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Continental-scale assessment of the African offshore wind energy potential: Spatial analysis of an under-appreciated renewable energy resource

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Abstract

Offshore wind energy is rapidly becoming a technology that developing countries could consider because project costs have recently fallen substantially. Further reductions are expected as the industry matures. For most African coastal states, specific information about their offshore wind potential is not available. This study aims to address this shortcoming by evaluating the technical offshore wind potential of the entire continent using spatially explicit models and long-term satellite data. Two different scenarios were developed to reflect different levels of technological maturity in the wind industry: The shallow-water, near-coast scenario 1 represented the conservative assumption that technology will not improve beyond what is available already now. The deep-water, full-exclusive economic zone (EEZ) scenario 2 assumes the operational availability of floating platforms that would allow it to access wind resources at much deeper water depths across the entire EEZ. It is emphasized that the model results are subject to a number of uncertainties and therefore should be treated as first order estimates only. Both scenarios indicate very good technical offshore wind energy potential for one third of the African coastal states, with Mozambique, South Africa, Somalia, Madagascar and Morocco exhibiting particularly good resources. More than 90% of the offshore wind resources are concentrated in coastal zones associated to three African Power Pools. These are the Southern African Power Pool (SAPP), the Eastern African Power Pool (EAPP), and the Comité Maghrébin de l'Electricité (COMELEC). A joint and integrated development within these power pools could offer a promising approach to utilising offshore wind energy in Africa.

1. Introducton

The African continent is facing substantial energy challenges. 620 million people do currently not have access to electricity, which represents more than 50% of its population. This number is set to increase by 45 million in the upcoming decade [1]. This problematic situation is expected to become more challenging in the future, as the energy demand of Africa is projected to increase by 600% between 2010 and 2040 [2]. The International Energy Agency (IEA) is estimating that the electricity generating capacity will need to at least quadruple by 2040 to supply sufficient electricity [3]. These figures outline the pressing need for Africa to meet the seventh UN Sustainable Development Goal (SDG 7) which stipulates the access to affordable, reliable, sustainable and modern energy for all [4].

A potentially attractive clean energy technology that could provide electricity supply at scale is offshore wind energy (OWE) [5]. Large wind park projects located offshore have capacities in the order of several hundred MW and therefore could form a significant element of a clean energy pathway. A central disadvantage of early OWE projects were its costs that were substantially higher than onshore wind energy or fossil fuel-based electricity generation. However, recent advances in technology such as larger turbines, growing installation experience and economies of scale have led to higher capacity factors and lower capital and operational expenditure costs [6]. This is documented by a sharp fall of contracts for difference (CFDs) prices that European governments awarded to offshore wind energy developers in the year 2017. A number of those license terms were only half the CFDs awarded in tenders a few years earlier [7].

It is expected that the cost reduction trajectory will continue as the OWE industry matures further, with projections that operating expenditure will fall by 40% in the upcoming decade [8]. There is hence a clear trend that OWE will rapidly become a cost-competitive renewable energy technology. This means that OWE is increasingly an option that developing countries could consider when developing pathways towards decarbonising their electricity supply-system.

To date, offshore wind projects have not been considered by the African continent. Reasons include the perceived immaturity of this technology and also the large wind energy in the onshore domain that could be developed. However, a further reason for the absence of OWE in African energy scenarios is also the lack of robust quantitative analysis that evaluates the OWE potential of the continent. Such studies are an important platform from which more targeted policies and project plans can be developed. A number of authors have highlighted this "data paucity" in the African context and noted the negative impact it has for sustainable energy system planning [9–11]. This study aims to address this shortcoming by undertaking a continental scale, first order analysis of the technical OWE potential for all African Exclusive Economic Zones. The analysis will use two scenarios. The first scenario represents the current state of technology that is currently deployed in the offshore wind industry. The second scenario assumes the operational availability of new technological developments such as floating platforms.

The remainder of this paper is organised as follows: Section 2 will outline practises and methodological approaches of offshore wind potential studies. Section 3 introduces data sets and modelling methodology. The results are presented in section 4 and discussed in section 5. Section 6 presents concluding remarks.

2. Offshore wind potential study framework

A wide range of GIS-based studies have been carried out to estimate the potential of different coastal areas around the world. This includes assessment on a global scale [12,13] or focussing on resource areas such as the central and southern North Sea [14,15], the Aegean Sea [16], and the Mediterranean Sea overall [17]. Country scale investigations have been undertaken for e.g. the UK [18], India [19], and the U.S. [20]. A number of studies focused on the investigation of specific coastlines, e.g. the Californian coast [21], the U.S. Atlantic coast [22], the Kanto region in Japan [23], the Canary Islands [24], and Karnataka state in India [25]. Most of the studies focused on the European offshore market which reflects the main focus of policy makers and research community in the early phases of offshore wind energy development [11].

When attempting to evaluate the OWE potential, it is helpful to outline a clear conceptional framework that distinguishes and identifies different types of 'potential' [26]. This framework of cascading levels is illustrated in Fig. 1. The highest level is represented by the *physical resource potential* that solely considers the theoretical physical energy content of the wind resource. This is followed by the *technical potential* which can be defined as the energy potential that is limited by a number of assumed technical constraints such as turbine performance, geophysical setting of the location, and potential exclusions due to competing marine uses. The *economic potential* considers additionally monetary factors such as system costs and revenue estimates. The *market potential* eventually includes project specific factors such as policy incentives, regulations, and investor responses.

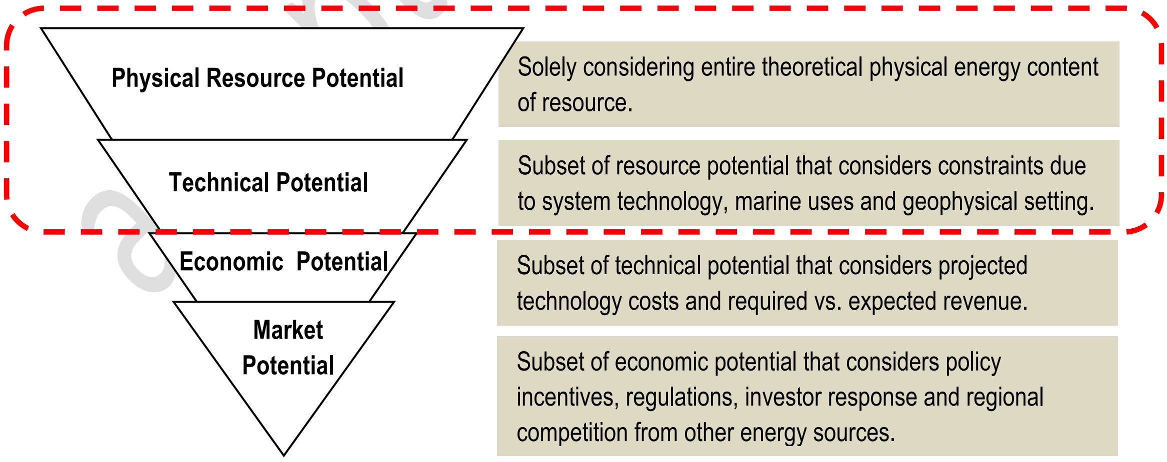

Fig. 1. Conceptional framework of various types of energy potentials. Dotted line indicates the focus of this study.

The focus of this continental-scale study has centred on the assessment of the technical resource potential as it provides an upper-boundary estimate of development potential. This can serve as indication about which African coastal states have meaningful OWE resources where a more detailed analysis of OWE in terms of economic and even market potential might be warranted [27,28].

3. Data and Methodology

3.1 Wind speed:

Of central importance for the estimation of OWE potential is the availability of data sets that provide long-term information about the wind characteristics. On a global scale, such data is either available from meteorological models or from satellite observations. Peng *et al.* [29] evaluated *in-situ* data from 11 buoys from the OceanSITE network against a range of global ocean range wind products such as modelled data from short range forecasts, reanalysis data and the satellite-based Blended Sea Winds (BSW) data set. Overall, they found a good and robust performance of all data sets. Modelled data tended to underestimate variability and showed a slight negative bias in terms of wind speed, whereas BSW data mildly overestimated variability and tended to show a mild positive bias in respect to wind speed. Reanalysis data showed the lowest overall error against ocean buoy data [29]. Hasager [30] notes that it remains difficult to assess the uncertainty of mesoscale models in the absence of independent observational data. As the coastal waters of the African continent largely belong to such poorly observed regions, the empirical BSW data was selected for this project.

The satellite data that form the basis of the BSM model are based on the deployment of space-borne microwave sensors. A central advantage of microwave radiation is that it can penetrate clouds and also its independence from the availability of sun light, i.e. can operate day and night. This makes microwave sensing an effective tool for systematic global monitoring campaigns. Active scatterometers measure the ocean roughness and infer from this wave height and associated wind fields. The BSW data is the most comprehensive scatterometer data set and is assembled by the NOAA National Centers for Environmental Information (NCEI). It combines observations from a range of U.S. sea surface wind speed observing satellites, including SSM/I, TMI, QuikSCAT, and AMSR-E [31].

The BSW data set consists of 6-hourly gridded wind data that is generated on a global 0.25° to 0.25° grid over ice-free oceans (65°S–65°N). To estimate the long term wind resource, a 11 year time series of monthly average wind speed (January 1995 to December 2005) was accessed via the

OPeNDAP/THREDDS Data Server (https://www.ncei.noaa.gov/thredds/blended-global/oceanWinds.html).

This BSW data set provided the basis for the calculation of the overall annual wind speed during this period. As BSW data provides wind speed data at 10 m above sea level, the data needed to be scaled up to the hub height of modern offshore wind turbines. The hub height of modern offshore wind turbines has increased substantially in the past decade. This is reflected in the assumptions made in previous studies, starting at 50 m [12,32] and subsequently rising to 70 m [23], 80 m [19,21,33], 90 m [17], and 100 m [13,20,34]. The 100 m assumption was adopted for this study as well. This means that the wind speed information from the BSW data set had to be upscaled from 10 m to 100 m. This was done using the established logarithmic wind profile law [17,19,21,35,36]:

$$v_h = v_{10} \frac{ln\left(\frac{h}{z_0}\right)}{ln\left(\frac{10}{z_0}\right)} \qquad (1)$$

where v_h is the wind speed at hub height h, v_{10} is the wind speed at reference height 10 m above sea level, and Z_0 (meters) is the surface roughness lengths. For this project, the standard open sea surface roughness coefficient of 0.0002 m was adopted [17,19].

To calculate the potential power generation with respect to wind turbines, it is necessary to estimate the probability of specific wind speeds. This can be expressed by the Weibull probability density function [36]:

$$\mathrm{f_W(v)} = \frac{\mathrm{k}}{\mathrm{c}} \times \left(\frac{\mathrm{v}}{\mathrm{c}}\right)^{\mathrm{k}-1} \times \exp\left(-\left(\frac{\mathrm{v}}{\mathrm{c}}\right)^{\mathrm{k}}\right) \qquad (2)$$

where c is the scale parameter in m/s and k is the dimensionless form parameter that specifies the shape of a Weibull distribution. A small value for k signifies variable winds, while constant winds are characterized by a larger k. As this study had a continental-scale perspective, it was challenging to parameterise c and k at a regional or even local scales. However, it is commonly assumed that a shape parameter of k = 2 can be used to describe the frequency distribution quite well [36,37]. This approach has been used for a number of large-scale studies [21,33,38] and was also adopted for this study. A shape factor of 2 has the further advantage that the Weibull distribution can be simplified to a Rayleigh frequency distribution that defines probability distribution in terms of average wind speed $\bar{v}$:

$$\mathrm{f_R(v)} = \frac{\pi}{2} \times \frac{\mathrm{v}}{\bar{\mathrm{v}}^2} \times \exp\left(-\frac{\pi}{4} \times \frac{\mathrm{v}^2}{\bar{\mathrm{v}}^2}\right) \qquad (3)$$

To estimate how much electricity can be generated at a particular area, a Rayleigh type of wind speed probability was assumed. This in turn could then be used to calculate the potential electricity generation of a modern wind turbine at a specific location. For the purpose of this paper, a Vestas V164-8 MW was selected as reference turbine. This model represents the current state of the art in offshore turbine technology: It is operational since 2014, has a hub height of approximately 100 m, a blade diameter of 164 m, and a rated capacity of 8 MW. The cut-in wind speed is at 4 m/s, full rated capacity starts at 13 m/s and cut-out wind speed is at 25 m/s. Using Eq. 3 and the turbine power specification for the Vestas V164-8MW, the respective CF for average wind speeds were calculated.

As Fig. 2 illustrates, there is a linear relationship between average wind speed and CF at medium to strong wind climates. This phenomenon can be observed for a wide range of wind turbine models [36]. A number of authors used this characteristic to model turbine CF with a simple linear empirical function, as such approach works well at locations where capacity factors between 30% and 50% are expected [21,32].

However, modern offshore wind parks are now starting to access locations with excellent wind resources that make it possible to gain capacity factors beyond 50%. An example for this is the *Hywind* floating wind park off the Scottish East-coast that reached an average CF of 65% during the months of November 2017, December 2017 and January 2018 [39].

The focus of this paper is a continental-scale analysis of offshore regions that include strong to excellent wind resources. Using a linear function would hence lead to an over-prediction of the CF at high wind speeds. Instead, it was necessary to model CF such that it levels off at wind speeds of >10 m/s and plateaus at approximately 66% (Fig.2). A further aspect was that the model could be optimised for higher wind speeds only, as low wind regions were not of interest in the context of this paper.

Following these considerations, a second order polynomial model was therefore fitted ($r^2 = 0.9993$) to derive the CF for $\bar{v}$ between 7 and 15 m/s. This line is displayed in Fig. 2 and defined as:

$$\mathrm{CF} = -0.684 \times \bar{v}^2 + 19.148 \times \bar{v} - 67.524 \qquad (4)$$

This empirical model was then employed to estimate CF and subsequently the annual electricity generation at respective locations and wind speeds.

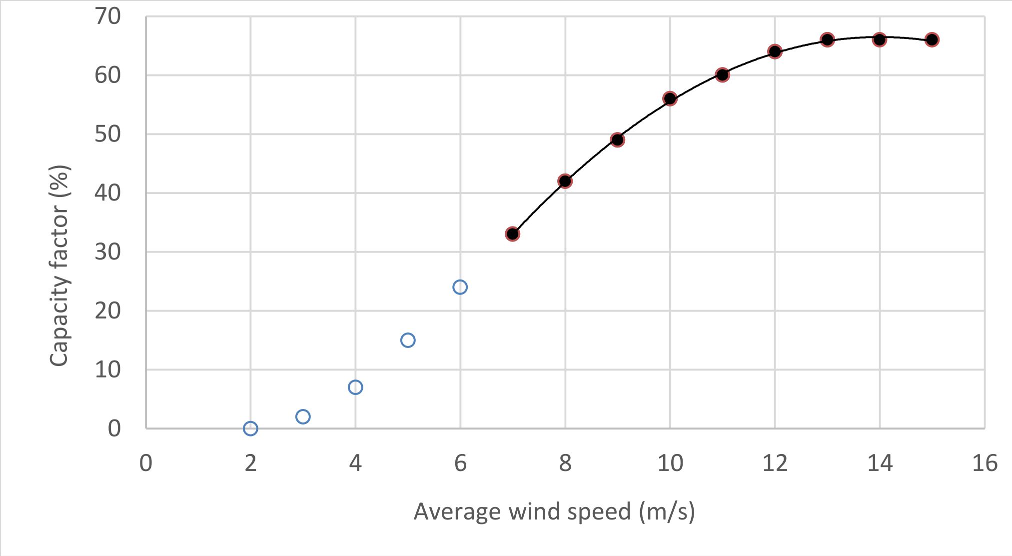

Fig. 2. Capacity factors for Vestas V164-8MW reference turbine. Data points for wind speeds >7m/s are displayed in black and fitted with a 2nd order polynomial curve.

In addition to the presence of stable and strong winds, the estimation of the technical OWE potential required the consideration of additional factors such as water depth, distance from the coast, and competing use of marine space, e.g. Marine Protected Areas (MPA). These factors will be discussed in more detail in the subsequent sections.

3.2 Bathymetry

An additional important criteria for estimating the technical offshore wind potential is bathymetry, as current projects are mostly installed in water depths of up to 50 m [40]. The bathymetry data for this analysis was accessed from the General Bathymetric Chart of the Oceans (GEBCO). GEBCO recently released the GEBCO_2014 data set which represents the currently best global bathymetry data set [41] with a spatial resolution of 30 arc-second.

3.3 EEZ data:

The coastal area that could be considered for OWE development is defined to by the Exclusive Economic Zones (EEZ) along the African coast line. These zones can be up to 200 nautical miles wide, measured from their coastal baselines. Within these areas a sovereign state has exclusive jurisdiction and rights to marine resources, including energy production [42]. EEZ data was accessed from the *Flanders Marine Institute* Marine Regions data depository [43,44].

3.4 Marine Protected Areas

It was assumed that OWE developments would not be possible in nature conservation areas [15,20]. This means that MPA were excluded in the modelling process. Data about protected areas was accessed from the World Database on Protected Areas [45].

3.4 Scenario Modelling

To estimate the technical offshore wind potential, a number of criteria were defined that needed to be met: As minimum average annual wind speed a cut-off of 7.5 m/s at 100 m hub height was identified, similar to Dvorak et al. (2010). This is equivalent to a CF of 37.6% of the reference turbine used in this study. The threshold can be considered as conservative, as a number studies used lower limits, e.g. 4.5 m/s at 10 m [16], 7.0 m/s at 100 m [20], or a CF of 20% [13]. BSW data set was resampled to a spatial resolution of 30 arc-second to align it with the GEBCO_2014 bathymetry data set.

A further criteria for the OWE project development was distance to shore and water depth. Early generation offshore wind projects were constructed near the coast in order to reduce costs for cabling and transport [14]. Currently, nearly all operational wind parks have been limited to water depth of approximately 50 m as this is the maximum water depth where turbine foundations can be deployed at reasonable costs [46,47]. However, recently floating platforms have become available which would make it possible to utilise deeper marine areas [48]. One example is the 30 MW *Hywind* Scotland project which is considered to be the first commercial offshore wind floating platforms [49].

Given the wide variety in technological approaches and uncertainty about operational practices that will be available in the near-future, it was decided to develop two scenarios when modelling the technical offshore wind potential of the African continent. Their respective criteria are outlined in Table 1. Scenario 1 represents the shallow-water, near-coast model. This represents the conservative assumption that potential offshore wind projects in African waters will be restricted to the limitations that applied to early generation projects in the North Sea and Baltic Sea region.

The alternative scenario 2 is the deep-water, full-EEZ model. It is based on the assumption that in the near future offhore wind technology will mature to a stage where the full EEZ is available for project development and where floating platforms are commercially viable. This would mean that areas with water depths deeper than 50 m would be available for development. As upper threshold a water depth of 800 m was adopted, as this is the operational limit of the *Hywind* floating platform that is currently operating off the coast of Scotland [49].

Table 1
Criteria for model scenarios estimating the technical offshore wind energy potential

Scenario 1	Scenario 2
distance from coast < 50 nautical miles	entire EEZ
water depth < 50 m	water depth < 800 m
marine protected areas excluded	marine protected areas excluded
annual average wind speed > 7.5 m/s at 100 m	annual average wind speed > 7.5 m/s at 100 m

4. Results

This section introduces the results of the GIS-based OWE technical potential model for the African continent. This will be done by firstly introducing the resource potential of the African continent, followed by the outcome of the scenario 1 and scenario 2 models.

In addition to this, the results will be contextualised to the energy demand of the respective coastal states in 2015. This aims to evaluate the relevance of the potentials and the role OWE could play for future energy supply.

4.1 Resource Potential

The gross resource area for each coastal state was considered to be the entire EEZ of each coastal state. The gross capacity was calculated by adopting the approach of Musial et al. who used a generalised array density of 3MW/km^2. This estimate uses a general reduction of 70% from a standard wind park turbine layout to account for array buffers and setback to compensate for wake losses [20,50]. This array density is similar to the array density of 3.14 MW/km^2 adopted by Bosch *et al.* [13], who used a 5 MW turbine as reference model and a spacing distance of 10 rotor diameters. Calculating a 10 rotor diameter distance for the Vestas V164-8MW turbine results in a packing density of 2.97 MW/km^2. This underlines the appropriateness of using a general array density of 3 MW/km^2 for this study.

The wind resource for the African coast at 100 m above sea level is displayed in Fig. 3. There is a clear geographical differentiation of wind resource along the continents coastline, with the southern part exhibiting the strongest winds, with an annual average of more than 11 m/s. Similar strong wind speed is found at the north and south coast of Madagascar and the east coast of the Horn of Africa. Very good wind resource with an annual wind speed of 9 m/s is found along the north-western coast and the central-eastern of the continent. Large parts of the African coast have limited wind resource of less the 7 m/s annual wind, including the central-western and the north-eastern coast.

The final analysis of the technical resource potential was carried out within a GIS environment to identify all areas that met the specified conditions for respective scenarios (Table 1). This included the downscaling of BSW wind speed data to the spatial resolution of Gebco bathymetry data. For each grid cell, the expected annual electricity production was calculated using the model defined in equation 4 and the results aggregated to EEZ level.

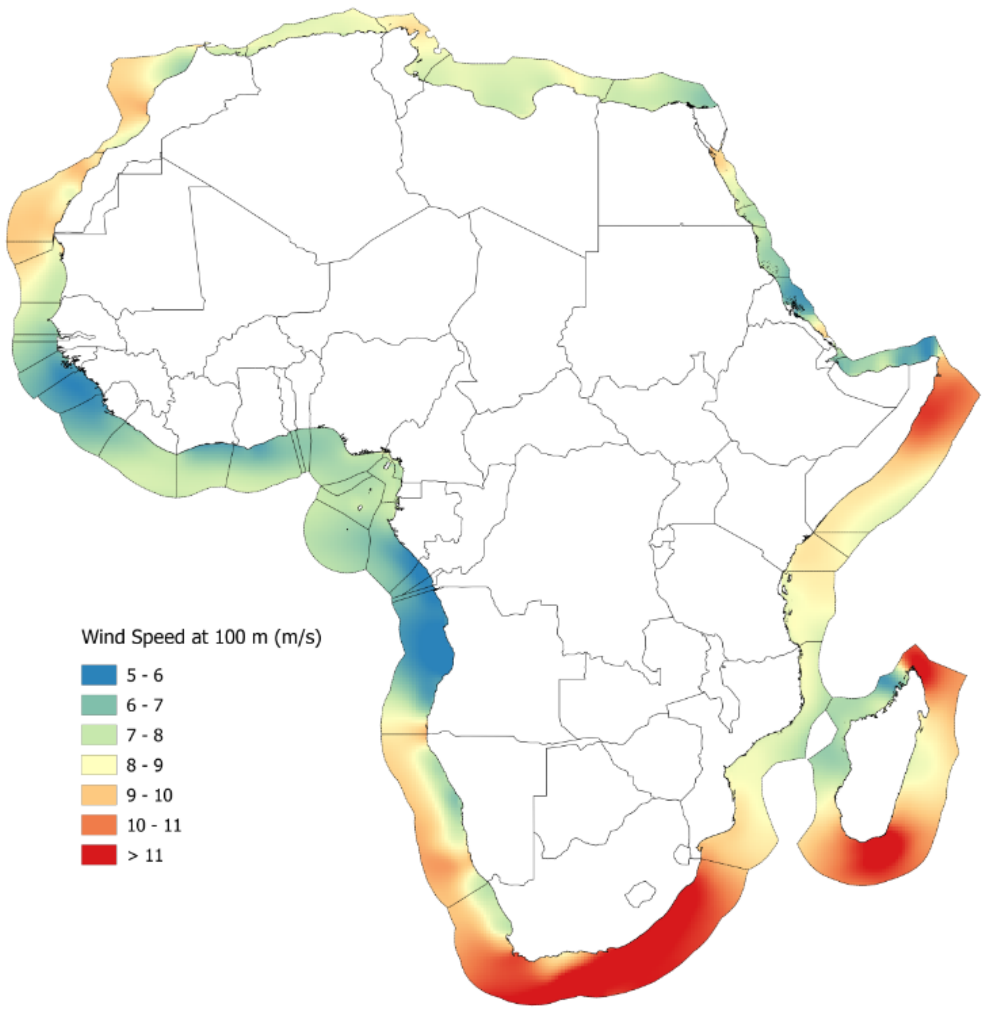

Fig. 3. Offshore wind resource in the African Exclusive Economic Zones, upscaled to 100 m above sea level.

4.2 Technical OWE potential in the shallow-water, near-coast scenario 1

The technical offshore wind potential for scenario 1 is displayed Fig. 4 to 6 which show the modelled capacity factor of the reference turbine. Overall, it can be seen that the strict scenario criteria in respect to water depth substantially limits the technical potential (Fig. 4). Some of the largest scenario 1 resource areas can be found along the coasts of Mozambique and Madagascar (Fig. 5) and Western Sahara/Morocco (Fig. 6). However, with capacity factors of approximately 40%, the actual wind resource in these areas is at the lower end of the defined threshold. Overall it can be observed that most of the attractive resource areas with the highest wind speeds have been factored out due to their unsuitable bathymetry.

A ranking of the coastal states in terms of technical capacity and the associated annual electricity production is presented in Fig. 7. It demonstrates that - despite the strict limitations of the scenario 1 model - many coastal states still have a significant technical OWE resource. The largest potential was modelled for Mozambique that has a technical capacity of 152 GW. This translated to a modelled annual electricity production (AEP) of 555 TWh, equivalent to an average capacity factor across its scenario 1 areas of 41.7%. The second highest technical capacity (88 GW) was modelled for Madagascar, resulting in an annual electricity generation of 379 TWh electric energy and a 49.2% capacity factor. The importance of wind resource for actual energy production is illustrated also with the example of Western Sahara and Somalia. Both countries have very similar modelled annual energy production, whereas their technical capacity differs by 36%. South Africa (39 GW/189.2 TWh) and Tunesia (49GW/174.7 TWh) illustrate the same effect.

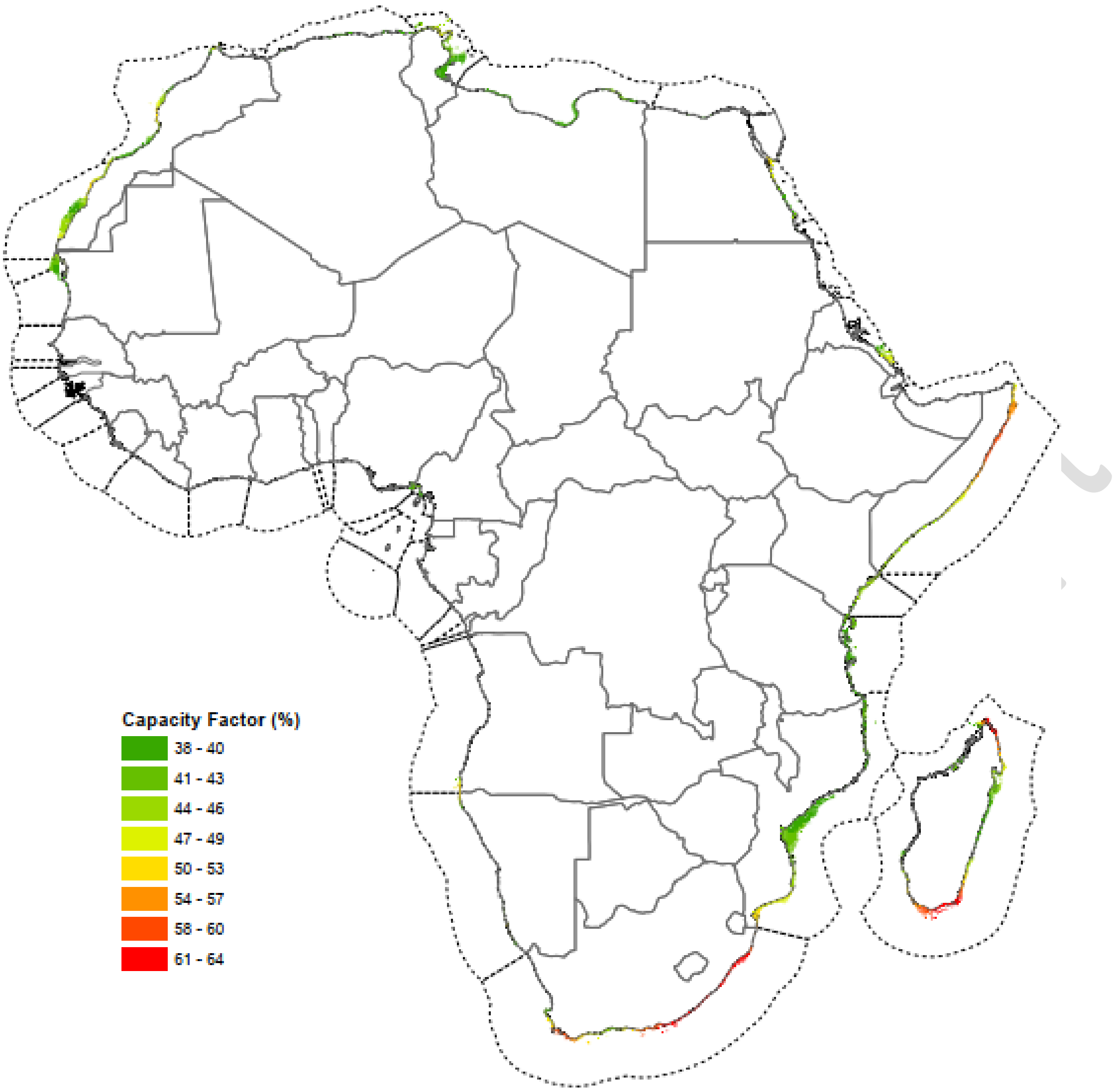

Fig. 4. Offshore wind technical potential modelled in the shallow water, near coast scenario 1, showing the modelled capacity factors of the Vestas V-164 8 MW reference wind turbine on continental scale. The dotted line outlines the EEZ boundaries.

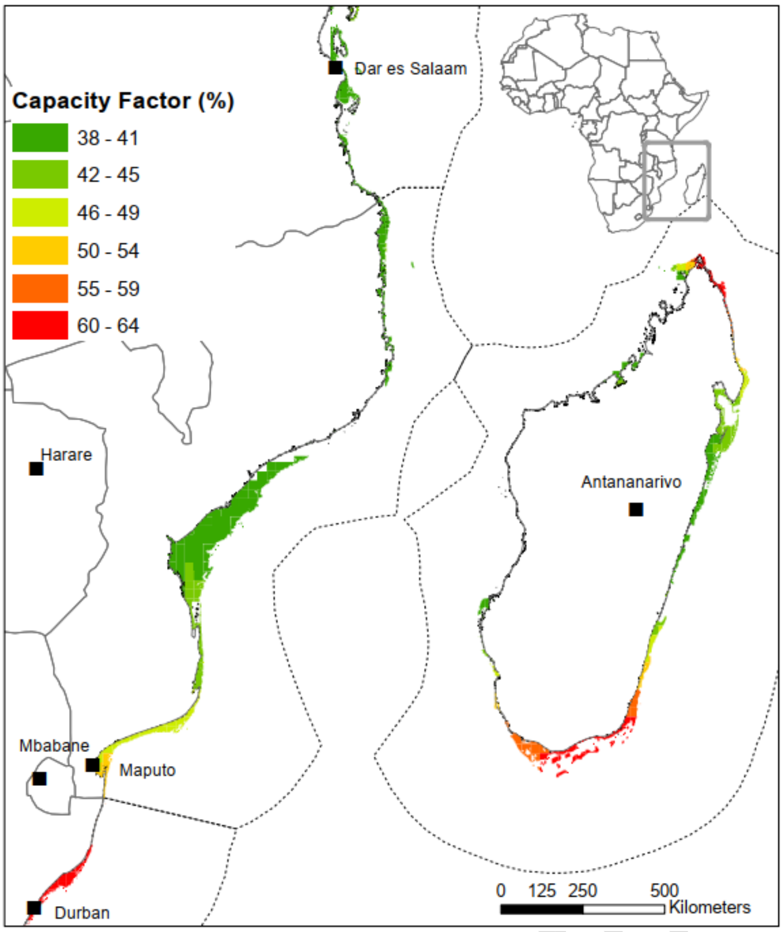

Fig. 5. Offshore wind technical potential modelled in the shallow water, near coast scenario 1, showing the modelled capacity factors of the Vestas V-164 8 MW reference wind turbine for the Mozambique/Madagascar region. The dotted line outlines the EEZ boundaries.

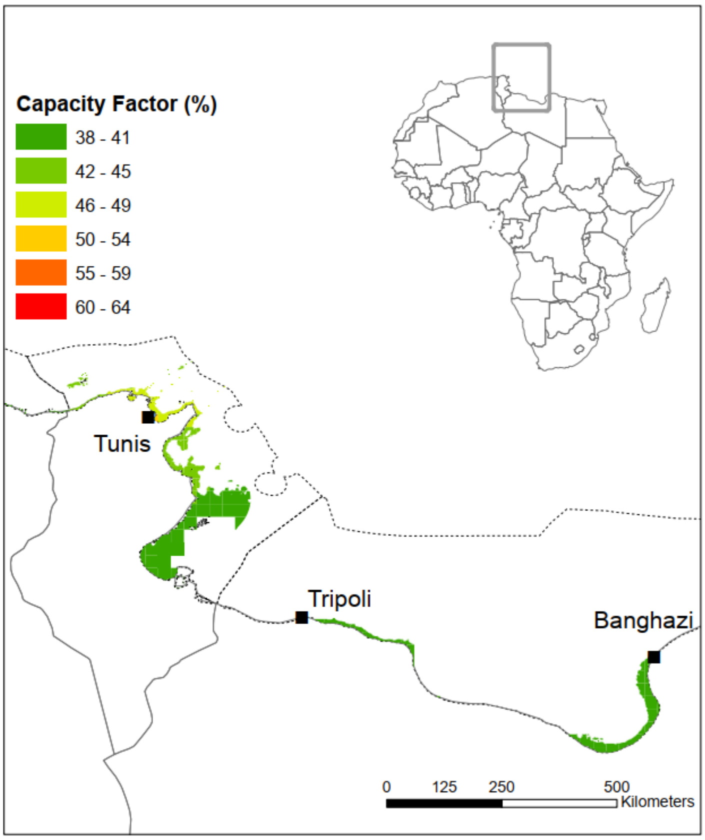

Fig. 6. Offshore wind technical potential modelled in the shallow water, near coast scenario 1, showing the modelled capacity factors of the Vestas V-164 8 MW reference wind turbine for the Morocco/Western Sahara coastline. The dotted line outlines the EEZ boundaries.

Table 2 provides a comprehensive overview of the offshore wind energy potential for all African coastal states for both scenarios and contrasts this with the actual electricity generation in respective coastal states in the year 2015. For the Mediterranean states the highest scenario 1 resource was modelled for Tunisia (48.5 GW), followed by Libya (28.2 GW), and Egypt (6.2 GW). Morocco, which partly also faces the Mediterranean Sea, exhibits a potential of 27.6 GW. However, most of its technical potential is actually located along its Atlantic coast (Fig. 3c). Its direct neighbours to the south have also a very large technical potential in scenario 1, with Western Sahara recording 71.3 GW and Mauritania 22.3 GW. The other Atlantic coastal states show very limited scenario 1 potential. This was due to the absence of a meaningful continental shelf and the lack of wind resource. Only Angola (3.7 GW) and Namibia (2.6 GW) have limited scenario 1 potential.

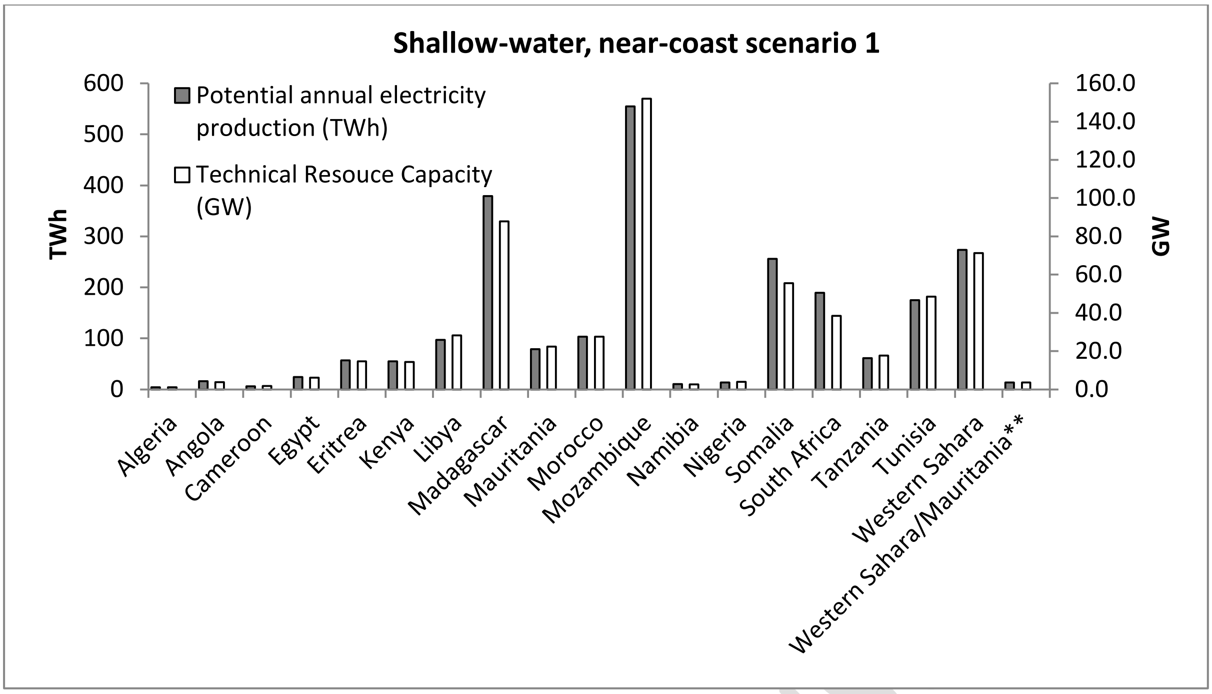

Fig. 7. Technical resource capacity and associated modelled annual electricity potential for scenario 1. *Western Sahara is a Non-Self-Governing Territory claimed by Morocco. **Disputed EEZ between Western Sahara and Mauritania.

For the Indian Ocean-facing side of the African continent, a much higher scenario 1 potential was modelled. Most eastern coastal states have substantial technical potential in scenario 1. This includes South Africa (38.5 GW), Mozambique (152 GW), Madagascar (87.9 GW), Tanzania (17.6 GW), Kenya (14.3 GW), Somalia (55.6 GW) and Eritrea (14.7 GW).

The scenario 1 model results can also be contextualised in terms of the potential actual energy generation, referenced to the actual national electricity generation in the year 2015 (Table 3). It can be seen that in many coastal states have a technical offshore wind capacity that could generate electricity multiple times that of their current national generation.

Table 2

Resource and technical offshore wind energy potential of all African coastal states. *Data from UN Statistics Division; **Western Sahara is a Non-Self-Governing Territory claimed by Morocco.

Coastal State	*Gross resource area of EEZ* *(km^2)*	*Technical resource area Scenario 1* *(km^2)*	*Technical resource area Scenario 2* *(km^2)*	*Gross resource capacity of EEZ* *(GW)*	*Technical resource capacity Scenario 1* *(GW)*	*Technical resource capacity Scenario 2* *(GW)*	*Technical resource energy potential Scenario 1* *(TWh)*	*Technical resource energy potential Scenario 2* *(TWh)*	*National electricity production in 2015** *(TWh)*
Algeria	128720	374	11295	386	1.1	33.9	3.9	117.3	68.8
Angola	492800	1247	5466	1478	3.7	16.4	16.1	68.1	9.8
Benin	30356	0	0	91	0	0	0	0	0.3
Cameroon	14671	602	838	44	1.8	2.5	6.1	8.5	6.8
D.R. of Congo	13272	0	0	40	0	0	0	0	8.9
Djibouti	7015	0	0	21	0	0	0	0	0.4
Egypt	236108	2054	20961	708	6.2	62.9	24.4	235.7	181.9
Equatorial Guinea	309674	0	0	929	0	0	0	0	0.9
Eritrea	78653	4893	11212	236	14.7	33.6	56.6	129.6	0.4
Gabon	192863	0	0	579	0	0	0	0	2.1
Gambia	22692	0	0	68	0	0	0	0	0.3
Ghana	226271	0	0	679	0	0	0	0	11.7
Guinea	109995	0	0	330	0	0	0	0	1.1
Guinea-Bissau	106298	0	0	319	0	0	0	0	0.004
Côte d’Ivoire	174453	0	0	523	0	0	0	0	8.7
Kenya	112222	4782	24352	337	14.3	73.1	54.7	282.1	9.5
Liberia	247211	0	0	742	0	0	0	0	0.3
Libya	357269	9414	69624	1072	28.2	208.9	96.9	710.9	37.7
Madagascar	1203110	29312	69210	3609	87.9	207.6	379.3	933.1	1.7
Mauritania	155729	7444	10088	467	22.3	30.3	79.1	107.2	1
Morocco	275566	9185	58372	827	27.6	175.1	103.2	663.9	31.2
Mozambique	573484	50663	122455	1720	152	367.4	554.8	1420.2	19.6
Namibia	561283	882	74316	1684	2.6	222.9	10.4	856.7	1.5
Nigeria	182459	1288	1235	547	3.9	3.9	13.4	13.9	31.4
Rep. of Congo	39782	0	0	119	0	0	0	0	1.7

Sa Tome and Principe	131417	0	0	394	0	0	0	0	0.1
Senegal	158074	0	0	474	0	0	0	0	3.6
Sierra Leone	160095	0	0	480	0	0	0	0	0.2
Somalia	782807	18519	74475	2348	55.6	223.4	255.9	1015.6	0.4
South Africa	1066697	12823	200096	3200	38.5	600.3	189.2	2821	249.7
Sudan	66641	0	0	200	0	0	0	0	13
Tanzania	242541	5879	21934	728	17.6	65.8	61.3	231.3	6.3
Togo	15469	0	0	46	0	0	0	0	0.4
Tunisia	100407	16171	68676	301	48.5	206	174.7	777.4	19.7
Western Sahara**	251211	23791	73938	754	71.3	221.8	273.7	877.6	n/a
Other:									
Disputed EEZ Kenya/Somalia	51521	0	0	155	0	0	0	0	n/a
Disputed EEZ Sudan-Egypt	25880	0	0	78	0	0	0	0.2	n/a
Disputed EEZ Western/Mauritania	49896	1217	3500	150	3.7	10.5	13.3	39.3	n/a
Joint Development Zone Nigeria - Sao Tome and Principe	34691	0	0	104	0	0	0	0	n/a
Africa	**8989304**	**200547**	**922043**	**26968**	**601.5**	**2767.3**	**2367.2**	**11308.8**	**736.9**

Examples are Eritrea, Kenya, Libya , Madagascar, Morocco, Mozambique and Somalia. In South Africa, offshore wind could supply a significant share of the national electricity generation. Also, even in countries which have limited capacities under scenario 1, offshore wind energy could make a substantial contribution to the national electricity supply, e.g. Angola, Cameroon, Egypt, and Namibia.

Overall, the scenario 1 model estimates a technical OWE capacity of the African continent of 601.5 GW in total which could generate an estimated 2367 TWh of electric energy. 12 coastal states have a technical capacity of more than 14 GW. This demonstrates that even under the conservative scenario 1 assumptions, a substantial OWE capacity appears to be available for one third of the African coastal states. At the same time, it also needs to be recognised that for 17 coastal states, no OWE of significance is available.

4.3 Technical OWE potential in the deep water, full EEZ scenario 2

The results of the deep-water, full-EEZ scenario 2 model are presented in Fig. 8 to 11. It can be seen that the assumed availability of floating platforms significantly increases the available technical resource area. South Africa, along with Mozambique and Mauritania (see Fig. 9) could utilise substantial parts of their excellent wind resources and belong to the coastal states that have the largest technical capacities of the continent. Somalia again belongs to the countries with the best technical potentials, similar to scenario 1.

Namibia, in contrast, had very little technical capacity in scenario 1 (2.6 GW) but in scenario 2 has excellent technical capacity (223 GW). Egypt, Tunesia and Morocco (Fig. 10) are examples for North African coastal states that had limited potential in scenario 1 and have much more significant technical capacity in the deep-water, full-EEZ scenario. This would enable these countries to utilise offshore wind generation as a much more meaningful source towards meeting its electricity demand (Table 2).

Compared to scenario 1, the overall resource capacity of the African continent increases by more than four times. It is interesting to note that the same 17 coastal states that had no significant OWE capacity in scenario 1 remain without OWE capacity in scenario 2. For this group, the limiting factor is not bathymetry but the absence of a relevant wind resource itself.

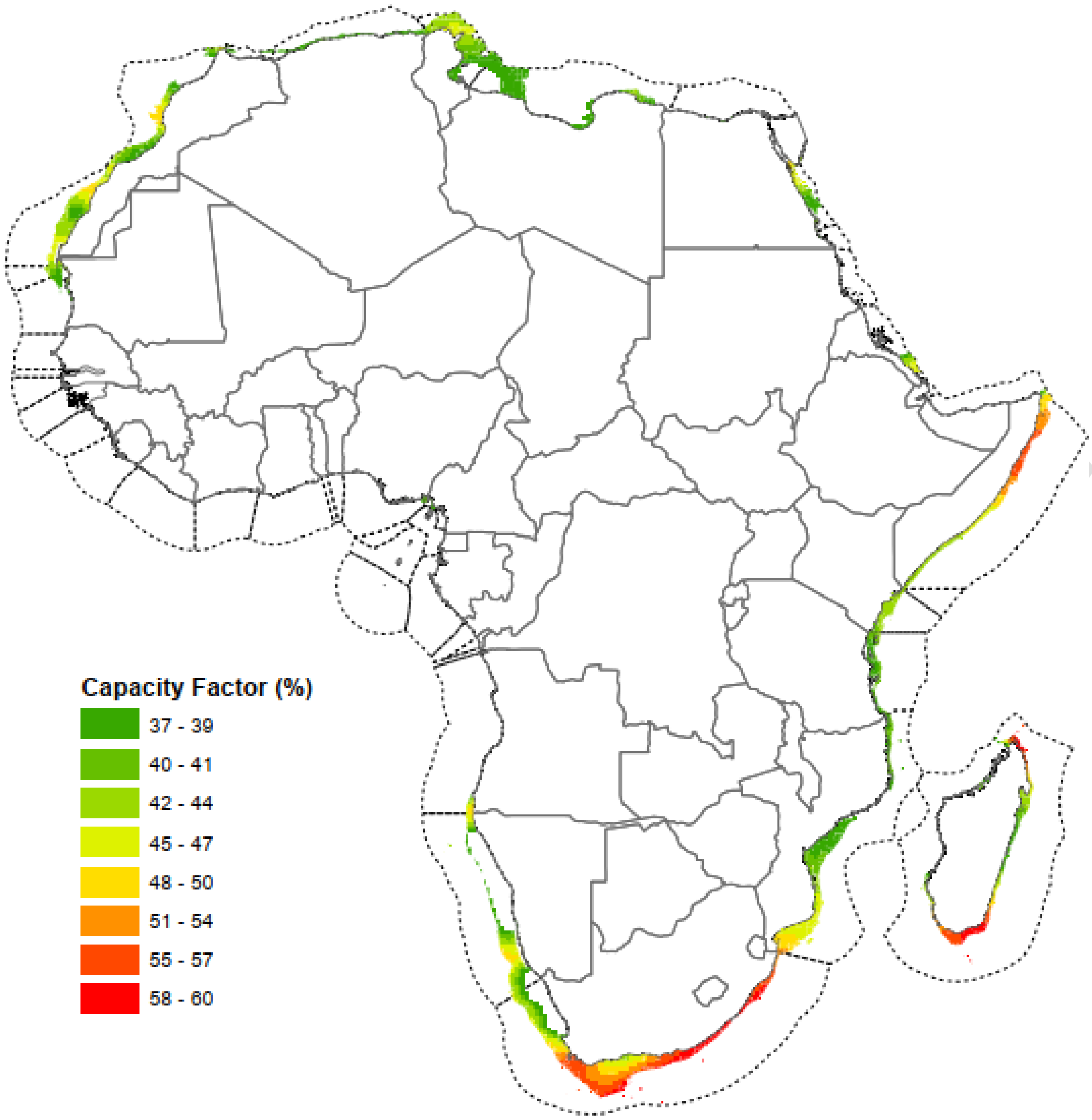

Fig. 8. Offshore wind technical potential modelled in the deep-water, full-EEZ scenario 2, showing the modelled capacity factors of the Vestas V-164 8 MW reference wind turbine on continental scale. The dotted line outlines the EEZ boundaries.

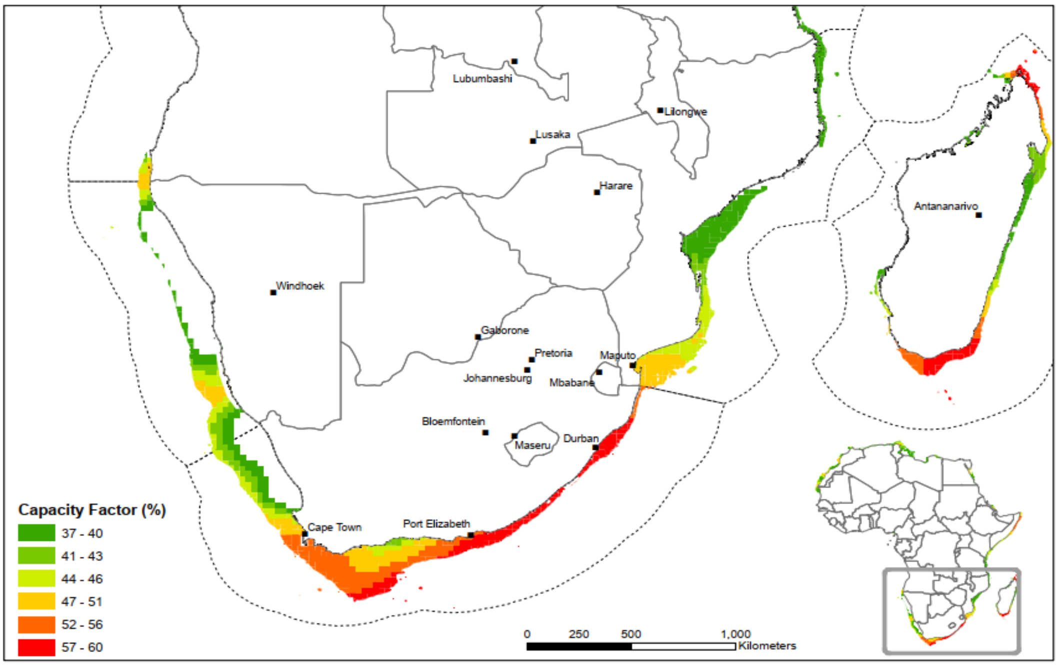

Fig. 9. Offshore wind technical potential modelled in the deep-water, full-EEZ scenario 2, showing the modelled capacity factors of the Vestas V-164 8 MW reference wind turbine for southern Africa. The dotted line outlines the EEZ boundaries.

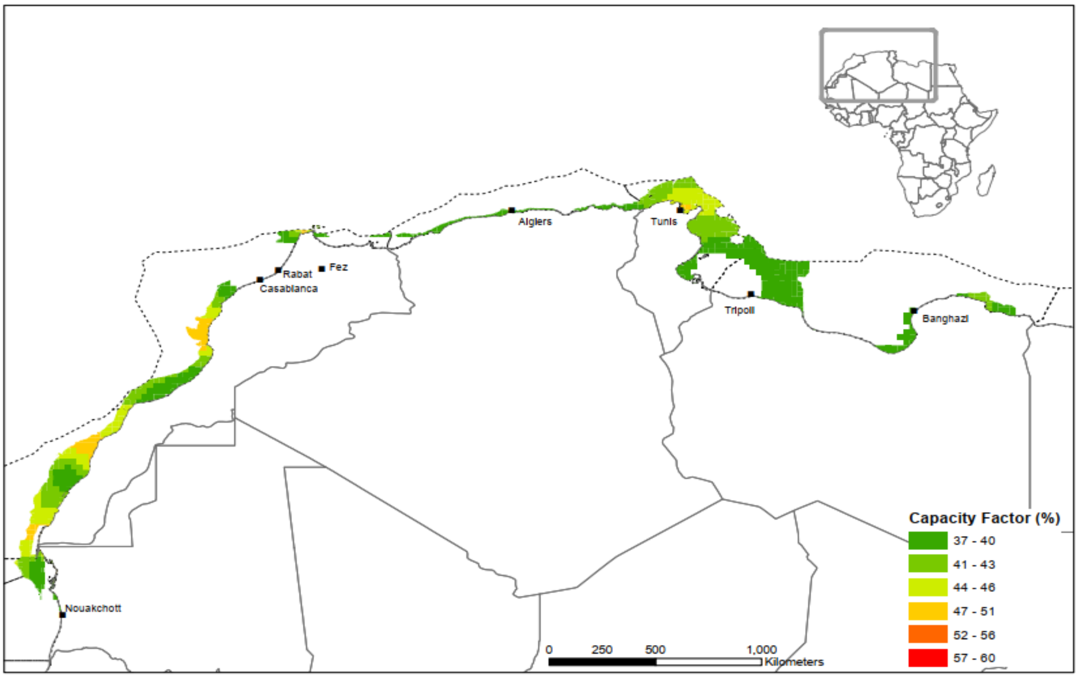

Fig. 10. Offshore wind technical potential modelled in the deep-water, full-EEZ scenario 2, showing the modelled capacity factors of the Vestas V-164 8 MW reference wind turbine for North-West Africa . The dotted line outlines the EEZ boundaries.

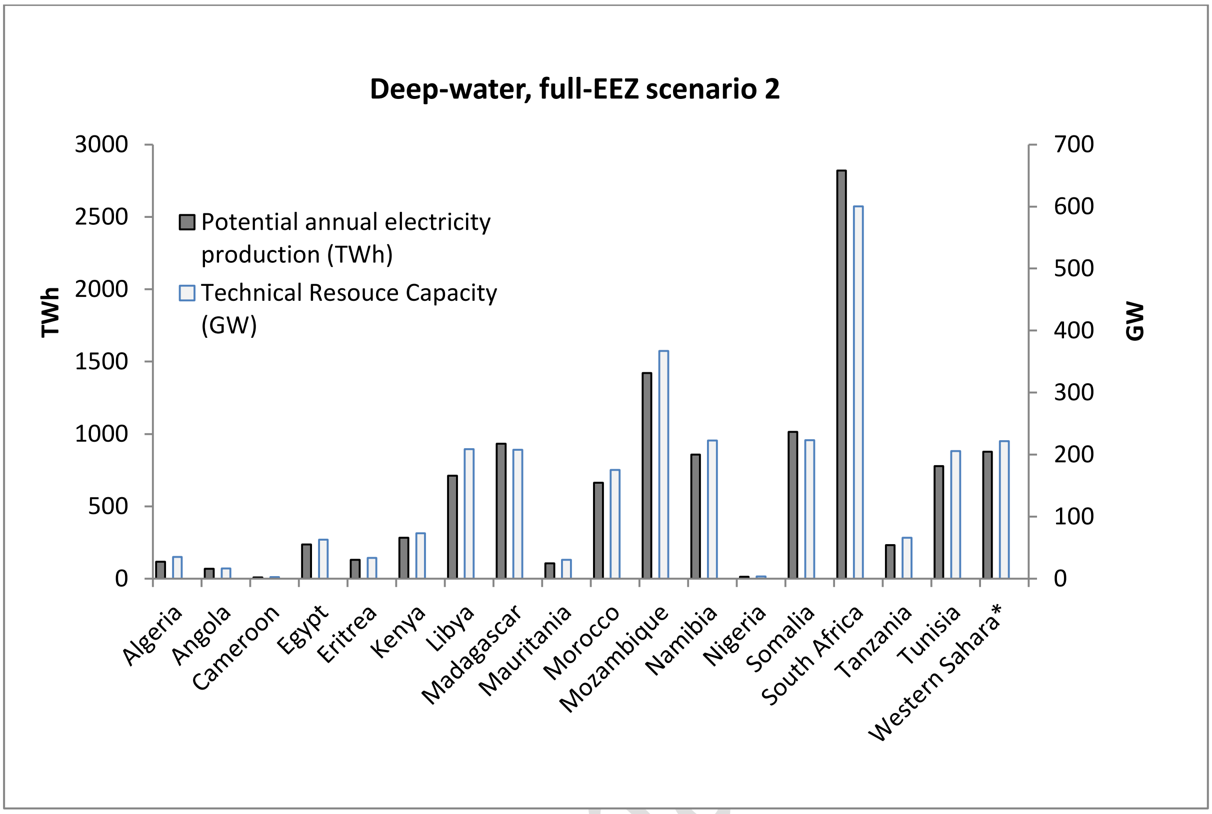

Fig. 11. Technical resource capacity and associated modelled annual electricity potential for the deep-water, full EEZ scenario 2. Western Sahara is a Non-Self-Governing Territory claimed by Morocco. **Disputed EEZ between Western Sahara and Mauritania.

5. Discussion

It should be emphasized that the results of the technical resource analysis are associated with substantial uncertainties. This includes fact that the basis of the analysis are satellite data with a relatively coarse spatial resolution. It has been shown that, when compared to in-situ buoy data, satellite data tends to slightly overestimate wind speeds [16,29]. Particularly problematic is the information in near-coast areas, as winds in coastal zones have larger spatial variability than farther offshore. Such coastal zone-specific atmospheric dynamics phenomena occur that can regularly not be resolved in detail [30,51].

A further limitation of the satellite-based wind speed estimates is the fact that they provide wind speed data at 10 m above sea level [52]. To derive information about the wind resource in 100 m hub height, the data needed to be upscaled to 100 m hub height with the aid of a theoretical model, parameterised by a general surface roughness coefficient. Further to this, the estimation of turbine capacity factors was based on an assumed shape of the Weibull probability density function and its further simplification.

It is further important to be aware that the quantification of the energy generated by the modelled technical capacity in this paper is gross capacity. To derive realistic net energy estimates, a number of losses need to be factored in. This includes a more detailed estimation of wake losses and the wind farm availability [53]. Also, electrical losses in undersea cables need to be accounted for, which are largely a function of cable length/distance to shore. The detailed quantification of such losses is depending on site specific conditions and can vary substantially. An indication is the assessment of the U.S. OWE potential where such losses ranged between 12% and 23% [20].

Bosch et al. [13] recently undertook a global offshore wind energy potential analysis and report their results for all African UN sub-regions which allows a comparison with the estimates of this study (Table 3). Their approach was largely similar to this study but differs in a number of aspects: The core wind data set was based on calibrated MERRA-2 reanalysis data with a spatial resolution of 0.625° x 0.5° (compared to 0.25° x 0.25° of the BSW data used for this study) and a 1-hourly temporal resolution (compared to 6-hourly of BSW data). Similar to this study, Bosch et al. also used different water depth scenarios: The deep water case had a depth limit of 1000 m (800 m in this study), complemented by shallow water scenarios of up to 60 m water depth (50 m water depth in this study). The CF cut-off factor was set to 20% (37.6% this study).

For both scenarios, the AEP estimates of this study are approximately 50% lower compared to Bosch *et al.*. This is consistent with expectations, as the Bosch *et al.* parameterisation uses mildly more generous water depth limits. Most importantly, their AEP estimates include all energy generation from a CF of 20% upwards, which particularly in regions with moderate wind resources would result in much higher AEP estimates. This effect can be observed in the West Africa sub-region where this study reports 62% lower AEP in the deep water case. The difference reduces to 14% and 19% for the Eastern Africa and Northern Africa sub-regions, respectively, which have much better wind resources overall and fewer areas with low CF would be included in the AEP estimate.

However, substantial differences can be observed for the Middle Africa sub-region which are difficult to explain. According to Bosch *et al.*, this sub-region exhibits the best wind resource of the African continent, with an average CF of 67%. This appears to be exceptionally high, given that the theoretical maximum CF of many turbines plateaus at that level. The Middle Africa sub-region includes the coastal states Angola, Cameroon, the Democratic Republic of the Congo, Equatorial

Guinea, Gabon, the Republic of the Congo, and São Tomé and Príncipe. This study identified limited technical wind resource for this part of the African coastline (see Table 2), with an average CF of 46% and AEPs which are more than 90% lower than the estimates of Bosch *et al.* for that sub-region (Table 3).

Yet, despite the discrepancy for the Middle Africa sub-region, it can be stated that there seems to be a good general agreement with the Bosch *et al.* results on continental scale. This indicates that the wind resource information from both reanalysis data and BSW data provide similar estimates. The choice of data source therefore appears not to significantly affect the OWE potential analysis.

As the results of this study in terms of capacity modelling and AEP estimation are lower than other published studies, they can considered to be conservative estimates. Given the various sources of uncertainties outlined above, these OWE potentials should be treated as indicative only. They can not serve as actual input for detailed energy policies nor could they form the basis for investment decisions.

Table 3: Comparison of AEP estimates of Bosch *et al.* [13] and this study, grouped by UN sub-regions.

UN sub-region	**Bosch *et al.* shallow water case (0 - 60 m, CF >20 %) AEP (TWh)**	**This study (0 - 50 m, CF > 37.6%) AEP (TWh)**	**Difference**	**Bosch *et al.* deep water case (0 - 1000 m, CF >20 %) AEP (TWh)**	**This study (0 - 800 m, CF >37.6%) AEP (TWh)**	**Difference**
Eastern Africa	2541	1363	-46%	4650	4012	-14%
Middle Africa	236	22	-91%	6260	77	-99%
Northern Africa	1426	677	-53%	4160	3383	-19%
Southern Africa	286	200	-30%	5560	3678	-34%
Western Africa	255	93	-64%	321	121	-62%
Africa overall	4744	2355	-50%	20951	11271	-46%

However, it can also be stated that the results provide a first order estimate of the spatial distribution of the technical OWE potential along the African coastline. The results demonstrate that the African continent has substantial offshore wind energy potential. Many coastal states could use this resource to meet their growing electricity demand and to decarbonise their energy systems. Fig. 12 presents an overview of the results from respective analysis steps. It can be seen that the African resource area has a size of approximately 9 million km^2, which is nearly three times as big as the offshore resource area of the U.S. [20]. However, this is substantially reduced when realistic constraints are introduced to the resource model. In the conservative shallow-water, near-coast scenario 1, only 2.2 % of the original African resource area remains available. Even in the deep-water scenario 2 only approximately 10 % are suitable.

Gross Offshore Resource Area (0-200 nautical miles Exclusive Economic Zones): 8989304 km^2

Gross Offshore Resource Capacity (3 MW/km^2): 26968 GW

⇩

Technical Offshore Resource Area in Scenario 1 (shallow water, near coast): 200547 km^2

Technical Offshore Resource Area in Scenario 2 (deep water, full EEZ): 922043 km^2

⇩

Technical Offshore Resource Capacity in Scenario 1: 601.5 GW

Technical Offshore Resource Capacity in Scenario 2: 2767 GW

⇩

Technical Offshore Energy Potential in Scenario 1: 2367 TWh/year

Technical Offshore Energy Potential in Scenario 2: 11309 TWh/year

Fig. 12. Overview of results from respective analysis steps.

Musial et al. [9] assessed the technical OWE potential of the U.S. by using a maximum water depth of 1000 m in their model, which resulted in 886 000 km^2 technical resource area and 2658 GW of technical resource capacity. This is similar to the scenario 2 model result of this study for Africa (922 000 km^2 and 2767 GW, respectively). This indicates that Africa has - in the deep-water scenario - a similar technical offshore wind potential to that of the U.S. Offshore wind energy can therefore make substantial contributions in the transition of Africa towards a low-carbon energy system.

On a qualitative level, it is possible to identify a number countries that seem to have a particularly attractive offshore wind resource, even in scenario 1 which reflects the current technological level that is already operational and cost-competitive.

One example is Mozambique which has the gross technical offshore wind potential to generate 555 TWh of electricity. This is one order of magnitude higher compared to the countries' actual national electricity generation of 20 TWh in 2015. Madagascar and Somalia are other countries where scenario 1 generation substantially exceeds the actual electricity generation in 2015. In South Africa and Tunisia, shallow water offshore wind projects would offer interesting generation capacity as well. Floating-platforms would further enhance the potential for many more countries and could generate multiple times of the electricity than was actually generated in those countries in 2015.

The results provides a solid starting platform for further and more detailed regional analysis, including local siting studies that consider economic factors to evaluate the feasibility of specific wind farms projects [5,6]. This includes the consideration of losses from grid connection and transport to potential demand areas. This would help to assess the relative practical value of individual resource areas. For example, the identified strong offshore wind resources in the south of Madagascar and off the coast of Somalia are far away from significant demand centres.

A contrasting example is the excellent offshore wind resource in the vicinity of the South African metropolitan region of Cape Town (Fig. 9), which has a population of approximately 3.9 million people and substantial industrial activity. Despite having the nuclear power plant Koeberg in its vicinity, most of the electricity used in Cape Town is produced in the north east of South Africa. Coal-fired power stations provide more than 80% of electricity in South Africa [54]. The country has experienced chronic power shortages in the past and intends to diversify its electricity generation portfolio to include low carbon sources and renewable energy [55]. Offshore wind might offer an attractive option in this context.

5.1 African Power Pools

When considering the offshore wind energy generation potential, it is instructive to also contextualise this to the regional framework of the electricity networks. In Africa, this is organised in five power pools that correspond to respective African Regional Economic Communities [56]. Each power pool aims to promote energy trade between its member states. This means that electricity generated by offshore wind projects could not only meet demand of the respective coastal state but also supply to other members of its power pool.

The West African Power Pool (WAPP) has 14 member states. These are the coastal states Benin, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Nigeria, Senegal, Sierra Leone, and Togo. Three WAPP members (Mali, Niger, and Burkina Faso) are landlocked. The Eastern Africa Power Pool (EAPP) has 11 members, with Democratic Republic of Congo, Egypt, Kenya, Sudan, and Libya being coastal states. The Central African Power Pool (CAPP) has ten members, with seven of them being coastal states. These are Angola, D.R. Congo, Equatorial Guinea, Gabon, Sa Tome & Principe, and the Republic of Congo. The Southern Africa Power Pool (SAPP) consists of 12 member countries. Of these, six are coastal states: Angola, D.R. Congo, Mozambique, Namibia, South Africa, and Tanzania. All five members of the Comité Maghrébin de l'Electricité (COMELEC) power pool are coastal states. These are Algeria, Libya, Morocco, Mauretania and Tunisia.

Table 4 shows the technical offshore wind potentials aggregated to the level of the respective power pools. It demonstrates that nearly the entire offshore wind resource of the continent is concentrated in three power pools. Relative resource allocations are remarkably consistent for both scenarios. The coastal waters of SAPP coastal states exhibit more than half of the continents technical offshore wind resource (54% in scenario 1, 59% in scenario 2). In the shallow-water, near-coast scenario, the string of SAPP member states that have substantial offshore wind energy potential ranges from South Africa and Mozambique to Tanzania. In the deep-water, full EEZ scenario, nearly all member states (with the exception of the D.R.C.) have large potential. This means that the SAPP could strategically develop offshore wind energy to be a new pillar of their electricity generation capacity which would meet a significant part of its future energy demand.

The second largest share of Africa's offshore wind potential is found throughout the COMELEC countries. With the exception of Algeria, all member states have excellent potential in scenario 1 and collectively have a share of 29% of Africa's offshore wind potential. In scenario 2, all COMELEC states exhibit very good potential, representing 25% of the Africa's potential.

The third power pool where offshore wind energy could play a meaningful role for electricity supply is the EAPP. Both in scenario 1 and 2, approximately 15 % of Africa's technical offshore wind potential are situated in coastal waters of EAPP countries. It should further be noted that Somalia is currently not a EAPP member but is expected to join in the near future. This would add substantial additional offshore wind resource to the EAPP and bring its share of the continental offshore wind energy resource up to 27% in scenario 1 and 24% in scenario 2.

Table 4
Technical offshore wind resource for the five African power pools and their respective electricity demand in 2015 and 2040. *from IEA; **based on modelled results from Ouedraogo (2017).

Power Pool	Electricity generation 2015 (TWh)*	Electricity demand 2040 (TWh)**	Technical OWE resource energy potential Scenario 1 (TWh)	Technical OWE resource energy potential Scenario 2 (TWh)
WAPP	58.3	243.5	13.4	13.9
EAPP	273.3	774.1	237	1460
CAPP	89.3	94.5	22.2	76.6
SAPP	380.8	1060.6	831.8	5397.3
COMELEC	157.4	n/a	457.8	2376.7

The offshore wind potential for both the West African Power Pool and the Central African Power Pool is limited. Regardless of the scenario, WAPP and CAPP together have only 1-2% the continent's resource. Offshore wind energy is therefore unlikely to play a significant role in the future electricity supply of the WAPP or the CAPP grid networks.

6. Conclusion

This paper investigated the technical offshore wind potential of the African continent, employing long-term data of satellite-based wind speed measurements. Two different scenarios were developed to reflect different levels of technological maturity of the wind industry: The shallow-water, near-coast scenario 1 represented the conservative assumption that the current level of technology will not improve. The deep-water, full-EEZ scenario 2 assumes the operational availability of floating platforms that would allow it to access wind resources at much deeper water depths across the entire EEZ.

The results demonstrate that the small continental shelf of the African continent severely limits the OWE potential in the shallow-water scenario. The availability of floating platforms would substantially increase the technical potential. Because of the uncertainties associated with the model results, the resource assessments should be treated as first order estimates. Both scenarios, however, indicate excellent to very good technical offshore wind energy potential for approximately one third of the African coastal states. Mozambique, South Africa, Somalia, Madagascar and Morocco in particular exhibit promising resources. Offshore wind energy could therefore play a significant role in meeting the projected growth of Africa's energy need, the continents transition towards a low low-carbon energy system, and the quest to meet the UN SDG 7 on access to affordable, reliable, sustainable and modern energy for all.

The African power pools SAPP, EAPP, and COMELEC can have a strategic position by including offshore wind energy when developing energy pathways for the future. A joint and integrated development of their resources could offer a promising approach towards introducing offshore wind energy in Africa. However, there are significant challenges to be overcome before a large-scale offshore wind energy exchange can become reality. Central to this is the upgrade of the existing grid network that needs substantial investments in the regional transmission line network [57].

It also needs to be recognised that the establishment and development of a new market for offshore wind power requires a diverse set of support measures and policy frameworks so that OWE potential can be turned into real-world offshore wind projects. Examples of such difficulties in this respect include the ambitious targets for the Chinese market that had to be revised downwards [40,58] or the slow uptake of offshore wind in the U.S. due to the complexities in financing and conflicting state and federal policies [59]. Additional considerations are practical aspects of wind farm design and wind park siting. Experience from early generation European projects have demonstrated substantial cost saving potential due to the minimisation of wake effects and grid network optimisation [60]. A further consideration towards practical project development will be the available port and transport infrastructure, as the role of logistics and its associated costs need are a significant element for offshore wind projects [20,50].

It needs to be recognised that many of the cost reductions that recently were made for the European market might not be readily transferable to the African context, e.g. due to longer travel times of specialised ships and other logistical challenges. Still, the results of this study have demonstrated that a number of African coastal states have excellent technical resource potential for offshore wind energy. It would be good if this will be complemented by more focused studies that evaluate in detail their respective economic and market potential.

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