wind development.

Bird migratory routes

Due to its nascent nature, the impacts of floating wind farms on bird migration are unclear. Wind farms may have significant negative impacts on birds throughout its lifetime (from planning to operation) (Masden et al.,

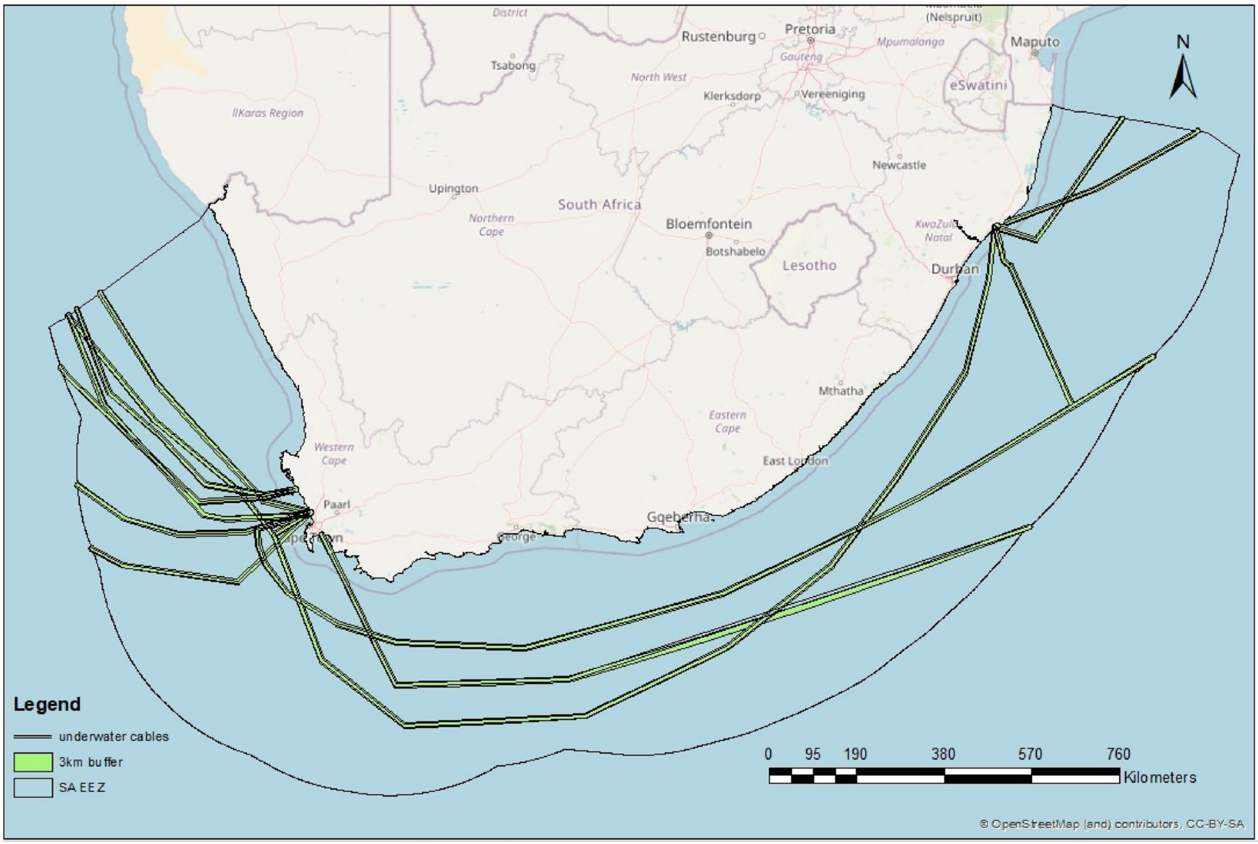

Fig. 7 Underwater cables is South Africa's Exclusive Economic Zone (data source: Koordinates, 2022)

2009). The risk of bird collision with wind turbines was considered in the environmental impact assessment of FOWT on the Brazilian continental shelf due to the presence of migratory birds such as the such as the Magellanic penguin and the yellow-nosed albatross (Ferraz and Bruno, 2022). South Africa's location on the map entails a limited risk of bird collision, especially as a result of the migratory behaviour of visiting birds—which fly from Asia and Europe to southern Africa and back every year (South Africa, 2023). Bird Life International's (2022) dataset also show a limited presence of migratory birds in South Africa's offshore region. A 1-km buffer was added to the migratory routes of the *Falco amurensis* and *Milvus aegyptius*, which migrate near South Africa's coastal areas (as displayed in Fig. 9).

Blue flag beaches

South Africa's Integrated Coastal Management Act 24 of 2008 was established to "ensure that development and the use of natural resources within the coastal zone is socially and economically justifiable and ecologically sustainable" (p.2) (South African Government, 2008). To that effect, the Department of Forestry, Fisheries, and the Environment (2022) have listed blue flag beaches as areas for consideration in relation to promoting biodiversity in South Africa's zones. The data points of over 50 blue flag beaches were identified via the Off-Road Vehicle Decision Support Tool and digitised using the ArcGIS software. Offshore wind farms can have negative socio-economic impacts on regions which are considered tourist destinations. Voltaire et al. (2017) found that the presence of wind farms influenced tourists' beach choices—as they preferred beaches without wind farms—and resulted in significant loss in tourism revenue. Lilley et al. (2010) also discovered, from a survey of more than one thousand participants, that at least 25% of beachgoers would switch beaches if an offshore wind farm was installed within 10 km of the shoreline. These studies emphasise the need to consider beaches during wind farm planning. Thus, a 2-km buffer

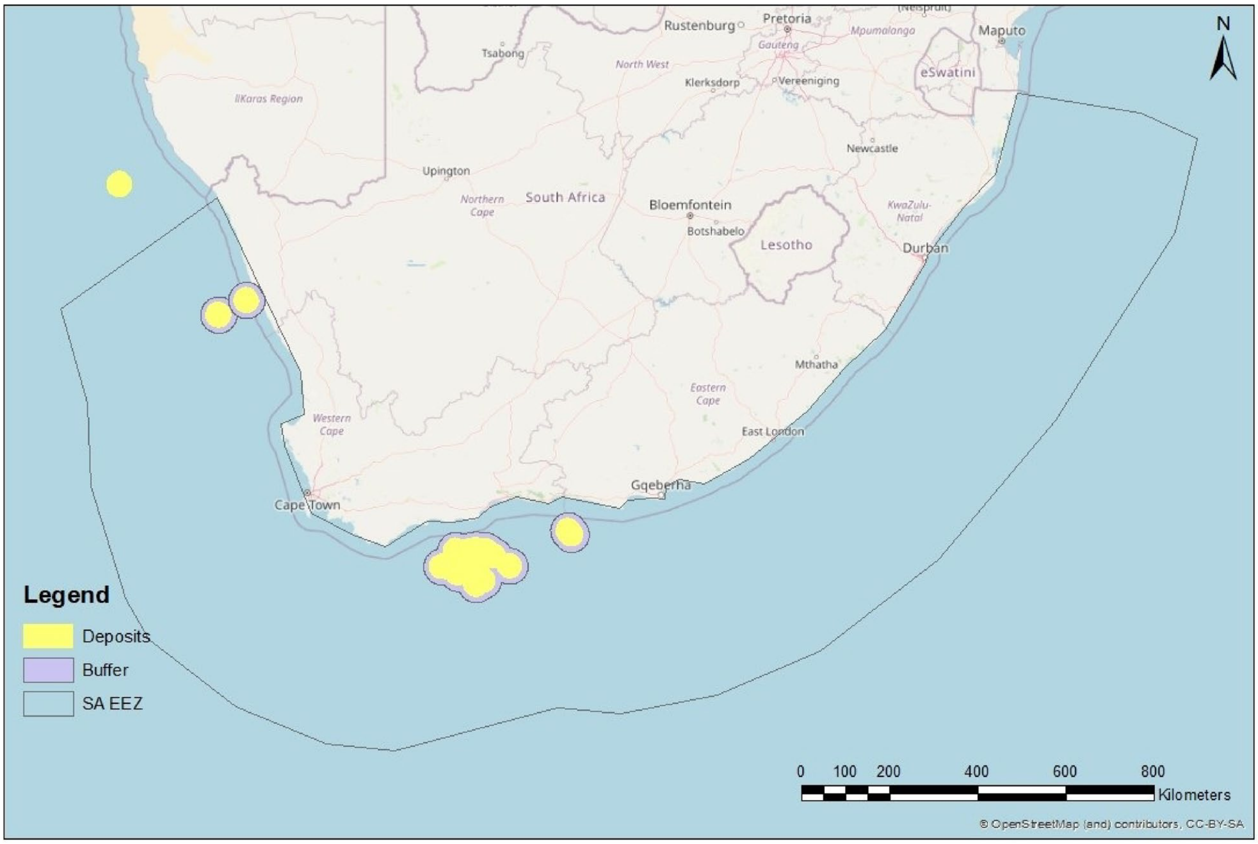

Fig. 8 Oil and gas deposits in South Africa's EEZ (data source: Petrodata, 2009)

zone was added around blue flag beaches in South Africa's coastal zones, as consistent with Taoufik and Fekri's (2021) study. Figure 10 shows a subset of the blue flag beaches in South Africa along with the stated buffer zone.

Figure 11 provides an overview of the sites excluded from consideration for floating wind development in the case study context.

Locational potential

Figure 12 displays the locational potential of floating offshore wind technology in South Africa with respect to provinces. ESMAP (2019) define locational potential as "a portion of the technical potential [...] where developers can obtain consent to build [due to being] available and suitable for offshore wind development" (p.10). This area has a total size of 246,105.4 km^2, which is approximately 2% of South Africa's EEZ. Sites with average wind speed ranging from 6.5 m/s and 11 m/s (considering the wind speed bins in Fig. 12) have wind power densities of 165 W/m^2 and 799 W/m^2 per unit of swept area, respectively. Considering the Vestas V164-8.0 MW turbine, with available power of 3.5 MW for average wind speeds of 6.5 m/s and 7 MW for mean wind speeds of 11 m/s, there is a potential to generate 142.61 GW or 89.08 GW of floating offshore wind power in South Africa using spar and semisubmersible foundations, respectively. This could translate to 1249 TWh or 780 TWh of annual electricity generation, which covers South Africa's annual power consumption (Global Data, 2023). Western Cape was found to have the highest harvestable capacity (80.52 GW), while Kwazulu Natal held the least potential with a generation capacity of 9.97 GW with semisubmersible floaters. Although this may advise industry and policymakers on key areas for floating wind development, it necessary to further assess the suitability of these areas in relation to other technical factors discussed in previous sections of this work.

Figure 12 shows the locational potential of FOWT in South Africa. This was generated on ArcMap 10.8 by excluding sites that are not feasible for floating wind

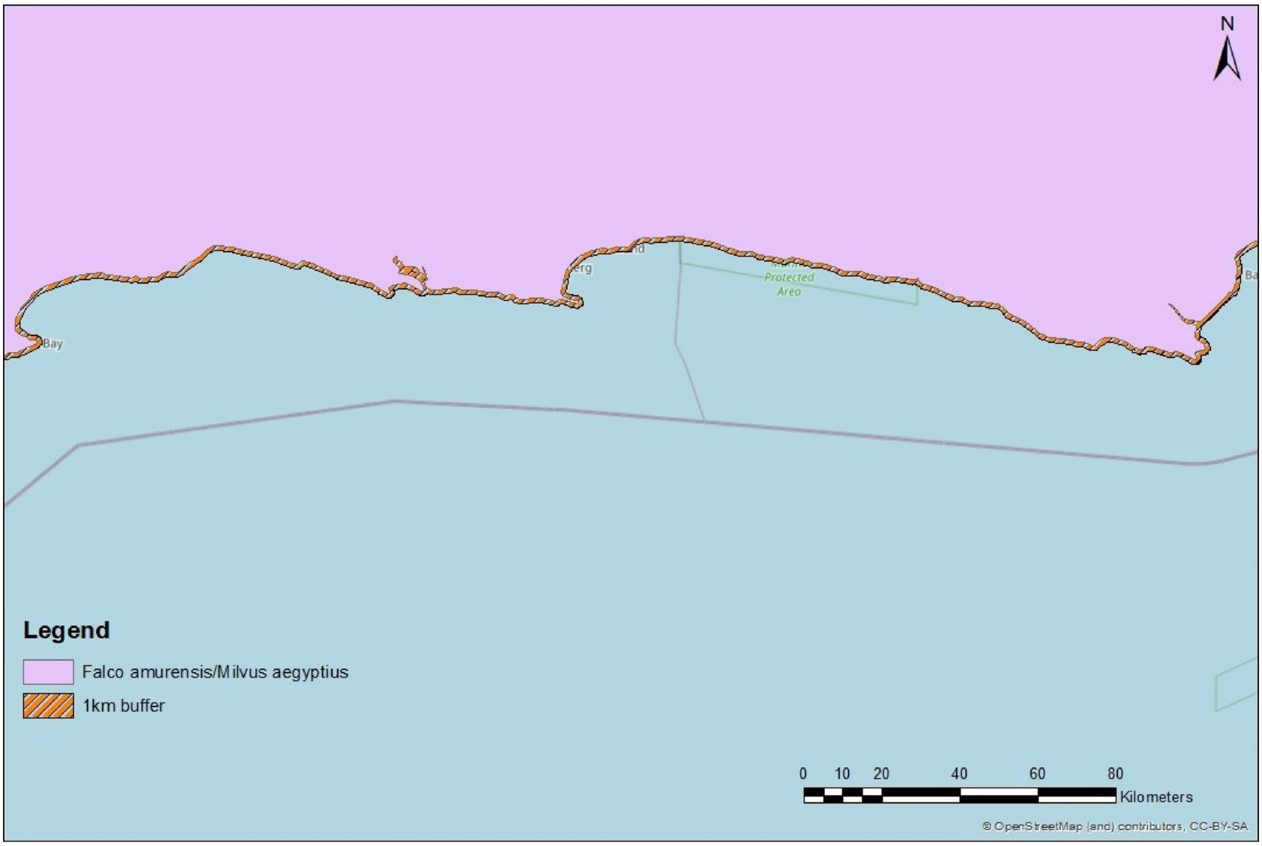

Fig. 9 Bird migratory routes in South Africa's coastal area (data source: Birdlife International, 2022)

development. Data sources for the non-feasible sites are listed in Table 3.

Table 5 summarises the power generation capacities in South African provinces.

Discussion

Having applied the exclusion criteria to the study area, the results shows that over 246,105 km^2 of offshore area in South Africa's EEZ could potentially host floating wind turbines. This represents over 2% of South Africa's EEZ spanning across the Northern Cape, Western Cape, Eastern Cape, and Kwazulu-Natal provinces of the country. There is a potential to harvest 142.3 GW or 89.08 GW of floating offshore wind power in South Africa using spar or semisubmersible floating foundations, respectively. These are significantly lower than the technical potential reported in the literature [589 GW in ESMAP (2019) and 764 GW in Karamanski and Erfort (2023)] as a result of marine constraints and technical considerations in wind energy production. It provides a realistic estimation of the development potential in the coastal regions of the country to assist policymakers and industry actors.

With the bulk of the available area concentrated in the Western Cape province, the total harvestable capacity in the region was found to be over 80 GW, which, if harnessed, could significantly address the country's energy crisis. The availability of suitable grid connection points in the area is contingent on current transmission reinforcement plans which is targeted at already procured generation capacity (Eskom, 2021). Sites in the Eastern Cape province, with a total harvestable capacity of 20.04 GW, may dominate early consideration for floating wind projects due to better grid connection and transformation capacities and limited oil and gas sector activities. Nevertheless, there is a need for major port upgrades in this region to meet the requirements of floating wind farms at various stages of their life cycle, including installation, operations, and decommissioning. Port of Ngqura in the Eastern Cape province, which has been designated as an Industrial Development Zone (Ricardo, 2022),

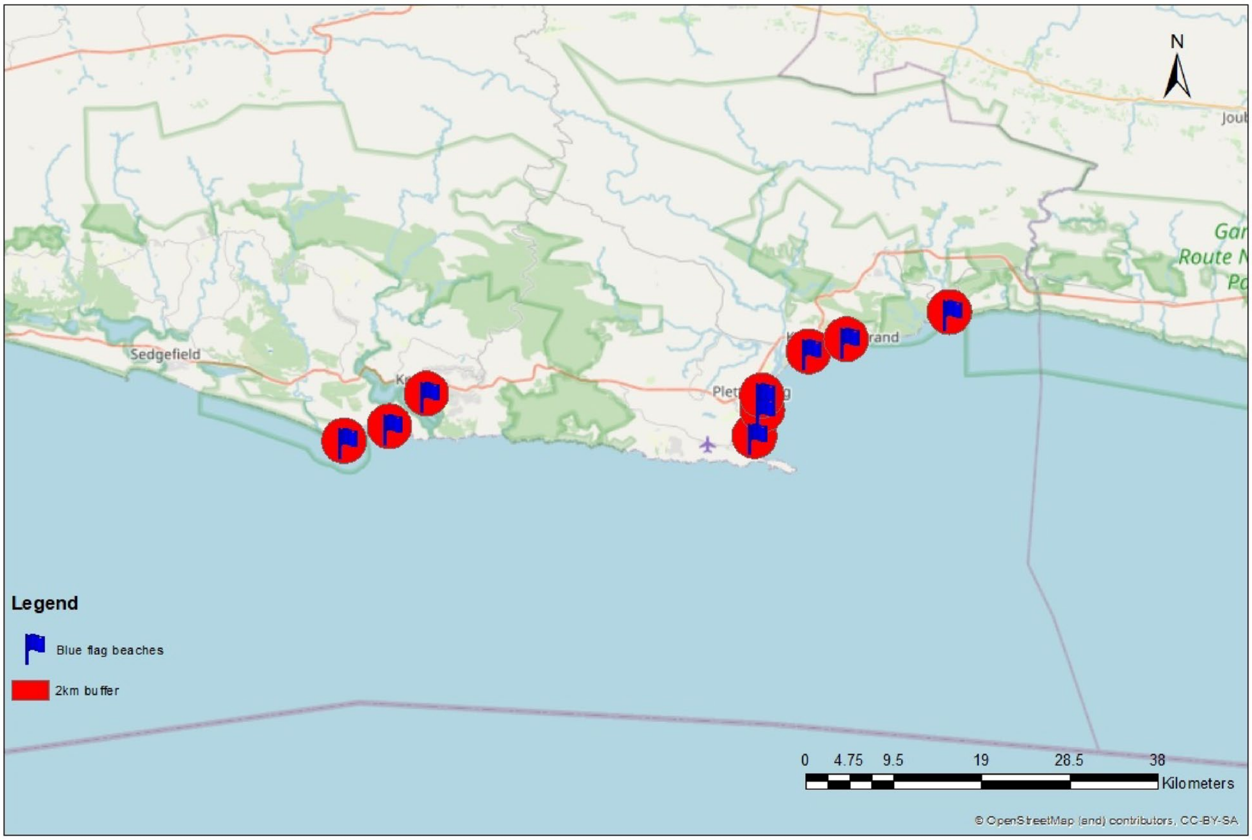

Fig. 10 Blue flag beaches in South Africa's coastal zones (data source: Department of Forestry, Fisheries and the Environment, 2023)

can be exploited due to its suitable laydown area, dock entrance width, and quay depth for the marshalling of wind farm components (National Ports Authority, 2023). However, port expansion endeavours are capital-intensive (Carbon Trust, 2015), thus may benefit from cross-sector collaboration, such as between the floating wind industry and the oil and gas, and shipping sectors.

The potential of generating approximately 143 GW of floating wind power presents a wonderful opportunity for not just South Africa, but the Southern African Power Pool (SAPP). Elsner (2019) called for an integrated and strategic development of offshore wind energy among the six coastal states (Angola, D.R. Congo, Mozambique, Namibia, South Africa, and Tanzania) of the SAPP to counteract increasing energy demand. This implies that the possibility of reaching 1249 TWh of annual energy production via floating offshore wind turbines, which could meet more than two times the energy demand in the SAPP (2023), should spur increased floating wind market activity in the region. A coordinated approach to developing this technology potentially addresses its current high levelized cost of energy (Wind Europe, 2017), for example, in the area of local supply chain development where a timely availability of materials, components, and services could drive down the cost of energy (Balanda et al., 2022). It could also serve as a basis for adequate engagement with key stakeholders, such as in the shipping sector where issues surrounding shipping density and heavy lift vessels availability are crucial to its sustainable development of FOWT (Carbon Trust, 2022; Rawson & Rogers, 2015).

This study is not without its limitations. For example, calculating the locational potential entailed assumptions regarding wake effects, a lack of buffer for neighbouring floating wind farms, and deploying non-standardised measures for turbine spacing, which implies that only a portion of the locational potential can be harnessed. However, the inclusion of the Betz limit and the resultant generation capacities points to the viability of floating

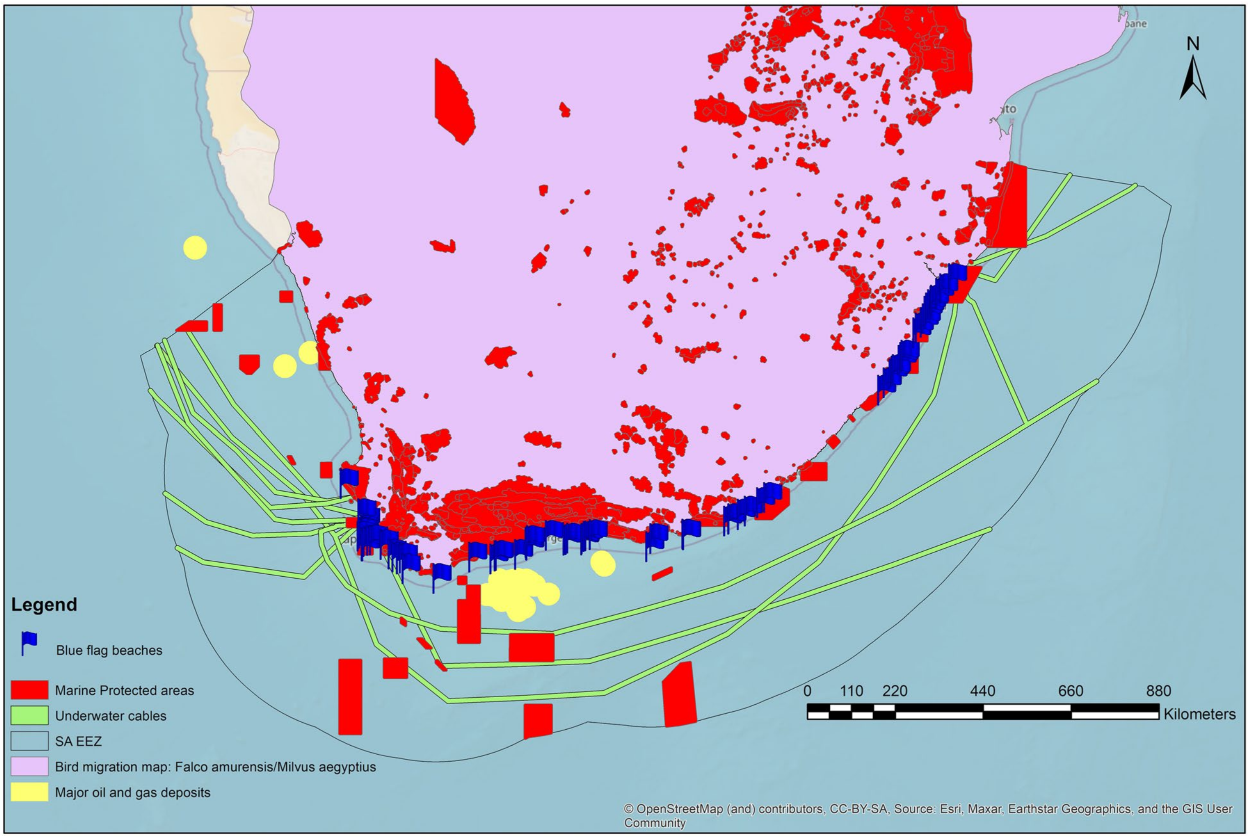

Fig. 11 Overview of excluded areas

wind power generation in the case study. There was limited focus on the economic implications of developing FOWT in South Africa, especially considering its high development costs. Wind energy critics in the African context may decry the technology's variability or emphasise on the need to achieve energy security through fossil-based sources; but the benefits of FOWT could span beyond the energy sector and yield significant economic benefits, including the potential for local supply chain development and creation of jobs in the region (GWEC, 2022a).

Further research can conduct technical assessments in relation to turbine spacing in floating offshore wind technology to enable a better quantification of the locational potential of the technology in new markets. Studies can also delve into the economic or techno-economic assessments of floating wind in distinct sites in South Africa. This could provide a better view of the technical or economic factors that may support or hinder the development of the technology in the country.

Conclusions

This paper developed a methodological framework for assessing the locational potential of floating wind, provided an analysis of the most relevant technical aspects of FOW development in South Africa, conducted a GIS analysis to excluded non-feasible zones from current considerations in FOW development in South Africa, and estimated the total locational potential of the technology in the case study context. Despite the highest locational potential for floating being found in the Western cape province, the Eastern Cape region is more appropriate for early-stage development due to the availability of grid connection points, limited marine traffic, and proximity to appropriate port facilities. Industry and policymakers could target integrated port expansion initiatives to ensure the suitability of port for project development, operations, and decommissioning activities. A greater potential lies in the possibility of a regional-scale development where countries in the Southern African Power Pool could collaborate to establish the region as a global renewable energy hub.

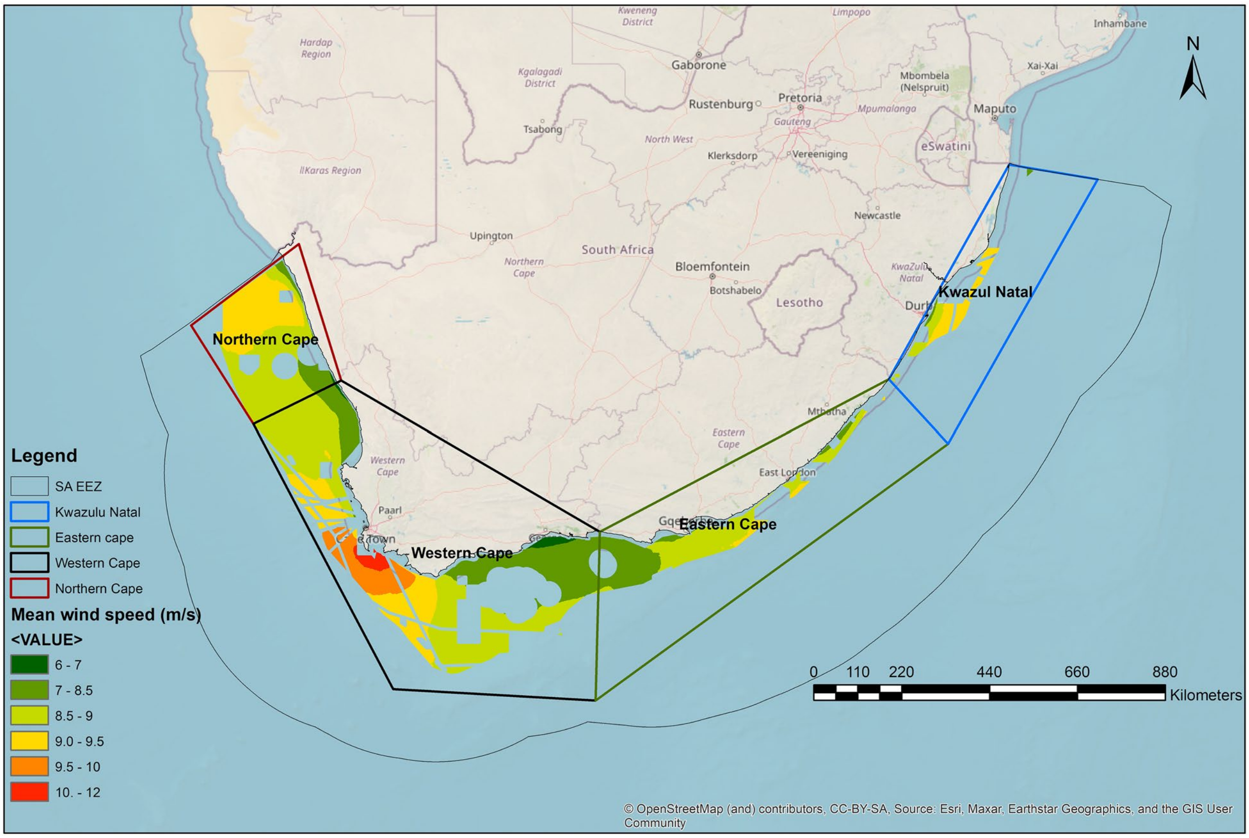

Fig. 12 Locational potential with respect to provinces

Table 5 A summary of the power generation for all potential zones

Provinces	Total available area (km^2)	Generation capacity (GW)	
		Spar	Semi-sub
Northern Cape	60,770.8	35.69	22.32
Western Cape	137,771.9	80.52	50.35
Eastern cape	37,290.3	20.04	12.43
Kwazulu Natal	10,272.4	6.36	3.98
Total	246,105.4	142.61	89.08

Abbreviations

CAPEX Capital expenditure
EEZ Exclusive Economic Zone
ESMAP Energy Sector Management Assistance Program
FOW Floating offshore wind
FOWT Floating offshore wind technology
GeoJSON This is an open standard geospatial data interchange format.
GHG Greenhouse gas
GIS Geographic Information System
GPS Global Positioning System
GW Gigawatts
IRR Internal rate of return
IRP Integrated resource plan
Km^2 Kilometres square
kV Kilovolt
LCOE Levelized cost of electricity
M Metre
m/s Metres per second
MW Megawatts
NPV Net present value
O&M Operations and maintenance
ORE Catapult Offshore renewable energy catapult
Raster Image file based on rectangular arrays of regularly sampled values, known as pixels
REIPPPP Renewable Energy Independent Power Producer Procurement Programme
SAPP Southern African Power Pool
SAWS South Africa Weather Service
Shapefile A digital vector format of storing geographic information
t Tonnes
TLP Tension-leg platform
TWh Terawatt hours
UNEP-WCMC UN Environment World Conservation Monitoring Centre
W Watts
WPD Wind power density
W/m^2 Watts per metres square

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Author contributions

Kubiat Umoh: conceptualisation, methodology, formal analysis, writing—original draft preparation, writing—reviewing and editing, visualisation; Abbas Hasan: writing—reviewing and editing, supervision; Amangeldi A Kenjegaliev: supervision, writing—reviewing and editing. Ayman Al-Qattan: supervision.

Availability of data and materials

The data will be shared upon request.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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References

4C Offshore. (2023). *Global offshore wind farms database*. https://www.4coffshore.com/windfarms/
Acteon. (2024). Floating Wind: What are the Mooring Options? A Q&A With Kent Longridge. https://acteon.com/blog/floating-wind-mooring-options/ (accessed: 14 Feb. 24)
Balanda, K., Ariatti, A., Monaghan, L., & Dissegna, C. (2022). The role of the local Supply Chain in the development of floating offshore wind power. *IOP Conference Series: Earth and Environmental Science, 1073*(1), 012010. https://doi.org/10.1088/1755-1315/1073/1/012010
Birdlife International. (2022). Bird life data zone, http://datazone.birdlife.org/species/search
Bloomberg. (2022). *The Dysfunctional Company That's Wrecking South Africa's Economy*. https://www.bloomberg.com/news/features/2022-09-27/south-africa-energy-crisis-power-company-sparks-blackouts-drags-down-economy?leadSource=uverify%20wall
BVG Associates. (2019). *Guide to an Offshore Wind Farm*. BVG Associates.
Carbon Trust. (2015). *Floating wind: Market and technology review*. Scottish Government.
Carbon Trust & ORE Catapult. (2017). *Floating Wind Joint Industry Project: Policy & Regulatory Appraisal*. https://www.carbontrust.com/media/673978/wp1-flw-jip-policy-regulatory-appraisal_final_170120_clean.pdf. [accessed 01 Feb. 23]
Castro-Santos, L., Filgueira-Vizoso, A., Carral-Couce, L., & Formoso, J. Á. F. (2016). Economic feasibility of floating offshore wind farms. *Energy, 112*, 868–882. https://doi.org/10.1016/j.energy.2016.06.135
Copernicus Climate Change Service (2018). *ERA5 hourly data on single levels from 1940 to present*. https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview (accessed: 15 Feb. 24)
Crowle, A., & Thies, P. (2022). Floating offshore wind turbines port requirements for construction. *Proceedings of the Institution of Mechanical Engineers, Part m: Journal of Engineering for the Maritime Environment, 236*(4), 1047–1056. https://doi.org/10.1177/14750902221078425
Department of Forestry, Fisheries and the Environment. (2023). *Coastal Viewer*. https://mapservice.environment.gov.za/Coastal%20Viewer/ (accessed: 08 Jan. 24)
Department of Mineral Resources and Energy RSA. (2019). *Integrated Resource Plan 2019*. Republic of South Africa, Department of Energy.
Department of Mineral Resources and Energy RSA. (2021). *Independent Power Producers Procurement Programme (IPPPP)—an overview: 30th June 2021*. Centurion: RSA.
Department of Mineral Resources. (2023). *Mineral and Petroleum Resources Development Act: Restriction on granting of new applications for technical cooperation permits, exploration rights and production rights*. https://www.gov.za/documents/mineral-and-petroleum-resources-development-act-restriction-granting-new-applications-2
Díaz, H., & Guedes Soares, C. (2020). An integrated GIS approach for site selection of floating offshore wind farms in the Atlantic continental European coastline. *Renewable and Sustainable Energy Reviews, 134*, 110328. https://doi.org/10.1016/j.rser.2020.110328
Díaz, H., & Guedes Soares, C. (2023). Cost and financial evaluation model for the design of floating offshore wind farms. *Ocean Engineering, 287*, 115841. https://doi.org/10.1016/j.oceaneng.2023.115841
DNV. (2020). *Floating wind: The power to commercialize*. DNV AS.
Elsner, P. (2019). Continental-scale assessment of the African offshore wind energy potential: Spatial analysis of an under-appreciated renewable energy resource. *Renewable and Sustainable Energy Reviews, 104*, 394–407. https://doi.org/10.1016/j.rser.2019.01.034
Equinor. (2019). *Equinor and ORE Catapult collaborating to share Hywind Scotland operational data*. https://www.equinor.com/en/news/2019-11-28-hywind-scotland-data.html (accessed: 08 Jan. 24)
Eskom. (2021). *Transmission Generation Capacity Assessment of the 2023 Transmission Network: Phase 2*. Sandton: Eskom Transmission Division; 2021
Eskom. (2022). *Transmission Development Plan*. Eskom Transmission Division.
ESMAP. (2019). *Going Global: Expanding Offshore Wind to Emerging Markets*. World Bank.
EWEA. (2013). *Deep water—The next step for offshore wind energy*. EWEA.
Ferraz de Paula, L., & Carmo, B. S. (2022). Environmental impact assessment and life cycle assessment for a deep water floating offshore wind turbine on the Brazilian continental shelf. *Wind*, *2*(3), 495–512. https://www.mdpi.com/2674-032X/2/3/27
Francis, M. V., Louis, D. A., & Largus, T. A. (2012). *Energy Systems Engineering: Evaluation and Implementation, Second Edition* (2nd ed.). McGraw-Hill Education. https://www.accessengineeringlibrary.com/content/book/9780071787789
GEBCO. (2022). *Gridded Bathymetry Data*. https://www.gebco.net/data_and_products/gridded_bathymetry_data/ (accessed: 08 Jan. 24)
Global Data. (2023). *The Power Consumption in South Africa*. https://www.globaldata.com/data-insights/power-and-utilities/the-power-consumption-in-south-africa-1083456/ (accessed: 08 Jan. 24)
Global Wind Atlas. (2022). *Global Wind Atlas*. https://globalwindatlas.info/ (accessed: 07 Aug 23)
GWEC. (2019). *Global Wind Report released 2019*. https://gwec.net/global-wind-report-2019/ (accessed: 08 Jan. 24)
GWEC. (2020). *Global Offshore Wind Report 2020*. Global Wind Energy Council.
GWEC. (2022a). *Floating Offshore Wind—A Global Opportunity*. https://gwec.net/wp-content/uploads/2022/03/GWEC-Report-Floating-Offshore-Wind-A-Global-Opportunity.pdf (accessed: 07 Sep 23).
GWEC. (2022b). *Africa is only tapping into 0.01% of its wind power potential*. https://gwec.net/africa-is-only-tapping-into-0-01-of-its-wind-power-potential/ (accessed: 02 feb 23)
Halpern, B., Frazier, M., Potapenko, J., Casey, K., Koenig, K., et al. (2013). *Cumulative human impacts: raw stressor data (2008 and 2013)*. KNB: https://doi.org/10.5063/F1S180FS
Hannon M, Topham E, MacMillan D, Dixon J, & Collu M. (2019). *Offshore wind, ready to float? Global and UK trends in the floating offshore wind market. University of Strathclyde, Glasgow*. https://doi.org/10.17868/69501.
Hexicon Group. (2022). *Projects*. available at: https://www.hexicongroup.com/projects/ [accessed: 28 Nov. 22]
Ioannou, A., Angus, A., & Brennan, F. (2018). A lifecycle techno-economic model of offshore wind energy for different entry and exit instances. *Applied Energy, 221*, 406–424. https://doi.org/10.1016/j.apenergy.2018.03.143
IRENA. (2016). *Floating foundations: A game changer for offshore wind power*. International Renewable Energy Agency.
IRENA. (2019). *Renewable Energy Statistics 2019*. The International Renewable Energy Agency.
Karamanski, S., & Erfort, G. (2023). Wind energy supply profiling and offshore potential in South Africa. *Energies*, *16*(9), 3668. https://www.mdpi.com/1996-1073/16/9/3668
Koordinates. (2022). *Underwater Cables and Pipelines*. https://koordinates.com/layer/3722-undersea-telecommunication-cables/data/ (accessed: 19 June 2022)
Kruger Africa. (2008). *South Africa's First Wind Farm in Operation*. https://www.krugerpark.co.za/kruger-park-news-south-africas-first-wind-farm-25505.html#:~:text=Construction%20on%20the%20project%2C%20which,was%20produced%20in%20May%202008. (accessed: 5 Jan 2022)

Leimeister, M., Kolios, A., & Collu, M. (2018). Critical review of floating support structures for offshore wind farm deployment. *Journal of Physics: Conference Series, 1104*(1), 012007. https://doi.org/10.1088/1742-6596/1104/1/012007
Lemmer, F., Yu, W., Müller, K., & Cheng, P. W. (2020). Semi-submersible wind turbine hull shape design for a favorable system response behavior. *Marine Structures, 71*, 102725. https://doi.org/10.1016/j.marstruc.2020.102725
Lilley, M., Firestone, J., & Kempton, W. (2010). The Effect of wind power installations on Coastal Tourism. *Energies*. https://doi.org/10.3390/en3010001
Maandal, G. L. D., Tamayao-Kieke, M.-A. M., & Danao, L. A. M. (2021). Techno-economic assessment of offshore wind energy in the Philippines. *Journal of Marine Science and Engineering*, *9*(7), 758. https://www.mdpi.com/2077-1312/9/7/758
Maienza, C., Avossa, A. M., Ricciardelli, F., Coiro, D., Troise, G., & Georgakis, C. T. (2020). A life cycle cost model for floating offshore wind farms. *Applied Energy, 266*, 114716. https://doi.org/10.1016/j.apenergy.2020.114716
Masden, E. A., Haydon, D. T., Fox, A. D., Furness, R. W., Bullman, R., & Desholm, M. (2009). Barriers to movement: Impacts of wind farms on migrating birds. *ICES Journal of Marine Science, 66*(4), 746–753. https://doi.org/10.1093/icesjms/fsp031
Myhr, A., Bjerkseter, C., Ågotnes, A., & Nygaard, T. A. (2014). Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renewable Energy, 66*, 714–728. https://doi.org/10.1016/j.renene.2014.01.017
National Planning Committee RSA. (2012). *National Development Plan 2030*. Department. The Presidency, South Africa.
National Ports Authority. (2022). *Port of Durban*. Durban: RSA.
National Ports Authority. (2023). *Port of Ngqura*. https://www.transnetnationalportsauthority.net/OurPorts/Ngqura/Documents/Port%20of%20Ngqura%20Brochurev4_SinglePages.pdf (accessed: 5 July 2023)
Nie, B., & Li, J. (2018). Technical potential assessment of offshore wind energy over shallow continent shelf along China coast. *Renewable Energy, 128*, 391–399. https://doi.org/10.1016/j.renene.2018.05.081
Norsea Group. (2023). *NorSea Stordbase*. https://norseagroup.com/en/bases/norsea-stordbase (accessed: 18 June 2023)
SBM Offshore. (2023). *SBM Offshore announces the successful installation of the 3 floating wind units for the Provence Grand Large pilot project*. https://www.sbmoffshore.com/newsroom/news-events/sbm-offshore-announces-successful-installation-3-floating-wind-units (accessed: 15 Feb. 24)
ORE Catapult. (2021). *Using floating offshore wind to power oil and gas platforms*. https://ore.catapult.org.uk/wp-content/uploads/2021/01/AI-paper-Floating-wind-for-oil-gas-v02.00.pdf (accessed: 17 Mar 2023)
Öztürk, S., & Karipoğlu, F. (2021). Determining suitable container ports for offshore wind farms based on geographical information system-analytic hierarchy process: A case study of Marmara Sea. *Arabian Journal of Geosciences, 15*(1), 24. https://doi.org/10.1007/s12517-021-09232-3
Petrodata. (2009). *Petrodata*. https://www.prio.org/data/11 (accessed: 17 Apr 2023)
Petroleum Agency SA. (2023). *Shape files, maps, and gallery*. https://www.petroleumagencysa.com/index.php/43-data-technical-information/viewing-our-technical-data/183-shape-files-and-maps-gallery (accessed: 14 May 2023)
Provincial Government of South Africa. (2022). *Richards Bay Industrial Development Zone*, https://provincialgovernment.co.za/units/view/151/kwazulu-natal/richards-bay-industrial-development-zone-rbidz (accessed: 19 Sep 2023)
Rae, G., & Erfort, G. (2020). Offshore wind energy—South Africa's untapped resource. *Journal of Energy in Southern Africa*, *31*, 26–42. http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1021-447X2020000400003&nrm=iso
Rawson, A., & Rogers, E. (2015). Assessing the impacts to vessel traffic from offshore wind farms in the Thames Estuary. *Scientific Journals of the Maritime University of Szczecin, 43*, 99–107.
RBIZ. (2022). *Richards Bay Industrial Development Zone*. https://www.rbidz.co.za/ (accessed: 10 Jan 23)
Ricardo, B. (2022). *South Africa: fuelling the future of shipping*. https://www.globalmaritimeforum.org/content/2022/06/Zero-carbon-shipping-South-Africa-Issue-2.pdf (accessed: 10 Jan 23)
Rinaldi, G., Garcia-Teruel, A., Jeffrey, H., Thies, P. R., & Johanning, L. (2021). Incorporating stochastic operation and maintenance models into the techno-economic analysis of floating offshore wind farms. *Applied Energy, 301*, 117420. https://doi.org/10.1016/j.apenergy.2021.117420
South Africa. (2023). *Migratory birds in South Africa*. https://www.southafrica.com/blog/migratory-birds-in-south-africa/#:~:text=Birds%20that%20migrate%20to%20South,%2C%20and%20European%20Bee%2Deater. (accessed: 05 Sept 2023)
South African Government. (2003). *National Environmental Management: Protected Areas Act 57 of 2003*. https://www.gov.za/documents/national-environmental-management-protected-areas-act (accessed: 10 Oct 23)
South African Government. (2008). *National Environmental Management: Integrated Coastal Management Act 24 of 2008*. https://www.gov.za/documents/national-environmental-management-integrated-coastal-management-act (accessed: 11 Oct 23)
Southern African Power Pool. (2023). *Demand and Supply*. https://www.sapp.co.zw/demand-and-supply (accessed: 9 Dec 2023)
Taoufik, M., & Fekri, A. (2021). GIS-based multi-criteria analysis of offshore wind farm development in Morocco. *Energy Conversion and Management X, 11*, 100103. https://doi.org/10.1016/j.ecmx.2021.100103
The Crown Estate Scotland. (2020). *Ports for offshore wind: A review of the net-zero opportunity for ports in Scotland.* Glasgow, United Kingdom: ARUP.
Trust, C. (2020). *Phase II Summary report*. The Carbon Trust.
Umoh, K., & Lemon, M. (2020). Drivers for and barriers to the take up of floating offshore wind technology: A comparison of Scotland and South Africa. *Energies*, *13*(21), 5618. https://www.mdpi.com/1996-1073/13/21/5618
UNEP-WCMC and IUCN. (2022). *Marine and Coastal Protected Areas*. https://www.arcgis.com/home/item.html?id=8fd234a5b08a4859885abda763f35b93 (accessed: 11 Jun 2022)
Vagiona, D. G., & Kamilakis, M. (2018). Sustainable site selection for offshore wind farms in the South Aegean—Greece. *Sustainability, 10*(3), 749.
van Haaren, R., & Fthenakis, V. (2011). GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State. *Renewable and Sustainable Energy Reviews, 15*(7), 3332–3340. https://doi.org/10.1016/j.rser.2011.04.010
Voltaire, L., Loureiro, M. L., Knudsen, C., & Nunes, P. A. L. D. (2017). The impact of offshore wind farms on beach recreation demand: Policy intake from an economic study on the Catalan coast. *Marine Policy, 81*, 116–123. https://doi.org/10.1016/j.marpol.2017.03.019
Wind Europe. (2017). *Floating Offshore Wind Vision Statement*. https://windeurope.org/wp-content/uploads/files/about-wind/reports/Floating-offshore-statement.pdf (accessed: 08 Jan 23)
Wind Europe. (2020). *Ports: a key enabler for the floating offshore wind sector*. https://www.hhwe.eu/download/europe-windeurope-ports-a-key-enabler-for-the-floating-offshore-wind-sector-09-2020/ (accessed: 6 Apr 2023)
World Port Source. (2022). *Port of Cape Town*. http://www.worldportsource.com/ports/commerce/ZAF_Port_of_Cape_Town_42.php (accessed: 22 Jun 22)

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