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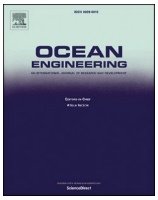

Research paper

Combined AHP-GIS methodology for floating offshore wind site selection in South Africa

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ABSTRACT

A sustainable approach to site selection can enhance the techno-economic feasibility of floating wind projects. This is because site selection is a multicriteria problem including technical, environmental, social, and economic factors. The issue is more pronounced in emerging and future markets where market and policy developments do not account for the complex life cycle aspects of technology development. Moreover, previous offshore wind site selection studies have utilised multi-criteria decision-making (MCDM) approaches that are not directly integrated with GIS software for mapping of the most attractive sites. The implication for prospective markets is that it fails to address the ambiguity regarding the feasibility of floating offshore wind technology, especially with knowledge of its high development costs. This study tackles the problem by deploying a multidisciplinary methodology for selecting the best sites for floating offshore wind turbines (FOWT) in South Africa. It included analytical hierarchy process (AHP) pairwise judgements from experts to assess the evaluation criteria, a Geographic Information System (GIS) analysis to implement results in South Africa's Exclusive Economic Zone (EEZ), and windPRO simulations to assess the actual development potential of the technology in the selected sites. The AHP final weights constitutes a comprehensive set of evaluation criteria for future studies in floating wind site selection. Results also show that 25 sites in the Northern Cape (NC), Western Cape (WC), Eastern Cape (EC), and Kwazulu Natal (KN) regions of the country can host over 71 GW of floating wind capacity. To achieve this potential, industry actors and policymakers must prioritise selected sites with considerations of the characteristics that may influence the techno-economic feasibility of future floating wind projects in South Africa.

1. Introduction

Significant increases in the global capacity of offshore wind energy have contributed to mitigating CO_2 emissions and counteracting climate change impacts. Following an average growth of 21% yearly in the past decade, total offshore wind installations currently stand at 64.3 GW, with China, the UK, and Germany leading the pack in installed capacity (GWEC, 2023). This growth has been attributed to technological advancements which have yielded significant reductions in levelized cost of electricity (LCOE) in that period (Beiter et al., 2021). Although further cost reductions are expected in the current decade and beyond, the sector would require around $100 billion of annual investments to meet the increasing demand for offshore wind between 2030 and 2050 (IRENA, 2019). There is a growing business case for the deployment of floating offshore wind turbines (FOWT), especially as the technology is projected to reach full commercialization after 2030 (GWEC, 2020). This is emphasised by the finding of enormous technical potentials for floating wind in future markets (ESMAP, 2019), which could see the technology play a vital role in the energy transition. In addition, the increasing rate of offshore wind development in shallow waters implies a future scarcity of adequate sites for bottom-fixed structures in current markets (Carbon Trust, 2015).

The floating wind market has over 170 MW of operational capacity from 14 projects across the globe, which represents 0.1% of total wind installations (GWEC, 2023). Financial challenges and supply chain constraints in relation to ports and the fabrication of floating foundations have stifled the growth of this sector in recent years (GWEC, 2022), thus necessitating a rethinking of the development strategies in current markets. It is essential for prospective markets to integrate best practices and lessons learned from operational projects to ensure a sustainable approach to technology deployments. A typical example is in undertaking the complex floating wind site selection process amidst the technical, environmental, social, and economic factors that are sometimes considered in relevant marine policies and regulations (Díaz and Guedes Soares, 2022). Moreover, the huge expanses of sea area required

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Abbreviations

AHP	Analytic hierarchy process
AIJ	Aggregation of individual judgments
AIP	Aggregation of the Individual Priorities
CI	Consistency index
CR	Consistency ratio
EC	Eastern Cape
EEZ	Exclusive Economic Zone
ESMAP	Energy Sector Management Assistance program
FOWT	Floating offshore wind turbines
GeoTIFF	Geographic Tagged Image File Format
GIS	Geographic Information System
GW	Gigawatts
GWEC	Global Wind Energy Council
IRP	Integrated Resource Plan
ISO 27001	an international standard that outlines the requirements for an organization's information security management system
Km^2	Kilometres square
KN	Kwazulu Natal
kV	Kilovolt
LCOE	Levelized cost of electricity
m/s	Metres per second
M	Metre
MCDM	Multi-criteria decision methods
MW	Megawatts
NC	Northern Cape
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
Raster	Image file based on rectangular arrays of regularly sampled values, known as pixels
SEIPPI	Renewable Energy Independent Power Producer Procurement Programme
SAPP	Southern African Power Pool
SAW	Simple Additive Weighting
TLP	Tension-leg platform
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TWh	Terawatt hours
UNEP-WCMC	UN Environment World Conservation Monitoring Centre
WC	Western Cape

for developing commercial offshore wind farms – when compared to other ocean energy plants – calls for a strategic approach towards selecting offshore wind development zones (Gourvenec et al., 2022). Existing literature agrees that a multifactorial method in offshore energy could mitigate the risk of marine conflicts as well as contribute to harnessing synergies in the marine sector (Flannery et al., 2018; Yates and Bradshaw, 2018).

Several authors have rallied for the acceleration of renewable energy projects in South Africa to tackle the ongoing energy crisis and facilitate a sustainable energy transition in the country (Adebayo et al., 2021; Hanto et al., 2022; Umoh and Lemon, 2020). This is in line with South African's plan to retire 24.1 GW of its coal-fired power stations through the Integrated Resource Plan (IRP) 2010–2030, that has seen the procurement of 6.4 GW of renewable energy projects to date (DMRE, 2019). It indicates a growing appetite for clean energy development among policymakers in the country, consistent with the government's net zero emission targets (UNDP, 2023). Despite its great potential for offshore wind energy in deeper waters (ESMAP, 2019), a combination of limited policy developments and inadequate market activity has hindered the take up of this technology in South Africa (Umoh and Lemon, 2020). A recent study estimated that a total of approximately 143 GW of floating offshore wind energy can be harvested in water depths between 50 m and 1000 m in South Africa's EEZ to meet more than two times the energy demand in the Southern African Power Pool (SAPP) (Umoh et al., 2024). The current work builds upon the previous paper by conducting a site selection study with respect to the relevant technical, economic, environmental, and social factors of the technology in the case study context. It is worthy of note that no study has mapped out the most suitable sites for offshore wind development in South Africa to date.

Academics and practitioners have deployed multi-criteria decision making (MCDM) tools in tackling issues involving multiple criteria and numerous objectives (Nijkamp et al., 2013). Specifically, techniques including AHP, Simple Additive Weighting (SAW), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and outranking models including Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), have been utilised to confront such problems in the energy, environment, and sustainability sectors (Govindan and Jepsen, 2016; Shao et al., 2020; Tian et al., 2013). The choice of method lies with the MCDM practitioner, who must select the appropriate techniques having considered their strengths and limitations. Some well-known drawbacks in existing tools include decision-making difficulties experienced by participants in PROMETHEE (Azhar et al., 2021) and challenges in ranking objectives in ELECTRE (Sabaei et al., 2015). Conversely, the AHP method, which was developed by Saaty (1987), can support: the breakdown of complex decision-making problems into a domain of alternatives, ranking of evaluation criteria to inform judgements, evaluation of qualitative and quantitative attributes, and the mitigation of inconsistencies. The technique is relevant in offshore wind energy development due to the presence of multiple technical, economic, social, and environmental criteria which may differ from context to context. A key advantage of the

Table 1
AHP fundamental scale (Saaty, 1987).

Intensity of importance	Definition	explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement slightly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is favoured very strongly, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is required

Table 2
Random consistency values (Saaty, 1987).

n	1	2	3	4	5	6	7	8	9	10
Random consistency index	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

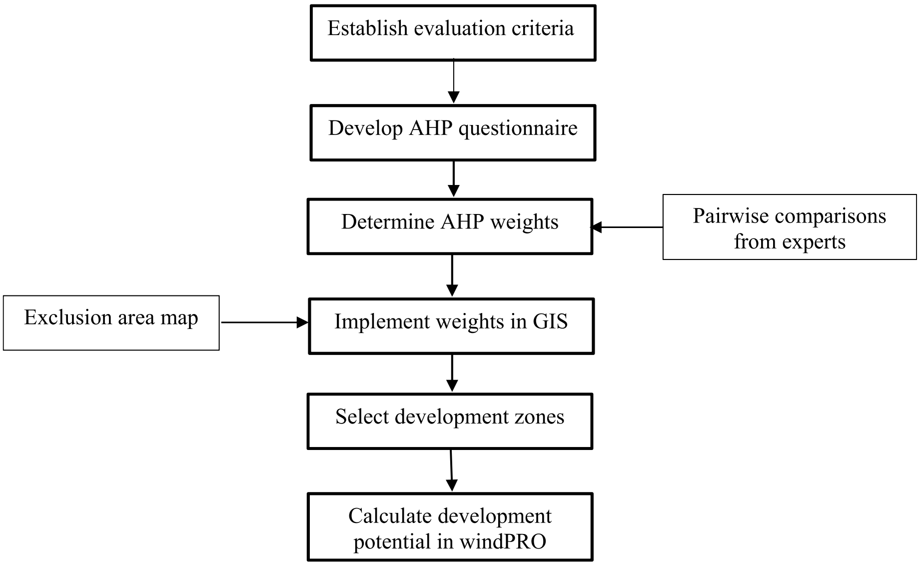

Fig. 1. Methodological approach.

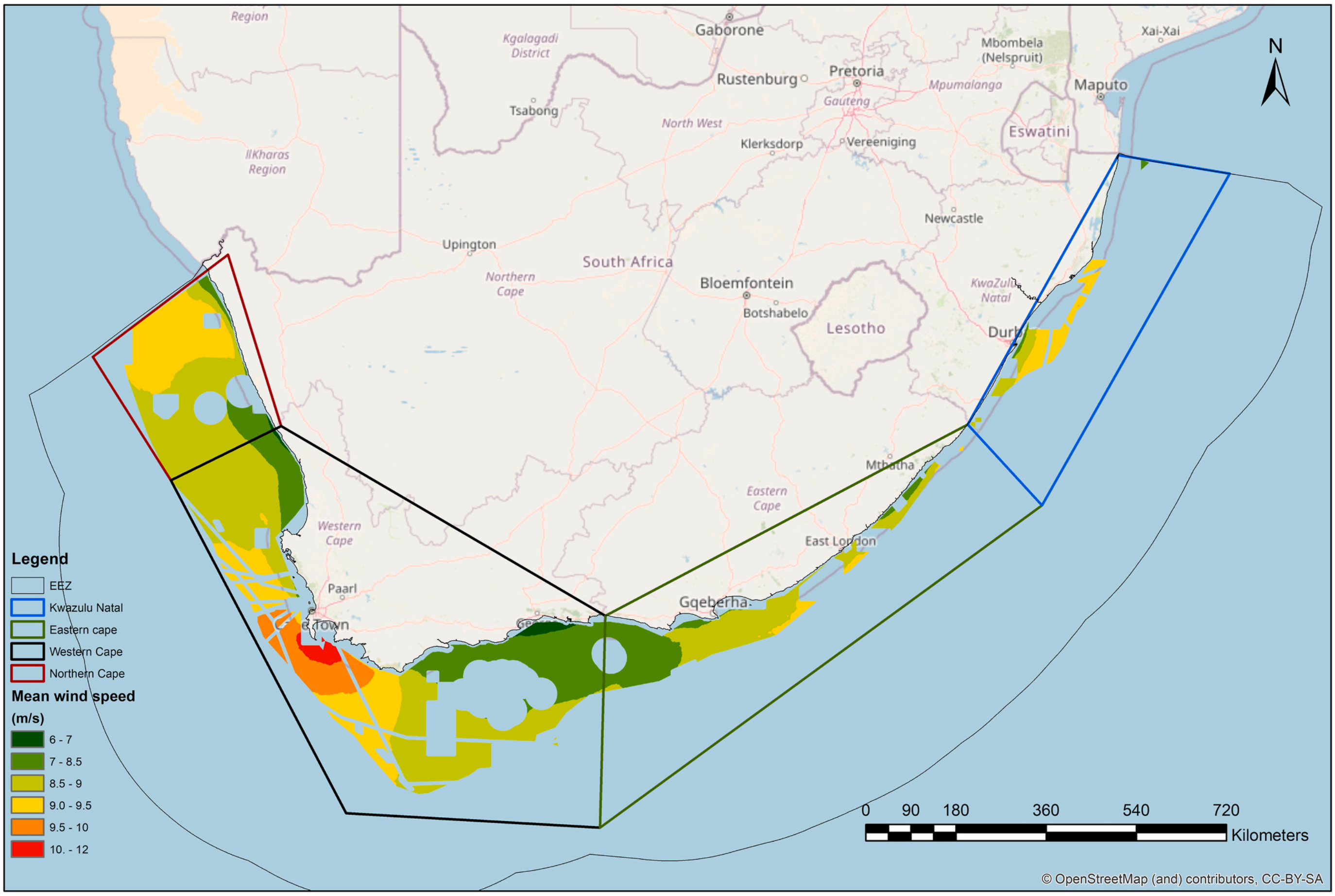

Fig. 2. Feasible sites for floating wind development in South Africa (Umoh et al., 2024).

AHP method is that it allows renewable energy practitioners to integrate results within available GIS tools (Höfer et al., 2016).

Several authors have applied the GIS-MCDM methodology in bottom-fixed offshore wind studies for site selection studies (Caceoğlu et al., 2022; Taoufik and Fekri, 2021; Vagiona and Kamilakis, 2018). Vagiona and Kamilakis (2018) adopted a GIS tool and MCDM methods including AHP and TOPSIS for offshore wind site selection in the South Aegean region of Greece. They excluded noneligible sites with respect to national policies and literature, consistent with a sustainable approach for the take up of the technology. Their MCDM evaluation stage was based on subjective pairwise comparisons from the authors which can be associated with a high potential for bias. The relevant weights of their

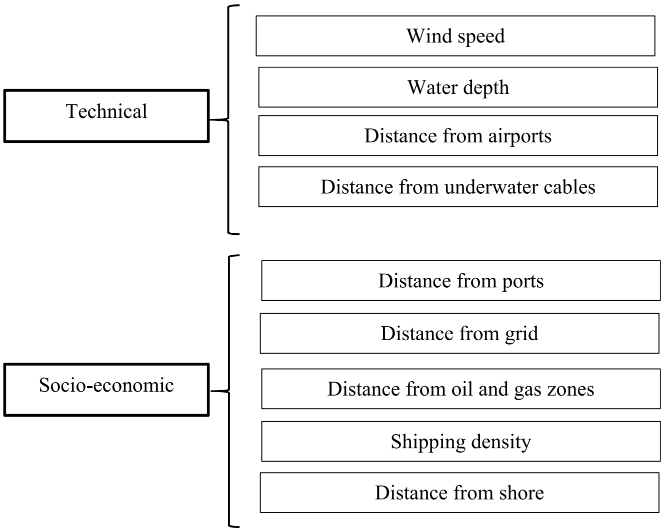

Fig. 3. Segmentation of the evaluation criteria.

Table 4
Location and job position of experts.

Experts	Position	Location
Participant A	Final year PhD Student in floating wind	UK
Participant B	Project Officer in Offshore Wind	UK
Participant C	Commercial Manager in floating wind	UK
Participant D	Principal Engineer in Offshore Wind	South Africa
Participant E	Researcher in Offshore wind	UK
Participant F	Commercial manager in floating wind	UK

evaluation criteria informed the ranking of proposed sites mapped out arbitrarily following exclusion of nonviable zones. This methodology may not be suitable for a country-wide study that focuses on larger expanses of offshore waters with contrasting multicriteria attributes. A similar approach was deployed in Caceoğlu et al. (2022) where AHP analysis enabled the ranking of five alternative sites (Kıyıkoy, Bandırma, Karabiga, Bozcaada, and Gokçeada) in Turkey. AHP analyses were based on scenario and consensus analysis, with the former aimed at aggregating the relative weights and pairwise comparisons of the alternatives to arrive at multiple scenarios while the latter was an iterative approach that resulted in a single group decision on the most viable site. As GIS analysis was limited to the considered alternatives, there is a possibility that more viable sites were excluded especially considering that the cost and technoeconomic feasibility of offshore wind projects are determined by a combination of distinct site factors. Taoufik and Fekri (2021) combined a fuzzy AHP methodology with the ArcGIS ArcMap 10.3 software for offshore wind resource assessment in Morocco's EEZ. A range of technical, socio-economic, and environmental aspects were included in their evaluation criteria, along with six exclusion factors to select the most suitable zones for offshore wind farms in the country. Although a weighted overlay analysis in a GIS environment produced three highly viable sites, there was no evidence to suggest the integration of the AHP and GIS tools nor was there a detailed explanation of the GIS analysis process to enable its replication in other offshore wind site

Table 3
Suitability scores of evaluation criteria.

Criteria	0	1	2	3	4	5	Source
Wind speed (m/s)	<6	6.0–7.0	7.0–8.0	8.0–9.0	9.0–10.0	>10.0	
Water depth (m)	<50, >1000	50–1000	300–500	200–300	50–100	100–200	(BVG Associates, 2023; Carbon Trust, 2015)
Distance from oil and gas zones (m)	<5000	5000–10000	10,000–15000	15,000–20000	20,000–30000	>30,000	(Díaz and Guedes Soares, 2020; Maandal et al., 2021)
Distance from cables and pipelines (m)	<3000	3000–4000	4000–5000	5000–6000	6000–7000	>7000	(Mandaal et al., 2021)
Distance from port (km)	<2	>40	30–40	20–30	10–20	2–10	Spyridonidou et al. (2020)
Distance from grid (km)	–	>50	40–50	30–40	20–30	<20	(Taofik and Fekri, 2021)
Shipping density	1500–2500	1000–1500	5000–1000	250–500	50–250	0–50	Author
Distance from Airports (km)	<2.5	2.5–5	5–8	8–10	10–15	>20	(Taoufik and Fekri, 2021; Yousefi et al., 2022)
Distance from shore	<1	1–5	5–10	10–15	15–20	>20	(Taofik and Fekri, 2021)

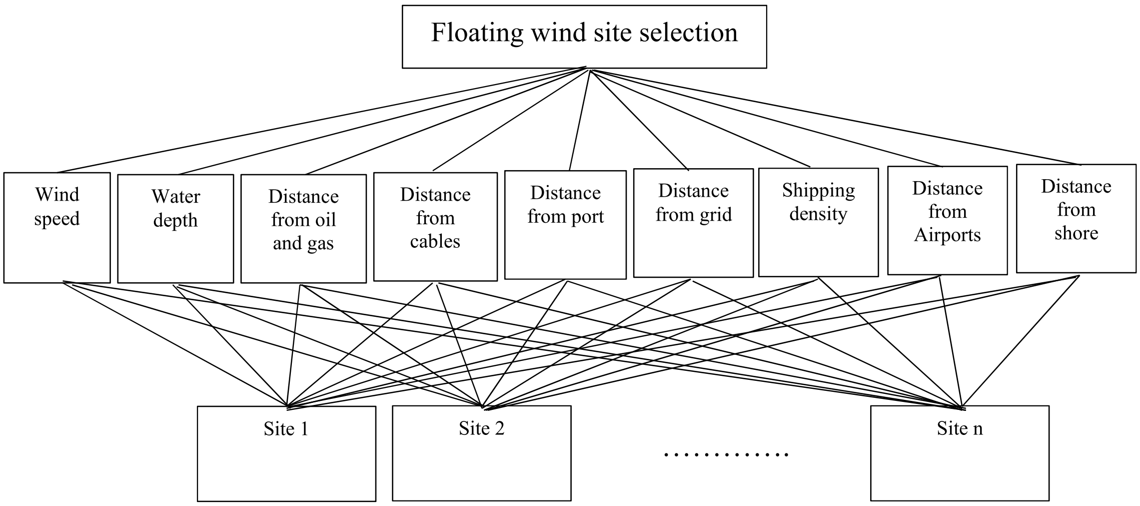

Fig. 4. AHP hierarchical structure.

Table 5
Completed pairwise comparison matrix.

	Wind speed	Water Depth	Distance from Oil and gas	Distance from cables	Distance from port	Distance from grid	Shipping density	Distance from airports	Distance from shore
Wind speed	1	3	9	7	6	5	4	9	6
Water Depth		1	7	7	6	3	4	9	4
Distance from Oil and gas			1	1/4	1/7	1/7	1/6	3	1/5
Distance from cables				1	1/2	1/2	1/3	3	1/2
Distance from port					1	2	3	7	2
Distance from grid						1	3	8	4
Shipping density							1	9	3
Distance from airports								1	8
Distance from shore									1

Table 6
GIS layers and formats.

Component	Source	Format
Wind speed (100 m)	Global Wind Atlas	Raster
Water depth	GEBCO	Raster
Ports	World Port Source	GPS coordinates
Shipping density	Halpern et al.	Raster
Underwater cables	Koordinates	Shapefile
Oil and gas fields	Petrodata	Shapefile
Grid data	World Bank Group	GeoJSON
Airports	Humanitarian Data Exchange	Shapefile
Shoreline	National Oceanic and Atmospheric Administration	Shapefile

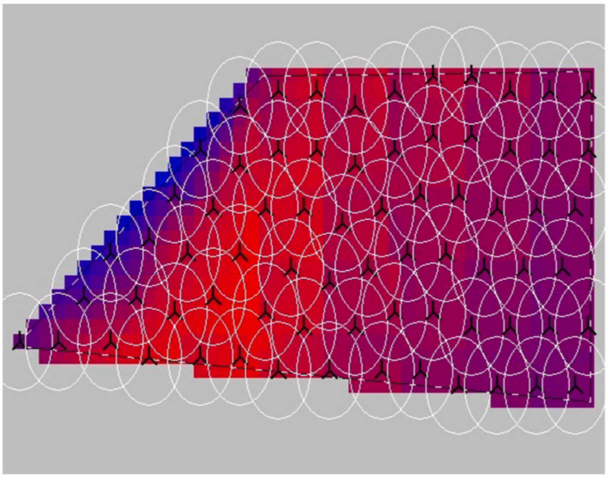

Fig. 5. Wind farm array layout on windPRO.

selection studies.

The utilization of the GIS-MCDM methodology in floating wind research is limited. Two studies have used this approach to evaluate selected sites for floating wind development in Europe (Díaz and Guedes Soares, 2022; Díaz and Soares, 2021). Díaz and Soares (2021) integrated a GIS tool with the AHP tool to assess the relative suitability of floating wind sites in Spain. The evaluation criteria included wind velocity, distance from grid, distance from protected areas, distance from shore, proximity to migratory bird paths, etc., which were ranked following pairwise comparisons undertaken by experts; nevertheless, the resulting weights were only utilised to rank previously selected sites based on their quantitative characteristics (e.g., wind speed, shore distance etc.), as in bottom-fixed offshore wind site selection studies (Caceoğlu et al., 2022; Vagiona and Kamilakis, 2018). A similar methodology was deployed in Díaz and Guedes Soares (2022), where the authors conducted a second round of pairwise comparisons involving the selected sites and with respect to each evaluation criteria to allow for synthesis with the initially established priorities. This mitigated uncertainties in the variation of quantitative attributes of the floating wind sites and is consistent with the example provided in Saaty (1987) for selecting the best alternative. It also ensured that forty-two potential wind farms in the EEZ of Portugal, France, and Spain were ranked to support project planners and developers. Nevertheless, future floating wind markets can benefit from an AHP-GIS methodology that enables an advanced integration of the tools for floating wind site selection. Established priorities from AHP analysis which consider relevant marine policies and regulations can be implemented on GIS software using a single map algebraic expression to inform the mapping of the most attractive sites based on a rated area map. The results can be further incorporated on wind resource assessment tools to study the feasibility of floating wind farms in the selected sites based on energy production.

Table 7
Priorities of evaluation criteria.

Criterion	Relative importance (%)
Wind speed	27.69
Distance to port	14.10
Water depth	13.95
Distance from grid	12.95
Distance from shore	9.28
Distance from underwater cables	8.95
Shipping density	7.69
Distance from airports	3.34
Distance from oil and gas deposits	2.05

Therefore, the specific contributions of this paper are three-fold. First, it conducts pairwise comparison surveys involving actors in the South African wind industry and the wider floating wind sector. This was based on the AHP method and included a comprehensive list of multilevel factors associated with floating wind development in the case study context, which allowed for the ranking of priorities to inform site selection. Second, it integrates the AHP results with the ArcGIS ArcMap 10.8 software to enable mapping of the most suitable sites in South Africa's EEZ as well as provides a description of the GIS analysis process. Third, it imports the selected sites into EMD's windPRO software to calculate the development potential of the selected sites. The findings of this paper are relevant to researchers, policymakers, and industry actors interested in developing floating wind in South Africa and other future markets.

The remaining sections of this work are organised as follows: section 2 provides an overview of the AHP methodology, section 3 discusses the

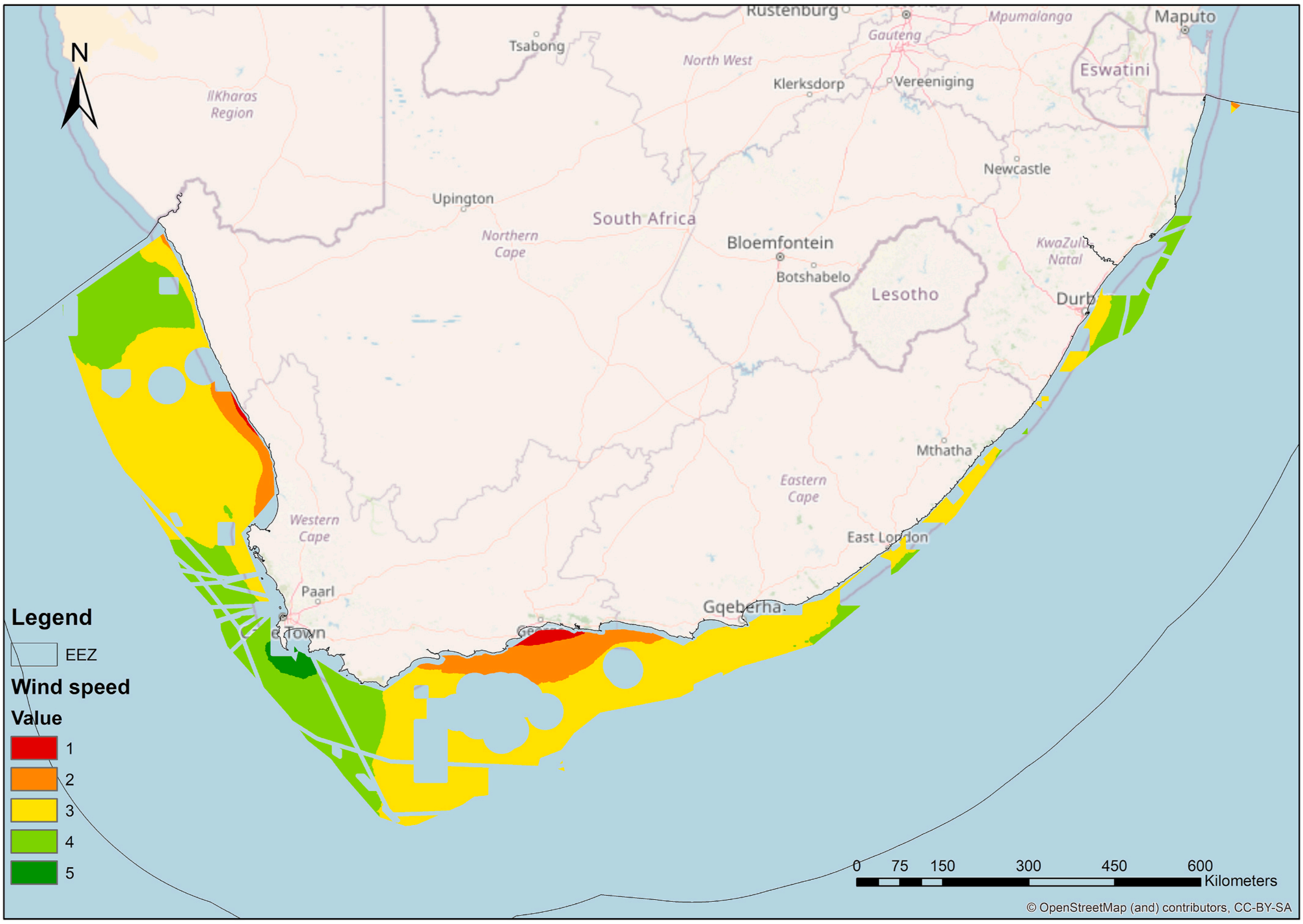

Fig. 6. Wind speed suitability score.

data and methods used in this study, section 4 presents the results, and section 5 concludes with a summary of the key findings.

2. Analytical hierarchy process

The AHP utility-based method has been selected for this study because it offers a systematic approach for tackling the problem of floating wind site selection, distinguished by a host of quantitative and qualitative factors. One of the major critiques of this method is the incident of rank reversal when a criterion is added or removed (Belton and Gear, 1983). However, several authors have argued for the legitimacy of the rank reversal phenomenon (Maleki and Zahir, 2013; Saaty, 2013; Tu and Wu, 2023). The body of research in relation to appropriate techniques for addressing the issue of inconsistency in participants' responses is also growing (Franek and Kresta, 2014; Shihui et al., 2019; Zeshui and Cuiping, 1999). Moreover, the AHP method has been successfully applied in a wide range of fields, including renewable energy, public administration, healthcare, manufacturing, telecommunications, and ICT (de FSM Russo and Camanho, 2015; Shao et al., 2020).

According to Saaty (1977), AHP is centred on four key axioms: the reciprocal axiom, the homogeneity axiom, the synthesis axiom, and the expectation axiom. The reciprocal axiom postulates that if criteria A is 5 times more important than criteria B, criteria B must be one-fifth as important as Criteria A. The homogeneity axiom entails that components being assessed are homogeneous to promote consistency. The synthesis axiom constitutes that the judgements concerning a component must not be influenced by inferior components. The expectation axiom contends that individuals must sufficiently root their judgements in practical data for outcomes to meet their expectations. Some good examples of AHP applications have been provided in Saaty (1987). They display the flexibility and efficiency of the AHP method.

Application of the AHP method usually involves three key stages: defining the goal of the problem, conducting pairwise comparisons of selected criteria, and determining the priority weightings of chosen criteria (Höfer et al., 2016). For the current study, the first stage in this research entailed that selected criteria and sub-criteria were primarily focused on technical and socio-economic aspects of floating wind development in South Africa (as represented in Fig. 3). Pairwise comparisons are conducted based on Saaty's (1987) fundamental scale of judgements (see Table 1). A pairwise comparison matrix $A = [c_{ij}]\ \forall\, i,j = 1,2,\dots,n$ displays the extent of the participant's preference of the n criteria over the selection of an alternative (Saaty, 1990). The judgement matrix A is shown in equation (1), where c_{ij} is the relative importance of criterion C_i over C_j. The reciprocal judgement specifies that if the importance of C_i over C_j is k, then c_{ji} should be the inverse of that element (i.e., 1/k).

$$A = \begin{bmatrix} C_{11} & \cdots & C_{1n} \\ \vdots & \ddots & \vdots \\ C_{n1} & \cdots & C_{nn} \end{bmatrix} \tag{1}$$

The priority weights can be calculated using the eigenvalue approach, which was first conceptualised by Saaty (1977). This involves normalization of the matrix by dividing each element by the sum of each column and calculating the average of each row of the normalized matrix (Saaty, 2008). The presence of bias in human thinking implies the need for inconsistency checks (Saaty, 1990). According to Brunelli

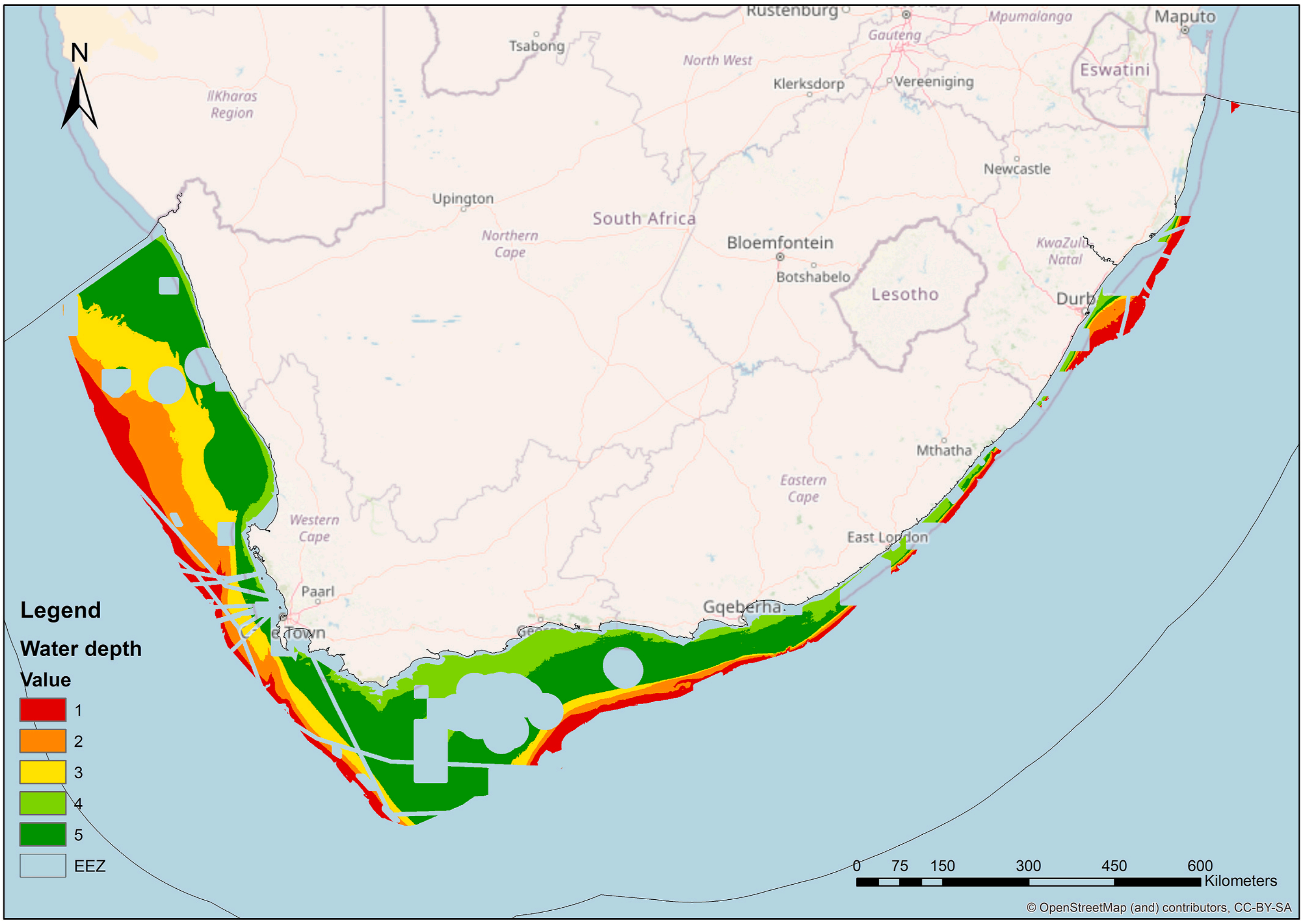

Fig. 7. Water depth suitability score.

(2018), a pairwise comparison should be considered consistent if:

$$c_{ij} = c_{ik}c_{kj} \ \forall \ i, j, k \tag{2}$$

Consequently, the consistency index (CI) and consistency ratio (CR) are assessed using equations (3) and (4) below (Saaty, 1987):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

$$CR = \frac{CI}{RI} \tag{4}$$

Where $\lambda_{\max}$ represents the principal eigenvalue, n stands for the size of the matrix, while RI are random index values utilised to calculate the consistency ratio for different matrix sizes (see Table 2). The judgements are considered consistent when CR is less than 0.1. Cases of inconsistencies can be addressed using the algorithm developed by Zeshui and Cuiping (1999), to enable the derivation of a positive reciprocal matrix with satisfactory consistency (i.e., $CR < 0.1$). In the method, the element c_{ij} of the inconsistent matrix A is replaced by $bij = c_{ij}^{\alpha}(w_i/w_j)^{1-\alpha}$, where $= (w_1, \ldots, w_i, \ldots, w_n)^T$ is the weight vector derived from A. The new matrix $B = [bij]$ has a reduced CR, and the process is repeated until a satisfactory consistency is obtained. The method is explained in greater detail in Zeshui and Cuiping (1999). An example is shown in Appendix A.

Furthermore, a combination of the individual priorities provided by experts can be computed using the Aggregation of the Individual Priorities (AIP) or aggregation of individual judgments (AIJ). The latter is suitable for when individuals are acting as a unit while the former is appropriate for when participants are making separate judgments (Forman and Peniwati, 1998). An aggregation of resulting priorities in the AIP method can be computed either by using a geometric or arithmetic mean as neither approach violates the pareto principle (Forman and Peniwati, 1998).

3. Data and methods

3.1. Methodological approach

This paper utilised a multidisciplinary approach to select the most suitable development zones and explore the development potential for FOWTs in South Africa. It builds on Umoh et al.'s (2024) work which excluded non-feasible sites from floating wind development considerations in the country. The first stage included an assessment of national marine regulations and reports as well as floating wind literature to establish the evaluation criteria for decision-making in relation to the most suitable sites for floating wind development in the study area. In the second phase, an AHP questionnaire was developed and sent to experts in the South African wind energy sector and the global floating wind industry to determine the priorities in relation to the technical, social, and economic factors influencing the development of the technology in South Africa. This was followed by implementing the AHP results in a GIS environment to enable site selection based on a rated area map, as obtained from the computation of raster layers with respect to the relative importance of each criterion. The final phase involved simulations of the actual development potential (i.e., total capacity, capacity factors, number of turbines, and annual energy production) of

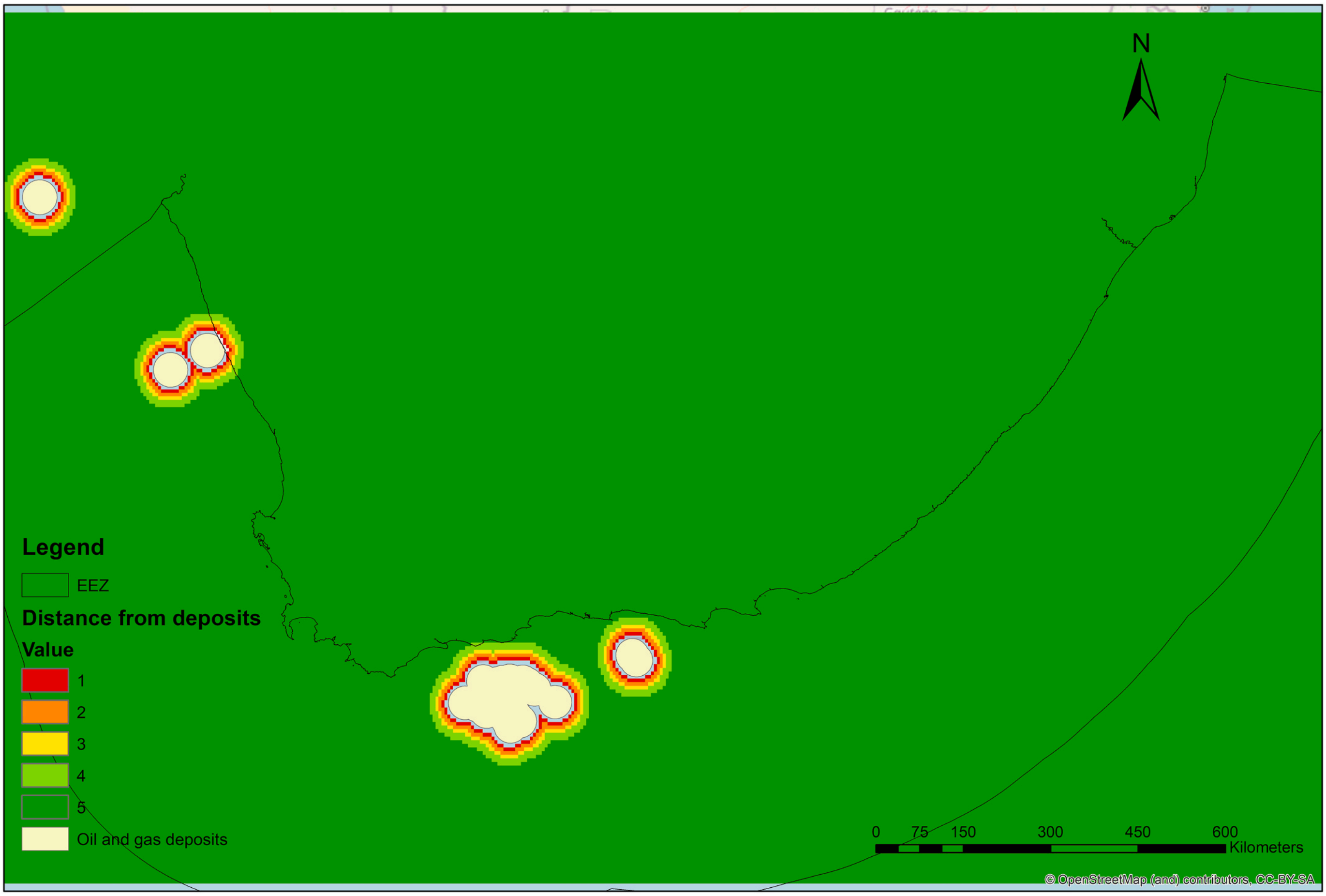

Fig. 8. Distance from oil and gas zones.

selected sites based on their wind resource map and the micrositing of wind turbine generators (WTGs) in the development zones. This was carried out using the Optimizer tool in EMD's windPRO software. Fig. 1 shows the different stages of this study.

3.2. *Study area*

South Africa is the southernmost country in Africa, bounded by 3113 km of coastline (stretching along the Indian Oceans and Southern Atlantic) and covering a total area of 1,221,037 km^2. The country is bordered by Mozambique and Eswatini to the East and Northeast, respectively, and by Namibia, Botswana, and Zimbabwe in the North. South Africa has a mainland EEZ that extends 370 km offshore and includes 1,072,716 km^2 of ocean. There are a wide range of marine-related policies and legislations regulating activities in the country's maritime sector (Nairobi Convention, 2021).

Umoh et al. (2024) applied exclusion criteria to South Africa's EEZ to generate a map showing the feasible sites for floating wind development in the country. The study excluded blue flag beaches, major oil and gas deposits, underwater cables, bird migratory routes etc., which resulted in an exclusion area map showing feasible sites in the Northern Cape, Western Cape, Eastern Cape, and Kwazulu Natal regions of the country. The map (see Fig. 2) displays the 246,105.4 km^2 of offshore area feasible for floating wind in South Africa' EEZ, as it forms the basis of the current paper.

3.3. *AHP evaluation criteria and suitability scores*

3.3.1. *Evaluation criteria*

The selection criteria included a wide range of technical and socio-economic factors that enabled the ranking and selection of suitable sites for floating wind development in South Africa. Environmental factors such as marine protected areas and bird migratory maps were excluded from consideration in Umoh et al. (2024), as consistent with the marine-related polices and regulations in the country. The remaining factors were selected with respect to the extant floating wind literature on site selection for technology deployments (Díaz and Guedes Soares, 2020, 2022; Díaz and Soares, 2021).

3.3.1.1. Wind speed. The average wind speed of potential sites can influence energy production in floating offshore wind farms and is highly associated with its techno-economic feasibility (de Assis Tavares et al., 2020; Maandal et al., 2021). Fig. 2 shows the mean wind speed at 100 m hub height in sites considered feasible for floating wind in South Africa's EEZ. The GIS data was obtained from the Global Wind Atlas and is based on a long-term reference data (2008–2017) of ERA5 (a climate dataset developed through the Copernicus Climate Change Service) reanalysis data (Global Wind Atlas, 2022). This is a publicly available dataset produced through a partnership between DTU Wind Energy and the World Bank Group. Sites with mean wind speeds below 6 m/s are considered not feasible for commercial-scale wind deployments (Carbon Trust, 2015) and therefore, were excluded from considerations in the previous study (Umoh et al., 2024). The resulting wind distribution in the feasible sites informed the assignment of suitability scores (as represented in Table 3) to enable the selection of floating wind development

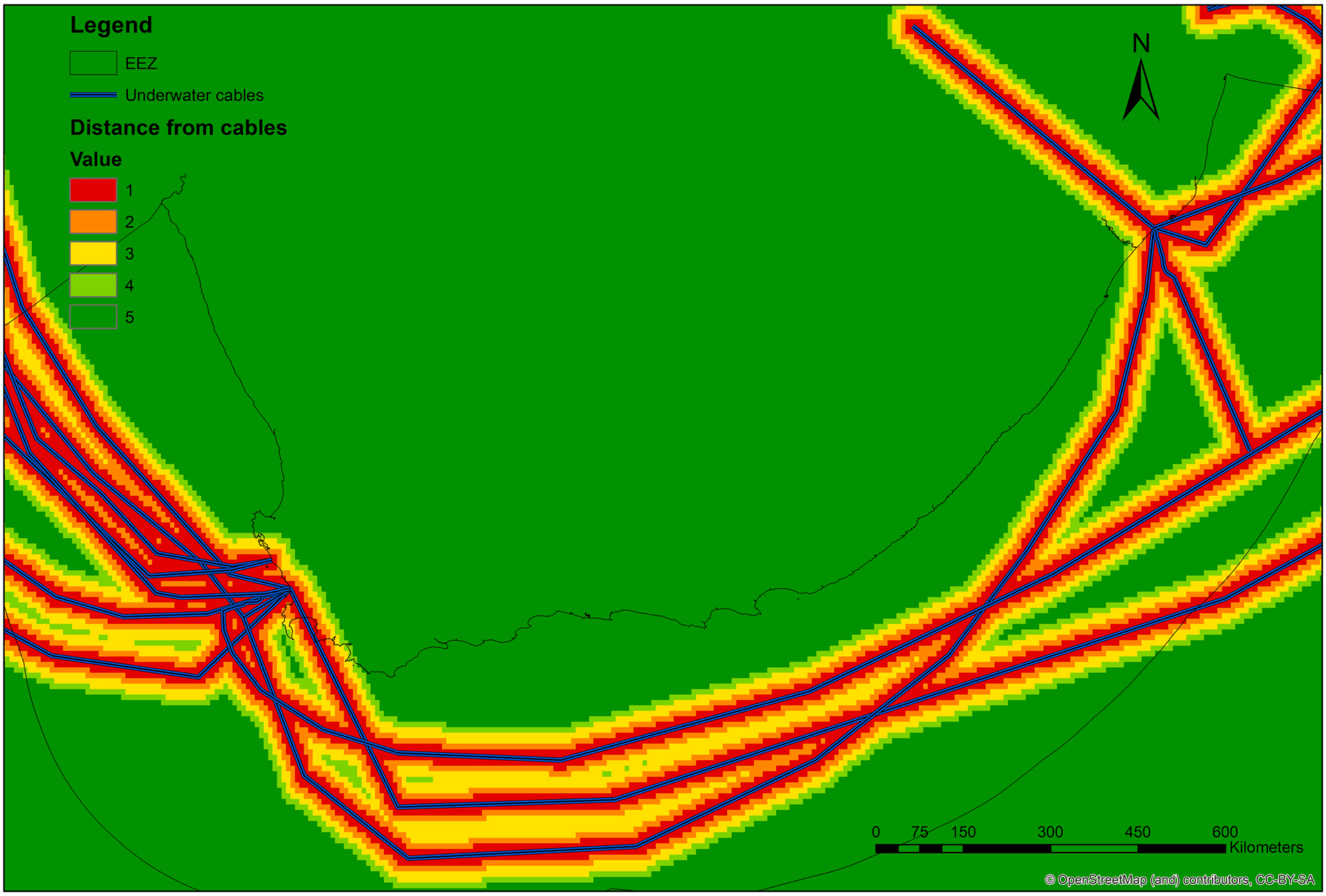

Fig. 9. Distance from underwater cables.

zones in the country.

3.3.1.2. Water depth. Bathymetry conditions can determine the choice and influence the capital costs of floating foundations and mooring system. Sites with water depths less than 50 m and greater than 1000 m, judged as not feasible for floating platforms such as spars, semi-submersibles, and tension-leg platforms (TLPs), were excluded in Umoh et al. (2024). Although the platform cost increases more significantly as a result of greater water depths in bottom-fixed offshore wind (Zhou et al., 2023), a similar relationship can be observed in relation to mooring and anchoring system costs (Carbon Trust, 2015). For example, catenary mooring spreads extends over a distance equivalent of 4–6 times the water depth and influences mooring and inter-array cabling costs (Carbon Trust & ORE Catapult, 2017). Nevertheless, floating wind farms in water depths between 100 and 150 m will experience lower balance of plant (substructure and mooring) costs when compared to those in water depths lower than 100 m, as a result of the complexities associated with designing and fabricating components to counteract waves and currents at these depths (BVG Associates, 2023). This is reflected in the suitability scores presented in Table 3. Moreover, water depths between 100 and 200 m can host spars, semisubmersibles, and TLPs (IRENA, 2016), thus making it attractive to a variety of project developers. The publicly available raster layer showing the distribution of water depths in South Africa's EEZ was obtained from the General Bathymetry Chart of the Oceans (GEBCO, 2022) by downloading the GeoTiff data based on a user-defined area.

3.3.1.3. Distance from airports. Wind turbines can interfere with aviation radar signals and lead to conflicts related to air traffic monitoring and safety (ORE Catapult, 2022). Specifically, blade rotation can trigger doppler shifts and bring about mix-ups in legacy and modern radar systems (Ayodele et al., 2018; Kim and Lim, 2014). Locating wind farms away from airports can mitigate the risk of interference and ensure the safety of the national airspace. Shapefile showing airports, aerodromes, helipads, and other aviation-related items in South Africa has been extracted from the Humanitarian Data Exchange platform, which exports data from OpenStreetMap for use in GIS software (Humanitarian Data Exchange, 2024). This open access platform is managed by the United Nations's Office for the Coordination of Humanitarian Affairs.

3.3.1.4. Distance from underwater cables and pipelines. Installation and maintenance activities in offshore wind farms can cause damage to existing submarine cables, as evidenced by The Crown State (2012). Thus, 3 km buffers on both sides of submarine cables in South Africa's EEZ were excluded from floating wind site selection considerations (Umoh et al., 2024). Maandal et al. (2021) also implied that situating offshore wind farms away from submerged cables can mitigate the risk of cable damage and enhance the techno-economic feasibility of projects. GIS data showing underwater cables were extracted from Koordinates (2022), which is an ISO 27001 compliant platform for geospatial data.

3.3.1.5. Distance from ports. Port can be considered a key socio-economic factor as proximity to port can influence installation, maintenance, and decommissioning costs as well as encourage investments in local ports (Crowle and Thies, 2022; Spyridonidou et al., 2020). This is highly relevant to the context of South Africa, as the country has seen no offshore wind farms to date. Considering nearness to port during floating

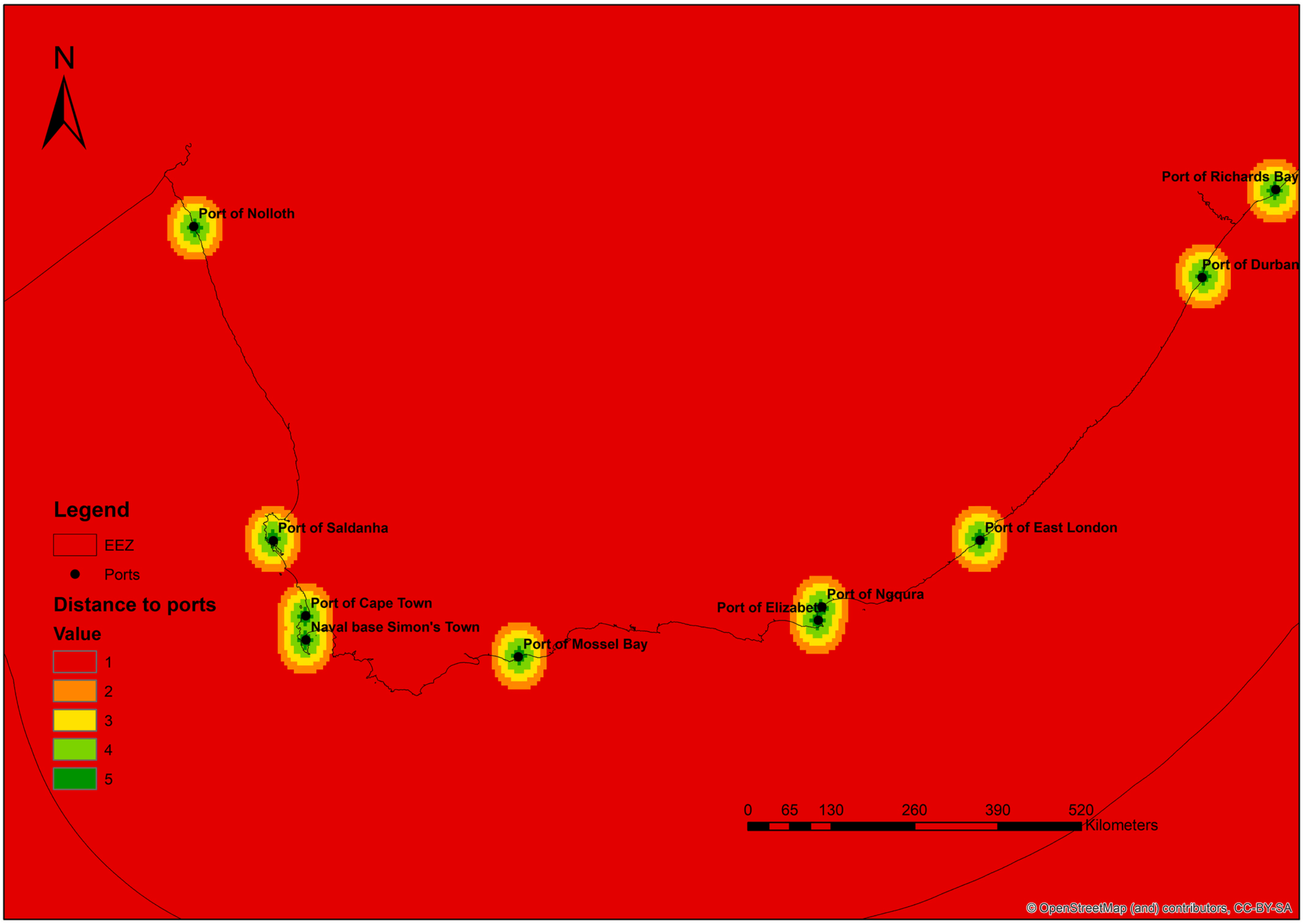

Fig. 10. Distance to ports.

wind site selection can yield development zone clusters which could inform future port development activities. High marine traffic in port regions (such as in the ports of Cape Town and Durban) also implies that situating offshore wind farms in safe distances away from national ports can mitigate the risk of collisions (Umoh et al., 2024). Therefore, a two-pronged approach aimed at maximizing techno-economic feasibility and minimizing marine conflicts has been adopted for the suitability scoring in this criterion. The location of ports in South Africa have been digitized on ArcMap 10.8 with respect to coordinates obtained from World Port Source (2020). The accuracy of port coordinates was justified using the OpenStreetMap Vector Basemap in ArcMap 10.8.

3.3.1.6. Distance from grid. Sites closer to the local electricity grid are more economically suitable for technology development due to lower transmission costs (Cavazzi and Dutton, 2016). This direct cost relationship has been adequately represented by authors in other wind energy studies (Höfer et al., 2016; Taoufik and Fekri, 2021). Open data showing the electricity transmission grid in Africa has been downloaded from the World Bank Group (2023).

3.3.1.7. Distance from oil and gas zones. Ensuring that potential floating wind farms are situated away from major hydrocarbons deposits can promote the sustainability of South Africa's offshore energies sector and guarantee that selected sites are available for early technology developments, especially as its offshore oil and gas industry is still in the nascent stage (Petroleum Agency SA, 2023). Therefore, a 5 km buffer was added around huge oil and gas deposits (Umoh et al., 2024) and the resultant sites were scored with respect to their distances from these hydrocarbon deposits. Data displaying hydrocarbon deposits from the period 1946 to 2003 was provided by PetroData (2009). The data is freely accessible and include information on all known oil and gas deposits across the world.

3.3.1.8. Shipping density. Shipping traffic is one of the key factors of sustainable offshore wind development (Rawson and Rogers, 2015). Developing offshore wind farms in sites with high passenger or cargo vessel traffic can lead to marine conflicts (Vagiona and Kamilakis, 2018), hence, the shipping density raster file from Halpern et al. (2013) informed floating wind farm site selection in this study. The GIS data is based on environmental stressor data in the offshore area in the time period 2008–2013.

3.3.1.9. Distance from shore. One of the relative advantages of offshore wind over onshore wind is its reduce noise and visual impacts (Rezaei et al., 2023). Nevertheless, the trend in existing studies in floating wind developments have been towards lower shore distances to reduce export cables costs and LCOE (Castro-Santos and Diaz-Casas, 2015; Maienza et al., 2022; Serri et al., 2020). This could negatively affect public perceptions of offshore wind, as research has shown that offshore wind turbines can induce significant visual effects (Gkeka-Serpetsidaki et al., 2022). Moreover, data from GEBCO (2022) shows the presence of deep water sites in near shore areas in South Africa's EEZ (see Umoh et al., 2024). To encourage a socially sustainable approach to developing floating wind in South Africa, this study will prioritise a balance between the social and economic factors of developing the technology. Shoreline data was obtained from the (National Oceanic and

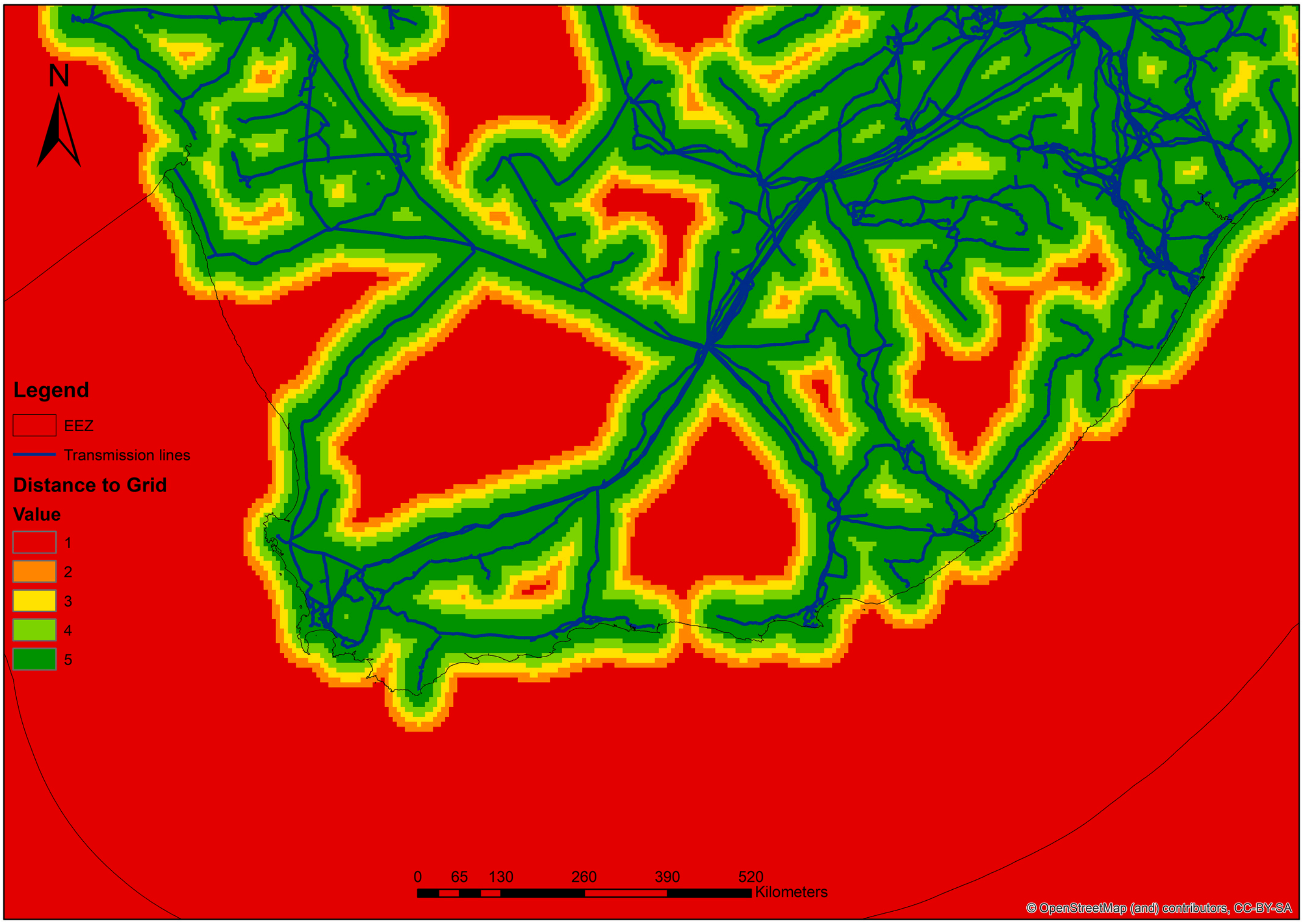

Fig. 11. Distance to grid.

Atmospheric Administration, 2017). Their Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) is a high-resolution geography data set, merged from two databases: World Vector Shorelines and CIA World Data Bank II. The most recent shoreline data version (GSHHG 2.3.7) used in this study was published in 2017 and includes new data which were inaccurately represented in the original dataset.

3.3.2. *Suitability scores*

Several authors have classified relevant evaluation criteria for offshore wind development (Vagiona and Kamilakis, 2018; Diaz and Soares, 2020; Kim et al., 2021), but literature on site characterisation for floating wind development is scarce and requires further research efforts. Such classifications can enable further integration of AHP results into GIS layers (as will be discussed in section 3.5). Despite the huge similarities between bottom fixed and FOWT, minor differences in site requirements for the deployment of floaters in areas such as water depth indicated the need to reevaluate the evaluation criteria for potential wind sites off the coast of South Africa. This was achieved through a combination of literature review, analysis of concerned secondary data, and assessment of the distribution of data in the study area. Criteria were ranked from 0 to 5 in order of suitability (0 - “not suitable”, 1 - “very low suitability”, 2 - “low suitability”, 3 - “medium suitability”, 4 - “good suitability”, and 5 - “highly suitable”). For example, wind speed values were segmented with respect to wind speed distribution in the study area (see Fig. 2). Water depths ranging between 50 m are 1000 m are considered technically feasible for floating wind deployment (Carbon Trust, 2015). Other criteria were determined with respect to existing offshore wind literature and floating wind secondary data.

3.4. *AHP weights*

The levels of hierarchy in the AHP structure for the floating wind farm site selection problem is represented in Fig. 4. It includes three levels: the main goal (selecting the optimal floating wind sites) at the top level, the evaluation criteria at the second level, and the suitable site alternatives at the bottom level of the structure.

The evaluation criteria formed the 9 × 9 judgement matrix, which enabled the calculation of the priority vectors for each criterion. Eleven experts with varying expertise in floating offshore wind technology were invited to conduct pairwise comparisons to facilitate the weighting of the evaluation criteria. Selecting experts with different skills and experiences in the offshore wind industry was intended to mitigate biases associated with specific disciplines in the industry. The questionnaire was developed, and participants were advised to complete their judgements within a 3-month period. Approval for this study was obtained from the University of Hull’s Faculty of Science and Engineering Ethics Committee. Six participants completed and returned their responses in the specified timeframe. The number of final responses from experts provided adequate focused data that informed the ranking of the evaluation criteria for floating wind site selection in this work. There are no strict requirements in relation to sample size in AHP applications, especially considering that majority of authors have utilised sample sizes ranging from four to nine (Darko et al., 2019). Table 4 shows the job roles and location of the experts.

Pairwise comparisons were completed based on the fundamental

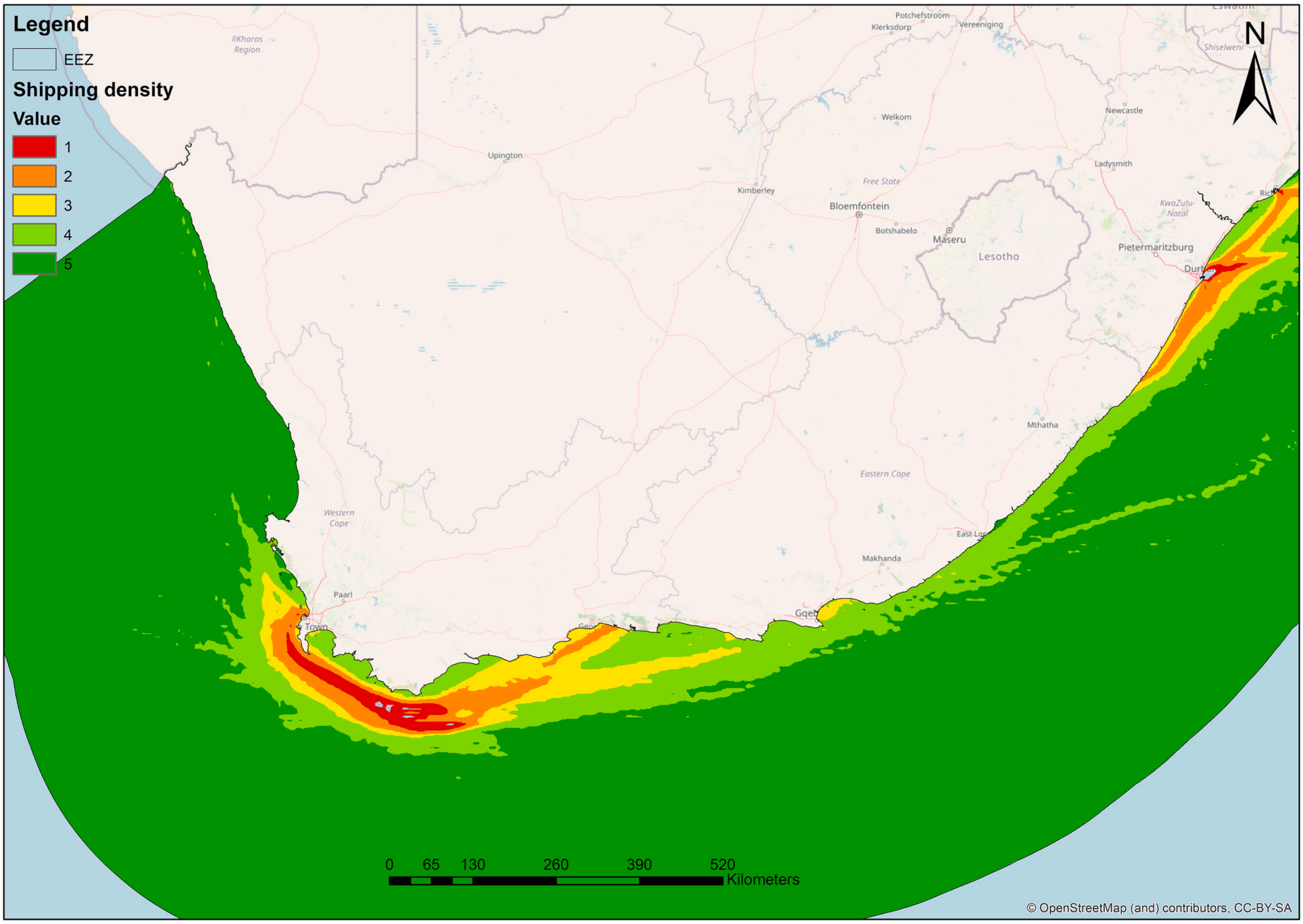

Fig. 12. Shipping density.

scale developed in Saaty (1987). An example of a completed 9 × 9 pairwise comparison matrix is provided in Table 5. Priority vectors were calculated using the eigenvalue method (Saaty, 1977). Consistency checks were carried out using equations (3) and (4). In cases where an individual matrix was found to be inconsistent (i.e., CR > 0.1), the algorithm developed by Zeshui and Cuiping (1999) was utilised to improve its consistency. The AIP method was applied to consolidate the individual priorities of experts and determine the aggregate ranking of the evaluation criteria. In this study, all experts received equal weights. The geometric mean method of priorities (AIP) can be obtained using equation (6) (Forman and Peniwati, 1998). This method was preferable as AHP judgements and priorities are based on ratio scales, implying that the weighted arithmetic mean method may lead to rank reversal as it violates the AHP reciprocity condition (Krejčí and Stoklasa, 2018).

$$P_g(C_j) = \prod_{i=1}^{n} P_i(C_j)^{W_i} \tag{5}$$

This was finally followed by the normalization of the geometric mean to ensure that it satisfies the following equation:

$$\sum_{i=1}^{n} P_g(C_j) = 1 \tag{6}$$

Table 5 provides an example of a pairwise comparison matrix.

3.5. GIS analysis

Analyses were conducted on ArcGIS ArcMap 10.8. GIS layers were obtained from various sources (as displayed in Table 6) and manually included on the software using the WGS 1984 Geographic Coordinate System. All layers were converted to raster format and same cell size to enable computation on the RASTER CALCULATOR. For layers related to distance/proximity, the EUCLIDEAN DISTANCE tool was utilised to compute the distance ranges. The RECLASSIFY tool was used to assign suitability scores to all layers based on Table 3. All layers were then combined using a single algebraic expression on the RASTER CALCULATOR, which uses a standard Python syntax to combine several geoprocessing tools and operations. This enabled the modelling of the weighted overlay function based on the relative importance of each criterion. Sites with suitability scores ranging from 4 (suitable) to 5 (highly suitable) were considered for floating wind development in the study area. A 20 km buffer between the development zones was also ensured to minimize wake effects between neighbouring wind farms (Hong and Möller, 2011).

3.6. WindPRO analysis

WindPRO 3.6 enabled the estimation of the development potential of selected sites in the study area. The accuracy of wind resource assessments conducted on windPRO has been validated by several authors (Kim and Lim, 2017; Sharma et al., 2019). Projects for each site were set up using the WGS 84 coordinate system. The shapefile including the polygons were imported through the WTG Area object. This object also enabled the researchers to input the layout demands for all sites. For instance, the 10D x 5D turbine layout was selected to reduce wake losses in the wind farms (Nie and Li, 2018; Zhang, 2015). Turbine orientation

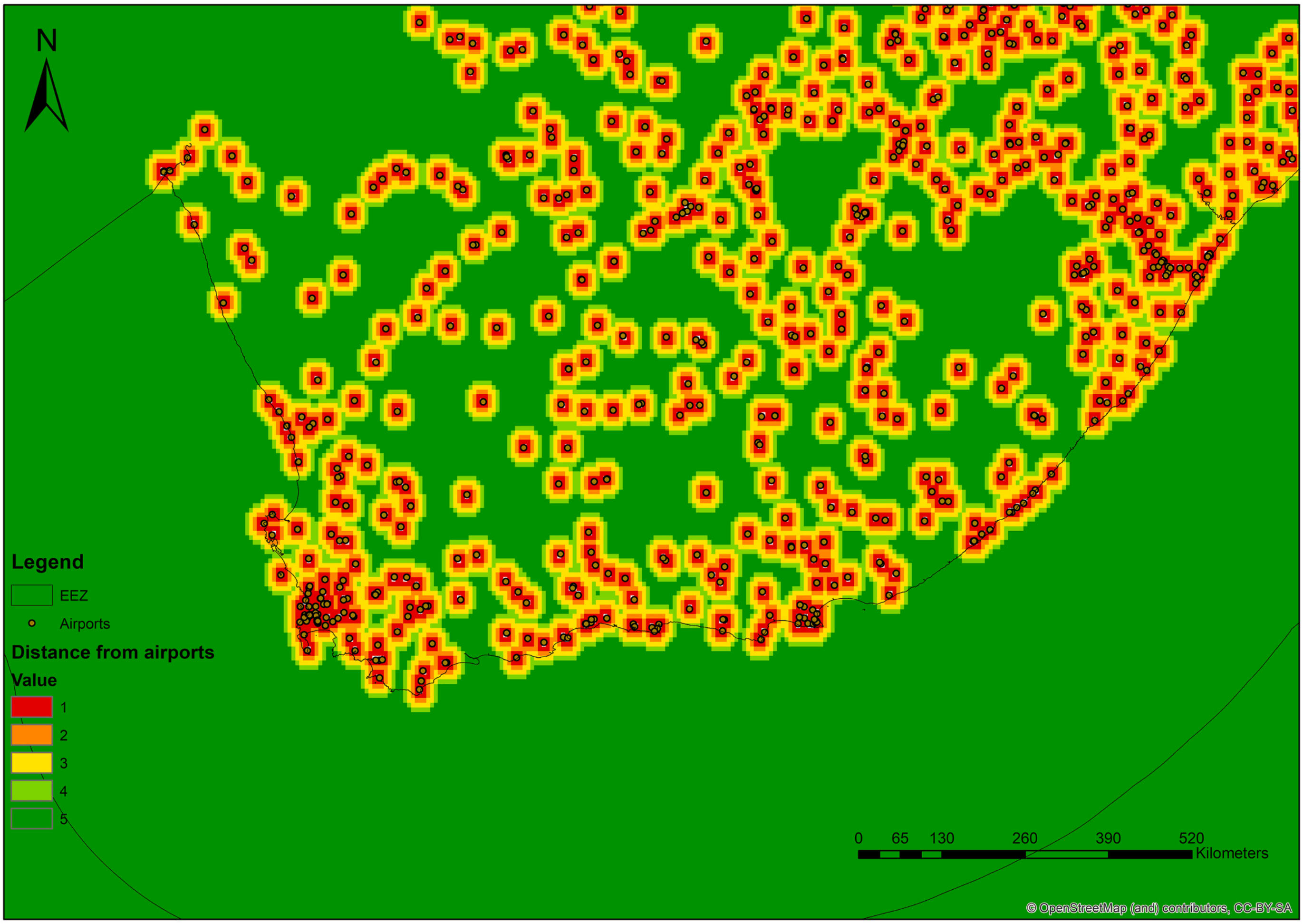

Fig. 13. Distance to airports.

was also selected with respect to the prevailing wind direction shown in the EMD's high resolution Meso scale datasets for South Africa. It includes spatial resolution of 0.029° × 0.029° or approximately 3 × 3 km with hourly temporal resolution and is based on the ERA5 Interim data from the European Centre for Medium-Range Weather Forecasts (2024). Data points nearest to the site centre were selected for all sites.

EMD's Global of Atlas of Siting Parameters (GASP 1.0) was used as the wind resource map for all sites. The maps are freely available on the windPRO 3.6 software and builds on the Global Wind Atlas datasets and EMD's Load Response technology (EMD, 2023). The reference period of the datasets is 2008–2017 and it covers up to 200 km of offshore area from the coastlines. The windPRO Optimizer tool was used to calculate the AEP and capacity factors of the sites. This was based on a "fill max" park size run to ensure that the WTG Area was maximised with respect to the layout demands. Wake effects were calculated using the PARK 2 wake model and a wake decay constant for offshore wind farms. The PARK 2 wake model has been calibrated from the traditional Jensen (1983) wake model, and with respect to data from existing offshore wind projects, to replicate wake conditions in large offshore wind farms (Rathmann et al., 2018; Sørensen et al., 2008). The wake decay constant is estimated as 0.060 for offshore sites with low to high turbulence intensity (Peña et al., 2016). The 6.6 MW S Gamesa turbine was selected for this work, as it has previously been deployed in a floating wind array project. Runs were carried out until the objectives converged at constant values for all sites. Fig. 5 shows a typical layout plot for in a windPRO AEP run completed in this work.

4. Results

4.1. AHP weights

Table 7 shows the relative importance of the exclusion criteria as judged by 6 participants with expert knowledge of floating offshore wind. Two responses met the consistency criteria (i.e., CR < 0.1), while Zeshui and Cuiping (1999) consistency improving algorithm was applied to the four inconsistent judgement matrices. A more complete representation of the final individual priorities provided by each participant, along with their CI and CR values are shown in Appendix B. To the best of the authors' knowledge, no other study has applied a similarly comprehensive set of criteria for floating wind site selection in a future market. Conducting pairwise comparisons with the help of experts from the South African offshore wind sector and the UK floating wind sector (with experience in floating wind development) emphasizes the relevance of our findings.

It is evident that wind speed (27.69%), distance to port (14.10%), water depth (13.95%), distance to grid (12.95%), and distance from shore (9.28%) are the most important selection criteria for floating wind farms. This is comparable with findings from similar offshore wind site selection studies (Caceoğlu et al., 2022; Díaz and Soares, 2021; Taoufik and Fekri, 2021); however, worthy of note is the ranking of "distance to port" as the second most important criterion. Ports are crucial to the development of floating wind projects due to the varying construction, assembly, and maintenance requirements of the different floating foundation types (Crowle and Thies, 2022). As issues related to port capability and availability have posed as barriers to floating wind

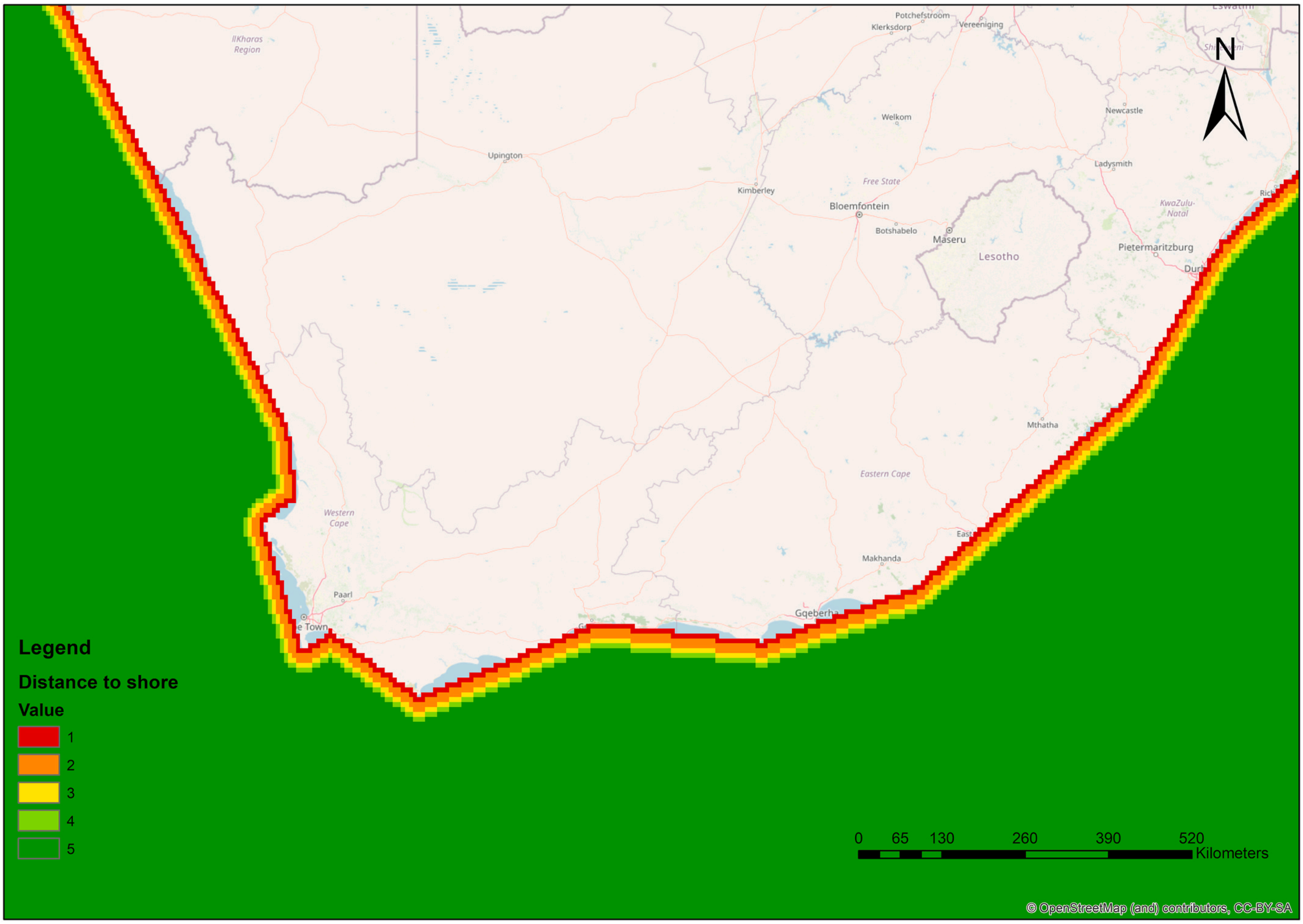

Fig. 14. Distance to shore.

development in the UK (Carbon Trust & ORE Catapult, 2017), future markets can benefit from a strategic port upgrade plan established alongside potential project developers to accommodate the construction, marshalling, and maintenance needs of floating wind projects.

4.2. Evaluation and rated area maps

The maps showing the suitability scores of the offshore areas in South Africa's EEZ based on the value scores assigned in Table 3 are shown in Figs. 6–14. Sites in the NC and WC areas have higher wind speed value scores (see Fig. 6), implying that the highest overall scores may be concentrated in these regions – as wind speed was judged as the most important criterion by the experts. As shown in Fig. 7, there is also a good distribution of sites with good and highly suitable water depths in near shore areas across the NC, WC, and EC areas, which are capable of hosting semisubmersible, spar, and TLP floating foundations. Fig. 8 shows locations of huge mineral deposits mainly in WC and NC which are more likely to be utilised for offshore oil and gas exploration. Situating future floating wind farms away from these locations can mitigate future marine conflicts. Similarly, Fig. 9 shows that sites furthest away from submerged cables are most suitable for floating wind, as distance from underwater cables was judged as the 6th most important criterion in the technology development. Shipping density value scores are lowest in sites near the coast in WC and KN (Fig. 12), which is related to the high vessel traffic in Port of Cape Town and Port of Durban (Umoh et al., 2024). Nevertheless, the criterion is only ranked as the 7th out of nine exclusion criteria. Fig. 13 also shows that sites nearest to airports have lower suitability scores, although its impact on the final suitability map will be limited by its AHP ranking (8th).

The distance for shore map (in Fig. 14) indicates that sites less than 8 km from shore have lower suitability scores (0–2) due to the social impacts of offshore wind farms. Locations situated farther than 8 km from shore have been assigned suitability scores (3–5) to balance for the economic consideration of export cable costs. Besides, distance from shore was 5th most important criterion in the final AHP ranking. The availability of possible grid connection points in all coastal regions indicates that near shore areas in NC, WC, EC, and KN have higher "distance from grid" value scores (Fig. 11). Similarly, ports are evenly spread across these regions along (Fig. 10), implying that a combination of high value scores for both criteria can result in a high overall score because "distance to port" and "distance from grid" are the 2nd and 4th most important criterion, respectively. As suitability was judged solely by proximity on ArcMap, it is important to consider the actual generation connection capacity and port capabilities in the coastal regions. A study found that the ports of Saldanha and Ngqura have relatively higher suitability, while the EC and KN zones can accommodate new generation capacities from renewable energy sources (Umoh et al., 2024).

Combining the map using a single map algebraic expression (based on the group AHP weights) in ArcGIS ArcMap yielded the rated area map for floating wind in South Africa. Fig. 15 shows that the suitability score of the rated area ranged from 2.25 to 4.14, with the most viable sites located near the shore in the Northern Cape, Western Cape, Eastern Cape, and Kwazulu Natal regions.

Reclassifying the rated area into five classes (1 - very low suitability, 2 - low suitability, 3 - medium suitability, 4 - good suitability, 5 - high

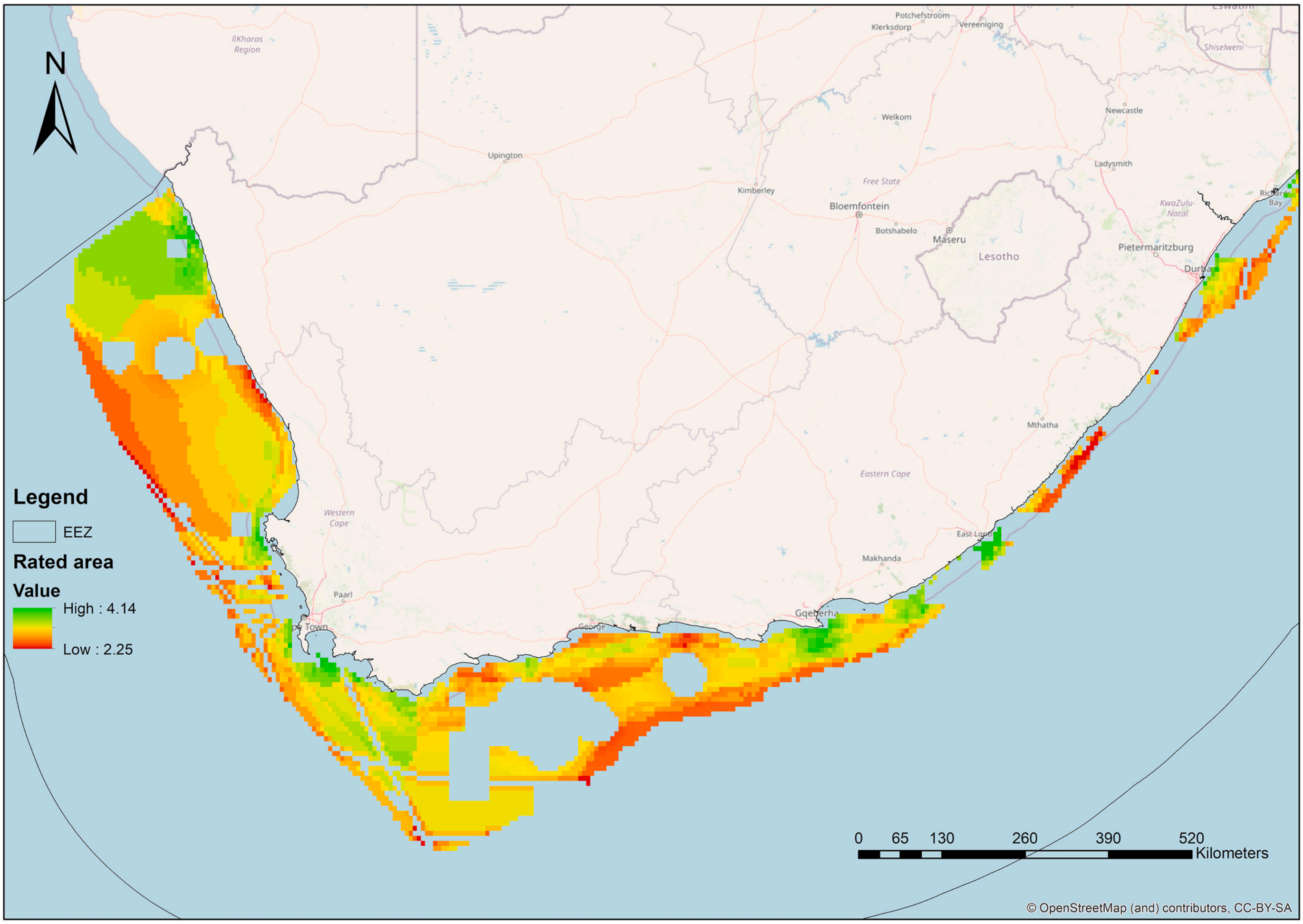

Fig. 15. Rated area for floating wind development in South Africa.

suitability) with equal interval enabled the selection of the development zones, as displayed in Fig. 16. Only areas with good and high suitability were considered for selection. 20 km circular buffers added around the sites ensured that sites were spread across South Africa's entire EEZ. It resulted in the mapping out of 25 sites in NC, WC, EC, and KN.

4.3. Site characteristics

Table 8 summarizes the site characteristics which will inform the economic feasibility of the development zones. It includes details such as water depths, wind farm capacity, number of turbines, AEP, capacity factor, distance to shore, distance to nearest port, shipping density etc., that are relevant to the industry actors and policymakers in the study area. The site characteristics were obtained from GIS analysis on ArcMap, while the actual development parameters (including number of wind turbines, AEP, and capacity factors) were simulated on windPRO. There is a potential to develop over 71 GW of floating wind capacity in the selected sites, with capacity factors ranging from 36.18% to 54.49%. It is important to note that the capacity factor values have been driven down by huge wake losses as a result of the large wind farm sizes (see Table 8). With average wind speeds as high as 10.17 m/s, distinct sites within the development zones could see higher AEPs and capacity factors, which are crucial to low LCOEs. Ports of Nolloth and Saldanha are located near a cluster of sites in the NC and WC regions, respectively. Ports of Richard's Bay or Durban can serve as construction and marshalling base for sites in the Kwazulu Natal region, while the Port of Ngqura can be upgraded to floating wind farms in the EC region.

4.4. Development potential

Selected zones in EC are generally nearer to shore, with low shipping density, a mean wind speed of 8.75 m/s, and average water depths ranging from 110.4 to 180.8 m. EC2 and EC3 can jointly generate 64.77 TW h/year of floating wind power and are located closer to the Port of Ngqura, said to hold a good potential for expansion (Umoh et al., 2024). WC zones have a slightly higher average wind speed (8.83 m/s), which can be attributed to higher mean speeds found in the WC7 (10.17 m/s) and WC8 (9.61 m/s) sites. Nevertheless, the region has sites with relatively lower water depths, which are not suitable for spar platforms and may result in higher mooring system costs for semisubmersibles (BVG Associates, 2023). The 12 selected zones in WC can accommodate a total of 25.6 GW floating wind capacity, thus enhancing the business scope for the development of the Port of Saldanha for construction and marshalling activities. Figs. 17 and 18 show the EC and WC development zones, respectively.

The five selected zones in the NC region have high mean wind speeds and are clustered around the Port of Nolloth. These sites have an average water depth of 152.4 m and experience low shipping traffic. They are sited at relatively greater distances from grid connection points, which, along with an absence of new generation connection capacity (Eskom, 2021), implies the presence of transmission-related barriers to the development of wind farms in this region. On the other hand, sites in KN have a 2.9 GW development potential, along with a possible 5.6 GW of generation connection capacity (Eskom, 2021). The highest mean wind speeds can be found in KN1 (9.25 m/s) and KN2 (9.34 m/s), which are near the shore and close to the Port of Richard's Bay. However, KN1,

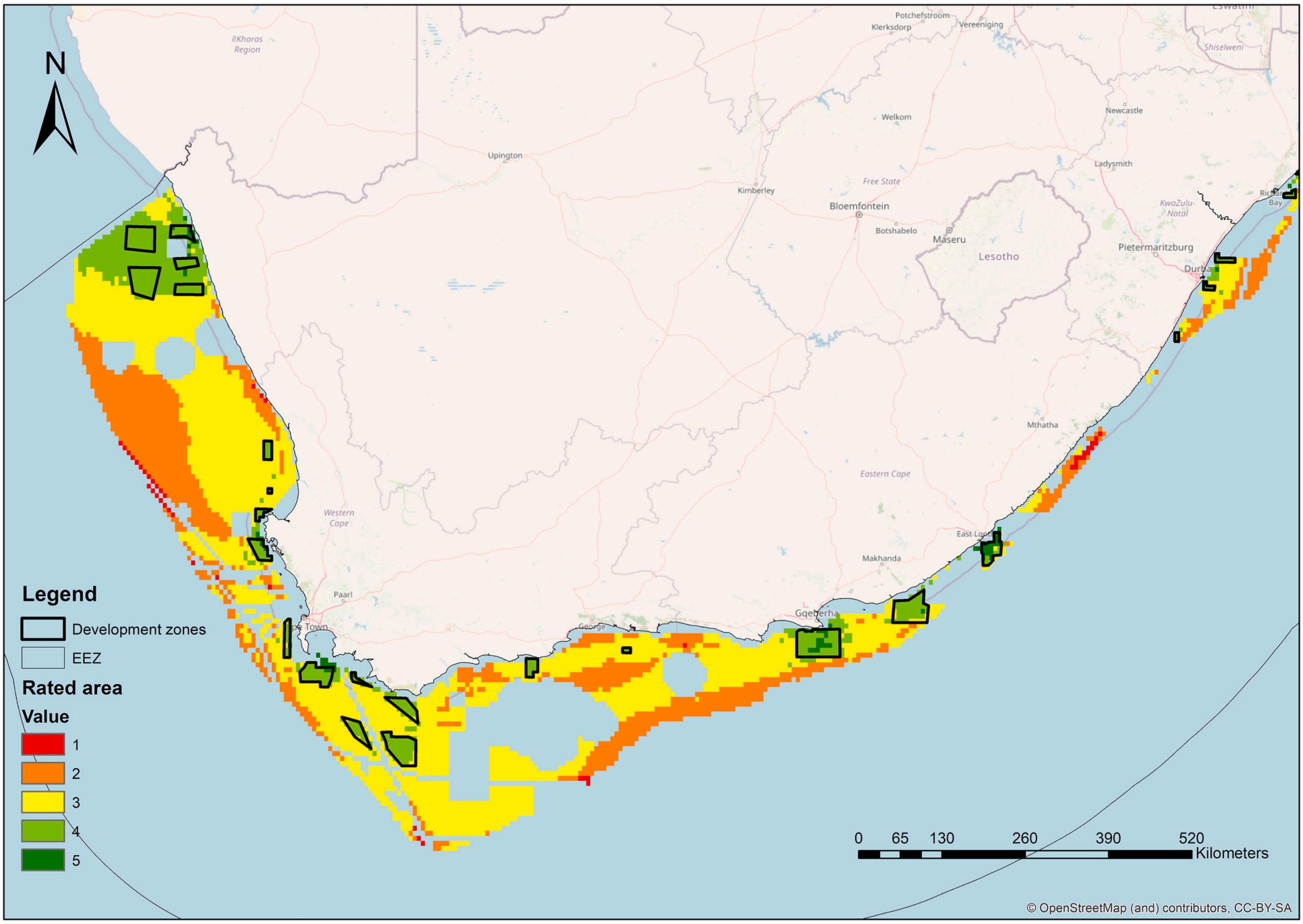

Fig. 16. Selected sites for floating wind development in South Africa.

KN3, and KN4 have lower average water depths which may not be capable of hosting spar floaters. Figs. 19 and 20 display the NC and KN development zones.

5. Conclusions

This paper has developed a new integrated approach for selecting floating wind sites in emerging and future markets. First, a literature and secondary documentation review helped determine the evaluation criteria for floating wind selection in South Africa. This was followed by an AHP methodology involving experts from the South African offshore and global floating wind sectors. The AHP results were implemented on ArcGIS ArcMap 10.8 to enable the selection of the most suitable zones based on evaluation and rated area maps. Shapefiles including the polygons of these areas were imported into windPRO 3.6 to calculate the development potential of the selected zones. The findings show that the development zones can host a cumulative generation capacity of over 71 GW. To achieve this potential, industry actors and policymakers must consider these findings along with the site characteristics (distance to shore, proximity to port, water depths etc.) that may influence the techno-economic feasibility of floating wind projects. Future research can apply the data provided in Table 8 to assess the economic feasibility of floating wind in distinct sites in the development zones.

The paper provides important findings for future floating wind development endeavours in South Africa and other emerging markets. It presents the site characteristics of 25 attractive sites for floating wind in South Africa that could inform both industry and policy activities. The study also provides an AHP ranking of a comprehensive set of evaluation criteria for floating wind site selection that can be easily applied to future studies.

This study is not without limitations. One limitation is that only one expert with extensive knowledge of the study area completed the AHP questionnaire. Although other participants had significant experience in the floating wind sector, more responses from experts with contextual knowledge may have enhanced the applicability of the findings to the study area. The reversal is that the comprehensive set of evaluation criteria and weights can easily be applied to similar site selection studies in future markets. In addition, the GIS analysis relied on the assumptions that proximity to existing ports and grid connection points influenced the suitability of sites in the study; however, by evaluating the available generation connection capacity and port capabilities in South Africa, it was possible to further analyse the actual development potential of floating wind in the selected zones. Future studies can conduct detailed local port assessments in relation to the construction, installation, and maintenance of floating wind components to guide future port infrastructure investments.

CRediT authorship contribution statement

Kubiat Umoh: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abbas Hasan:** Writing – review & editing, Supervision. **Amangeldi Kenjegaliev:** Writing – review & editing, Supervision.

Table 8
Floating wind site characteristics.

Region	Site	X cord	Y cord	Area (km2)	Dist. Port (km)	Nearest port	Dist. Shore (km)	Dist. Grid (km)	Avg w. Speed (m/s)	Avg w. Depth (m)	Ship. Density	AEP (MWh/ year)	Wake loss (%)	Capacity factor (%)	Turbines	Farm size (MW)
Eastern Cape	EC1	28.06810	−33.13570	947.12	23.04	Port of East London	3.43	25.28	8.88	180.83	Low	14,799,231.60	13.59	44.41	576	3801.6
	EC2	26.93950	−33.84560	2012.63	139.41	Port of Ngqura	6.56	38.1	8.84	122.2	Low	28,915,699.00	17.68	41.93	1192	7867.2
	EC3	25.64000	−34.23040	2873.05	35.98	Port of Ngqura	2.72	30.01	8.52	110.44	Low	35,855,639.20	19.98	39.45	1571	10,368.6
Kwazulu Natal	KN1	32.41030	−28.59350	64.11	47.27	Port of Richard’s Bay	1.56	32.57	9.25	98.5	Low	1,243,944.50	4.5	53.75	40	264.0
	KN2	32.26810	−28.86770	158.59	24.56	Port of Richard’s Bay	9.71	22.82	9.34	195.87	Medium - high	3,024,248.20	5.85	52.27	100	660.0
	KN3	31.33090	−29.65950	247.61	44.1	Port of Durban	3.23	26.49	8.71	85.61	low - high	4,315,791.60	7.2	46.62	160	1056.0
	KN4	31.11160	−29.99470	141.55	17.4	Port of Durban	3.07	18.11	8.52	266.05	High	3,024,248.20	5.36	45.85	85	561.0
	KN5	30.67050	−30.60150	83.62	101.04	Port of Durban	4.19	25.15	8.65	84.8	Medium - high	1,531,522.30	4.74	47.27	56	369.6
Northern Cape	NC1	16.80010	−30.02410	703.43	98.49	Port of Nolloth	14.51	56.5	9.08	152.07	low	12,225,049.40	10.89	49.25	429	2831.4
	NC2	16.75650	−29.70120	497.29	58.07	Port of Nolloth	13.48	35.31	9.17	136.64	low	8,894,516.30	9.20	51.08	301	1986.6
	NC3	16.17090	−29.92140	1809.95	115.12	Port of Nolloth	71.37	105.77	9.1	186.78	low	29,211,631.80	16.11	46.49	1086	7167.6
	NC4	16.69790	−29.32340	621.37	21.44	Port of Nolloth	2.88	58.43	8.57	115.9	low	9,691,473.90	9.31	46.27	362	2389.2
	NC5	16.11950	−29.40570	1636.53	85.32	Port of Nolloth	58.06	110.15	9.2	170.59	low	26,567,102.80	15.48	47.73	962	6349.2
Western Cape	WC1	22.94440	−34.31080	93.25	169.38	Port of Mossel bay	25.62	56.16	7.42	94.19	low	1,172,347.90	7.87	36.18	56	369.6
	WC2	21.60750	−34.50540	467.50	25.93	Port of Mossel Bay	1.88	41.64	7.66	68.51	Medium	5,506,959.90	12.22	36.89	258	1702.8
	WC3	19.78610	−35.44580	1836.32	232.43	Port of Mossel Bay	62.84	95.8	9.12	165.57	low - medium	24,015,952.50	15.10	43.97	944	6230.4
	WC4	19.83160	−34.96690	795.95	194.1	Port of Mossel Bay	12.31	34.58	9.24	68.62	Medium - high	11,387,614.20	12.9	46.75	421	2778.6
	WC5	19.16470	−34.65000	186.24	128.48	Port of Cape Town	8.46	55.58	9.63	88.93	low - high	3,341,840.20	7.27	54.49	106	699.6
	WC6	19.15990	−35.23730	715.17	196.73	Port of Cape Town	69.81	115.75	9.37	188.66	low - medium	10,454,022.70	11.14	48.31	374	2468.4
	WC7	18.59030	−34.59070	1333.18	93.34	Port of Cape Town	15.83	68.17	10.17	172.35	Medium to high	21,172,480.40	13.61	53.04	690	4554.0
	WC8	18.17710	−34.17860	520.92	46.41	Port of Cape Town	9.85	41.44	9.61	196.56	high	9,113,133.00	6.82	52.86	298	1966.8
	WC9	17.79670	−33.13520	706.34	25	Port of Saldahna	3.6	32.97	8.78	136.88	low	9,225,751.20	11.50	45.82	348	2296.8
	WC10	17.80420	−32.70990	235.47	46.78	Port of Saldahna	2.79	42.64	8.53	80.74	low	3,950,233.60	8.97	47.41	144	950.4
	WC11	17.93330	−32.44250	45.33	77.85	Port of Saldanha	41.26	71.4	8.14	99.21	low	748,778.10	5.06	44.63	29	191.4
	WC12	17.90430	−31.96010	365.55	141.39	Port of Saldanha	30.26	133.61	8.33	123.76	low	5,193,115.70	13.20	41.94	214	1412.4
Total																71,293.2

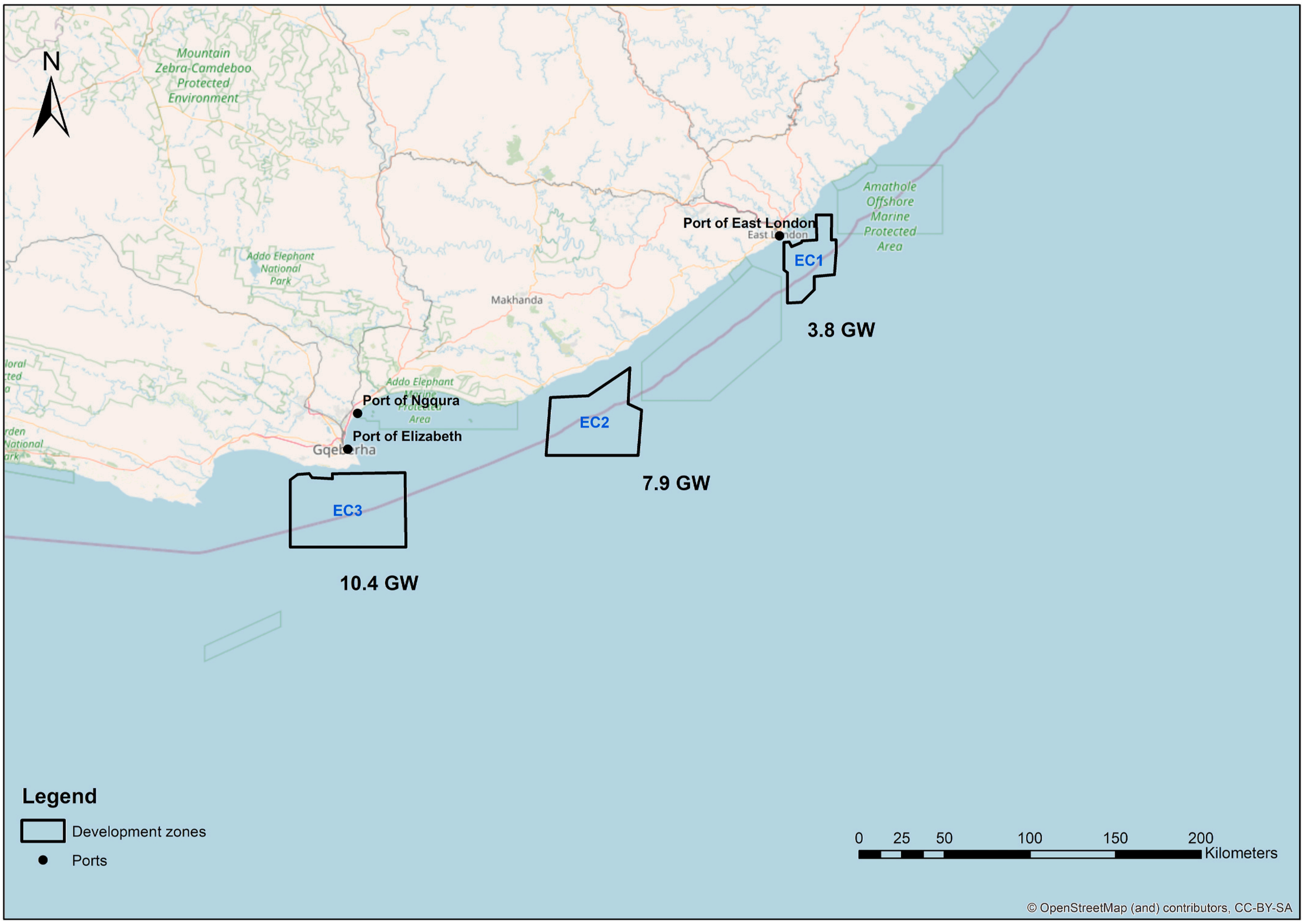

Fig. 17. Eastern Cape development zone.

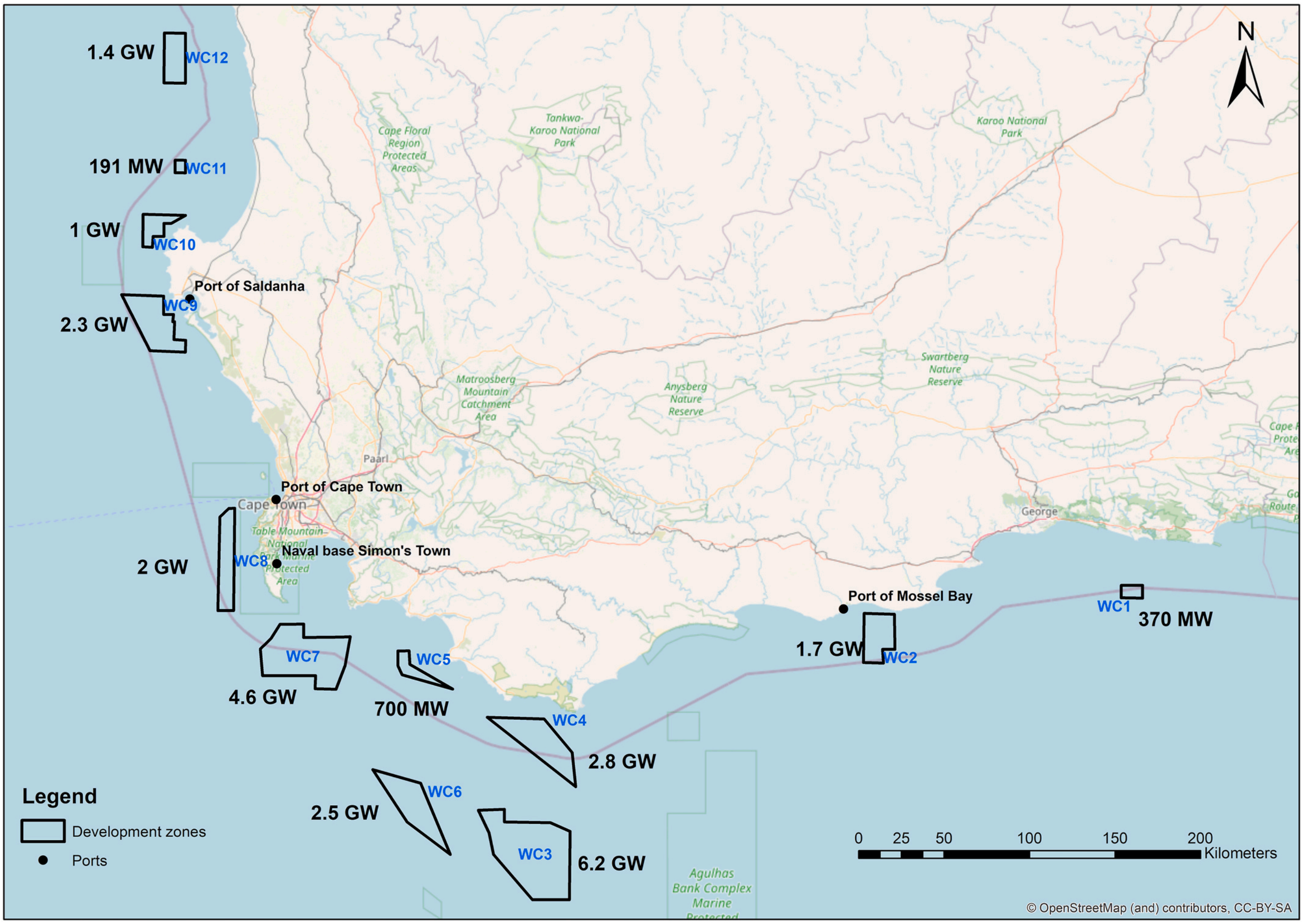

Fig. 18. Western Cape development zone.

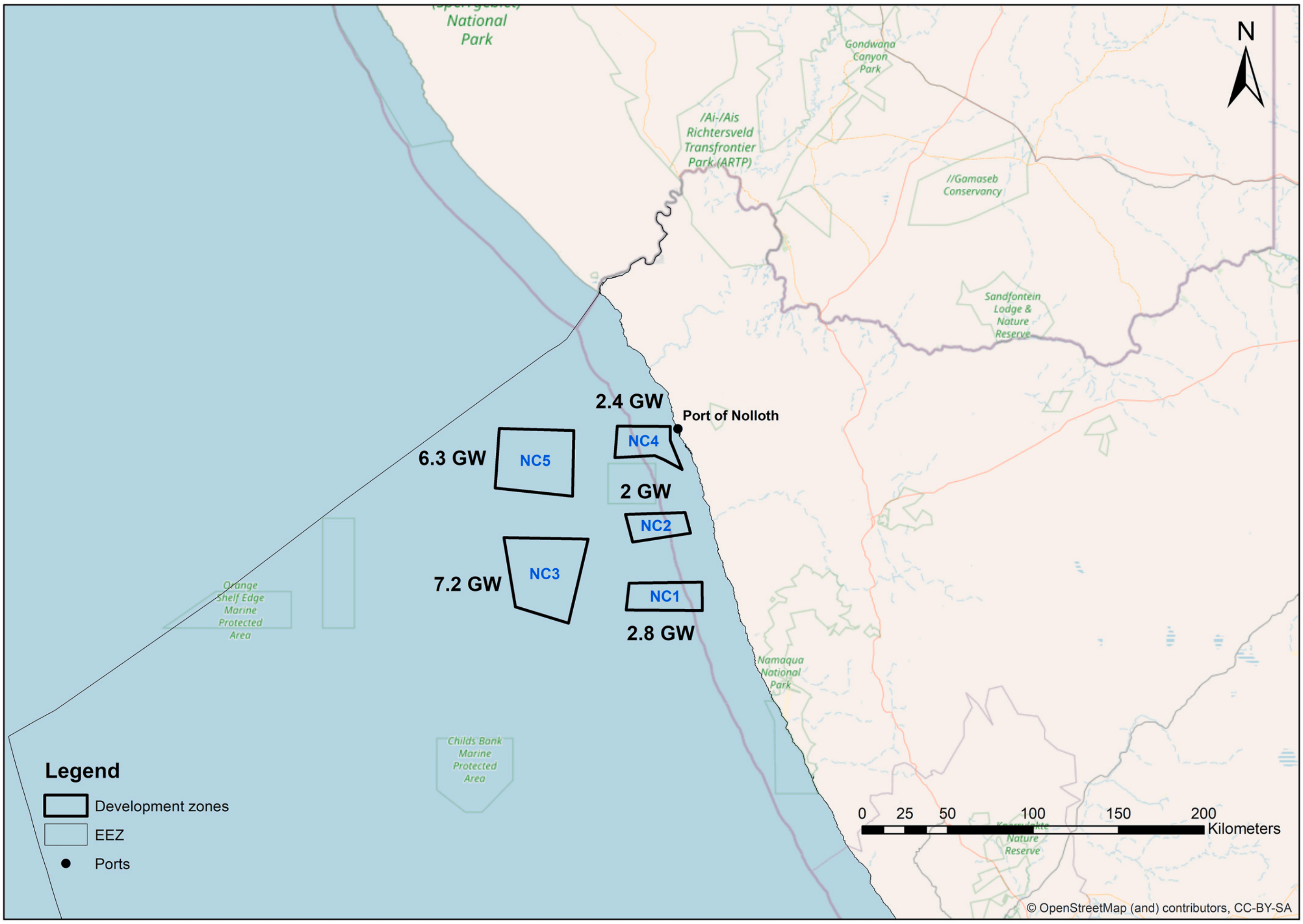

Fig. 19. Northern Cape development zone.

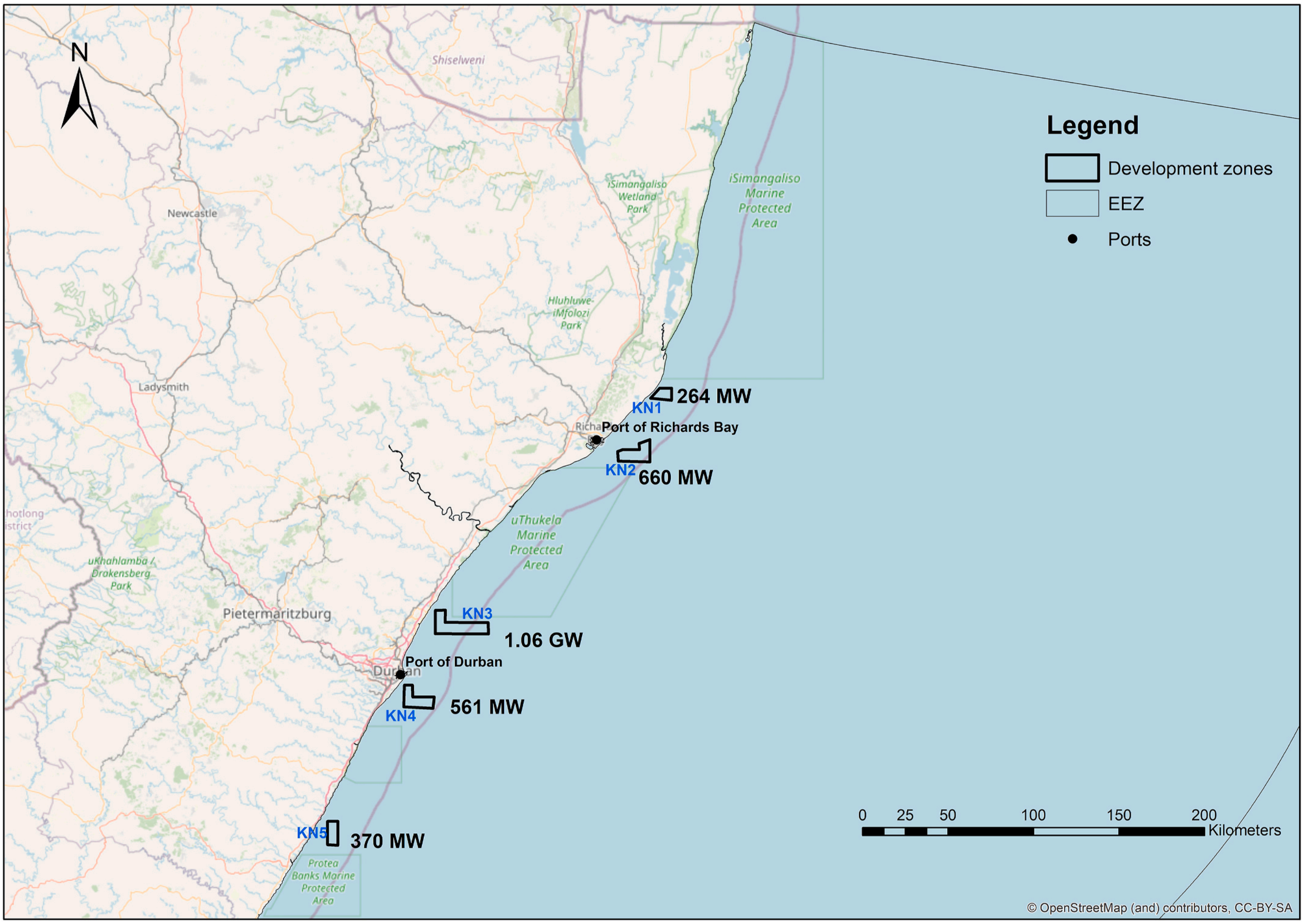

Fig. 20. Kwazulu Natal development zone.

Data statement

Data is available upon request.

Declaration of competing interest

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.

Appendix A

Table A1
pairwise judgement matrix, original version.

Criteria	Wind speed	W. depth	Dist. Oil and gas	Dist. From cables	Dist. To port	Dist. From grid	Ship. Density	Dist. From Airport	Distance from shore	Priority vector
W. Speed	0.2411	0.2958	0.1343	0.2462	0.2795	0.1569	0.1279	0.3128	0.3742	0.2410
W. Depth	0.0402	0.0493	0.1045	0.0821	0.0233	0.0523	0.0142	0.0447	0.1069	0.0575
Dist. Oil and gas	0.0268	0.0070	0.0149	0.0274	0.0078	0.0196	0.0053	0.0056	0.0067	0.0135
Dist. From cables	0.2411	0.1479	0.1343	0.2462	0.3494	0.3137	0.1279	0.1341	0.2138	0.2121
Dist. To port	0.0603	0.1479	0.1343	0.0492	0.0699	0.0523	0.2131	0.1341	0.1604	0.1135
Dist. From grid	0.2411	0.1479	0.1194	0.1231	0.2096	0.1569	0.1279	0.1788	0.0535	0.1509
Ship. Density	0.0804	0.1479	0.1194	0.0821	0.0140	0.0523	0.0426	0.0112	0.0134	0.0626
Dist. From Airports	0.0344	0.0493	0.1194	0.0821	0.0233	0.0392	0.1705	0.0447	0.0178	0.0645
Dist. From shore	0.0344	0.0070	0.1194	0.0616	0.0233	0.1569	0.1705	0.1341	0.0535	0.0845

λ max=10.7111; C1= 0.2139; RI=1.45; CR=0.1475·

Table A2
pairwise judgement matrix, adjusted version.

Criteria	WS	WD	DOG	DC	DP	DG	SD	DA	DS	Priority vector
WS	0.2460	0.2772	0.1850	0.2466	0.2709	0.1990	0.1851	0.2811	0.3141	0.2450
WD	0.0491	0.0553	0.0797	0.0696	0.0382	0.0561	0.0301	0.0519	0.0820	0.0569
DOG	0.0194	0.0101	0.0146	0.0194	0.0107	0.0166	0.0089	0.0089	0.0099	0.0132
DC	0.2308	0.1839	0.1735	0.2314	0.2841	0.2640	0.1737	0.1726	0.2228	0.2152
DP	0.0844	0.1345	0.1269	0.0757	0.0929	0.0789	0.1640	0.1263	0.1411	0.1139
DG	0.1947	0.1551	0.1380	0.1380	0.1856	0.1575	0.1465	0.1682	0.0940	0.1531
SD	0.0724	0.0999	0.0889	0.0726	0.0309	0.0585	0.0545	0.0271	0.0303	0.0594
DA	0.0481	0.0586	0.0902	0.0737	0.0405	0.0515	0.1106	0.0550	0.0355	0.0626
DS	0.0551	0.0253	0.1033	0.0730	0.0463	0.1179	0.1266	0.1090	0.0703	0.0808

λ max=9.365; C1= 0.0456; RI=1.45; CR=0.03146·

Appendix B. individual and group priorities

Criteria\Participants	A	B	C	D	E	F	Group Weight
Wind speed	0.145	0.245	0.348	0.325	0.307	0.217	0.2769
Proximity to port	0.151	0.114	0.081	0.106	0.137	0.229	0.1410
Water depth	0.247	0.057	0.178	0.223	0.185	0.042	0.1395
Distance from grid and connection points	0.121	0.153	0.087	0.109	0.102	0.157	0.1295
Distance from shore	0.122	0.081	0.097	0.042	0.088	0.105	0.0928
Distance from underwater cables and pipelines	0.130	0.215	0.077	0.042	0.030	0.109	0.0895
Shipping density	0.024	0.059	0.097	0.087	0.094	0.107	0.0769
Distance from Airports	0.021	0.063	0.021	0.044	0.039	0.017	0.0334
Distance from oil and gas zones	0.038	0.013	0.014	0.022	0.018	0.016	0.0205
CI	0.0817	0.0456	0.0929	0.0835	0.0475	0.0507	0.0641
CR	0.0564	0.0315	0.0576	0.0576	0.0328	0.0350	0.0442

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