Potential of Deep Sea Offshore Wind Energy

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Abstract:

As climate change worsens, nations across the world are enacting and attempting to meet aggressive carbon and clean energy goals in order to combat it. Only a great number of large-scale developments is able to achieve those objectives. Deep sea offshore wind energy has a high capacity factor, allowing it to provide both baseload and flexibility at the same time. The purpose of this work is to determine where the most suitable sites in Europe and Africa for this technology are situated. The potentials were calculated with an Analytic Hierarchy Process developed by A. Bahaj at the University of Southampton ([1]) which uses the Levelized Cost of Energy as a base. The results show that the majority of northern Europe is ideal for deep sea offshore wind energy. Just a few high potential areas exist in the seas of southern Europe: Bretagne, south of France, north of Spain, and between Greece and Turkey. Africa's potential comprises primarily of small desirable sites spread throughout various regions, including Morocco, Madagascar, Mauritania, Senegal, and Eritrea. The only wide high potential region extends through South African and Namibian waters.

Keywords: Wind Energy; Offshore Wind Energy; Deep Sea Offshore Wind Energy; Renewable Energy

1 Introduction

Offshore wind energy will become an increasingly important part of the global electricity generation. With the rapidly intensifying climate change, industrialized countries have to switch to clean energy and developing countries have to find a sustainable way for their electrification process. One advantage of the technology is its high capacity factor when compared to photovoltaics and onshore wind, which is comparable to that of gas power plants [2]. Another benefit of wind energy in general is that the seasonal production peak variations of wind and photovoltaics complement each other, with wind generating more in the winter and photovoltaics producing more in the summer. Deep sea offshore (water depths more than 60 m) and innovative transmission technologies will become increasingly necessary in order to meet the targets established for the next decades. The site's water depth and distance to shore expanded through time due to necessity, because suitable shallow water locations near to shore are the cheapest, they were used first [3]. These places will become increasingly rare in the coming decades. As a result, the currently used bottom-fixed structures will be replaced

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by their floating counterparts because they become less expensive than bottom-fixed substructures for water depths greater than 60 m [4].

The goal of this research is to identify potential locations for deep sea offshore wind power plants in Europe and Africa. There are global studies of offshore wind potential, such as the International Energy Agency's "Offshore Wind Outlook 2019."[2]. These calculations, however, were more concerned with determining whether or not there was a potential than with determining how much. There is literature that attempts to identify potential through a grading system, but it is limited to small areas or countries e.g. Bahaj et al.,2020 [1]. All of the literature reviewed had a general focus on offshore wind energy, often without distinguishing between shallow and deep sea. Our research goal is to scale up an existing grading system with a focus on deep sea offshore wind. This paper is presenting the results of the master thesis “Potential of Deep Sea Offshore Wind Energy”[5].

2 Methodology

The methodology is based on Bahajs 2020 paper "New approach to determine the Importance Index for developing offshore wind energy potential sites: Supported by UK and Arabian Peninsula case studies"[1]. The methodology was adapted for deep sea offshore wind potential for the purpose of this paper and broadened to a large scale application – from single countries to whole continents.

2.1 Analytic Hierarchy Process - Theory

Thomas L. Saaty established the Analytic Hierarchy Process in the 1970s as a multi-criteria decision-making process based on psychology and mathematics. It is utilized in a wide range of applications, from resource allocation to dispute resolution. The first step is to define the problem and determine what information is required. Following that, the criteria and sub-criteria, also known as factors, are defined. It is critical for the procedure that the problem be organized in the form of a network or hierarchy. To evaluate their significance, they are compared in pairs. This is accomplished by creating a pairwise comparison matrix with all criteria on both axes. The comparison might be based on measurements, but it can also be based on inclinations and sentiments. To weight their criteria, the appointed order is used. This may also be done using criterion sub-levels. In order for the process to operate correctly, all of the phases and claims created during the process must be consistent. A few computations utilizing the eigenvalue λ of the pairwise comparison matrix and the number of elements n can be used to confirm the consistency. The consistency ratio, which must be less than 0.10, is the ultimate indicator for consistency; otherwise, the judgments in the pairwise comparison must be changed. [6], [7]

2.2 Analytic Hierarchy Process - Application

Bahaj et al. ([1]) used the Analytic Hierarchy Process to develop a simple and robust method to calculate the potential of offshore wind energy for different sites. In addition to the Importance Index they adopted a new value the Representative Cost Ratio (RCR) which is calculated by the levelized cost of energy (LCOE) share of one factor divided by the share of the compared factor. The LCOE is a measure for analyzing specific investment costs. As shown in Equation 1 it is made up of three parts: capital expenditure, operating costs and decommissioning costs.

$$LCOE = \frac{CAPEX+OPEX+DECEX}{AEP} = \frac{cost\ over\ lifetime}{produced\ energy\ over\ lifetime} \quad (1)$$

$LCOE$ .... Levelized cost of energy in €ct/MWh
$CAPEX$ .... Capital expenditure in €ct
$OPEX$ .... Operating costs in €ct
$DECEX$ .... Decommissioning costs in €ct
AEP .... Annual Energy Production in MWh

Bahaj used the already established Important Indexes from onshore wind studies and calculated their RCR in order to establish a relationship between the two values. The next step is to calculate the RCR of offshore wind factors from the LCOE shares which are based on Cavazzis 2016 paper "An Offshore Wind Energy Geographic Information System (OWE-GIS) for assessment of the UK's offshore wind energy potential"[4]. Then the corresponding Important Indexes can be entered in the pairwise comparison matrix. In order to normalize the matrix every element is divided by the sum of the column it is in. The Factor weight is determined by computing the average of every row. The sum of all factor weights is one. In order to validate the made assumptions the eigenvalue of the matrix needs to be calculated. This is done by multiplying the column sum of the pairwise matrix with the corresponding factor weight. With a consistency ratio of 0.085 the model is consistent. The last step of the method is to compute the potential with Equation 2.

$$P = \sum_{i=1}^{n} W_i X_i \cdot \prod_{j=1}^{l} C_j \quad (2)$$

P .... Potential
W_i .... Weight assigned to factor i
X_i .... Criterion score of factor i
n .... Number of factors
C_j .... 0 or 1 score of constraint j
l .... Number of constraints

2.3 Factors and Constrains

The concept of factors and constraints is the common denominator of many offshore wind energy potential estimation methodologies. A factor can be thought of as a criterion on which the potential is calculated. All of the regions that are omitted from the computations would be viewed as a constraint. Table 1 shows possible factors and constraints, as well as markers for the ones used by the IEA in its 2019 offshore wind outlook, Bahaj et al. in their 2020 paper, and the actual ones used in this model. In comparison to Bahaj et al., unsuitable regions included a minimum wind speed, maritime protection areas, and undersea cables. The minimum and maximum distances to the coast were changed. Finally, water depth limitations were imposed since, in addition to a necessary upper limit, a lower limit was required in order to only look at deep water suitable for floating turbines. Due to a lack of implementable maps and the question of how regular maritime traffic must be in order for the area to be excluded, major shipping lanes were not included. Existing oil and gas infrastructure were not disregarded. The reason for this is because oil and gas platforms require a lot of electricity, and a wind farm nearby may be advantageous.

		IEA 2019	Bahaj et al. 2020	Gruber 2020
Factors	Water depth	x	x	x
	Distance to shore	x	x	x
	Wind farm design	x		
	Wind speed		x	x
	Turbine design (CF)	x		
	Distance to grid		x	x
Constraints	Wind speed < 5 m/s	x	x	x
	Maritime protection areas	x	x	x
	Submarine cables	x	x	x
	Major shipping lanes	x	x	
	Min. & max distance to shore		x	x
	Earthquake fault lines	x		
	Existing oil & gas installations	x	x	
	Min. & max water depth			x

Table 1: Factor and constraint comparison [2],[1],[5]

2.3.1 Factors maps

Following the identification of the factors and constraints, the following step was to obtain maps to be used in the computations. The bathymetry data came from the General Bathymetric Chart of the Oceans, a joint effort of the International Hydrographic Organization and the Intergovernmental Oceanographic Commission [8]. The wind speed data used comes from the global wind atlas, a World Bank and Department of Wind Energy at the Technical University of Denmark initiative that provides a high-resolution worldwide wind map for free [9]. The map's grid size is 250 m, and the wind speed data utilized in the model is at a height of 100 m. The grid network for the two continents was required for the third factor. The grid structure from ATLANTIS, a model of the European electrical industry developed by Graz University of Technology's Institute of Electricity Economics and Energy Innovation, was applied for Europe [10]. The UNHCR created the grid map for Africa using data from the Africa Infrastructure Country Diagnostic, Open Street Map, the Arab Union of Electricity and Country Utilities, the West African Power Pool GIS database, and the World Bank projects archive [11]. The last factor is the distance to shore. To calculate this number, the coastlines of Europe and Africa were required. This continent and county shapes were taken from the ArcGIS database.

2.3.2 Constraints Maps

The maps from the linked factors were utilized for wind speed and water depth constraints. The submarine cable routes are from a map created by TeleGeography, a telecom data research platform supported by Huawei Marine Networks and Equinix [12]. The map for the protected marine natural park comes from Protected Planet, a site operated by the United Nations Environment World Conservation Monitoring Centre that collects data from governments, non-governmental organizations, landowners, and communities and updates it monthly [13].

2.4 Potential Calculation in ArcGIS

The flowchart of the wind potential calculations in ArcGIS is illustrated in Figure 1. Before performing the calculations, the first step was to process the map data of the factors and constraints. Wind data from Europe and Africa were combined into a single raster per continent, Euclidian distances to the grid and the shore were calculated, and global bathymetry, nature reserve, and submarine cable maps were clipped for the continent in question. The constraints must then be set to zero in order to generate a Boolean mask. With the function "Is Null," this can be done directly for areas involving nature reserves and submarine cables. Wind and water depth constraints are created by excluding windspeeds less than 5 m/s and water depths shallower than 60 m and deeper than 1000 m from the raster using the raster calculator. After processing the factor maps they need to be standardized. The Fuzzy membership tool is used to linearly normalize the four factors to values ranging from zero to one. The components all have distinct scales and are not measured in the same units. This step is completed to scale them so that they are similar. Table 2 summarizes the boundaries that were chosen. The wind speed limits correspond to the rated and cut-in wind speeds of a typical 8 MW turbine. The maximum grid distance of 300 km was chosen since it is about half the length of the longest undersea power line deployed thus far, which is 580 km. It should be noted at this point that just because a cell has a value of zero for one of the factors does not mean it is eliminated as a constraint. It just indicates a lower total score.

FACTOR	MAX	MIN	CONDITION	VALUE	CONDITION	VALUE
WIND SPEED	12 m/s	5 m/s	>Max	1.0	<Min	0.0
WATER DEPTH	-1000 m	-60 m	<Max	0.0	>Min	1.0
DISTANCE TO SHORE	200 km	5 km	>Max	0.0	<Min	1.0
DISTANCE TO GRID	300 km	10 km	>Max	0.0	<Min	1.0

Table 2: Fuzzy Membership Inputs

FACTOR	WIND SPEED	WATER DEPTH	DISTANCE TO SHORE	DISTANCE TO GRID
FACTOR WEIGHT	0.58	0.28	0.09	0.05

Table 3: Factor weights

The model's final step is to apply Equation 2 by first multiplying the standardized factors by their factor weights from Table 3 and then multiplying the factors by the constraints to generate the potential, which is depicted as a potential scale ranging from zero to one. A score of less than 0.4 was deemed unsuitable, while one greater than 0.7 was deemed to have the most potential.

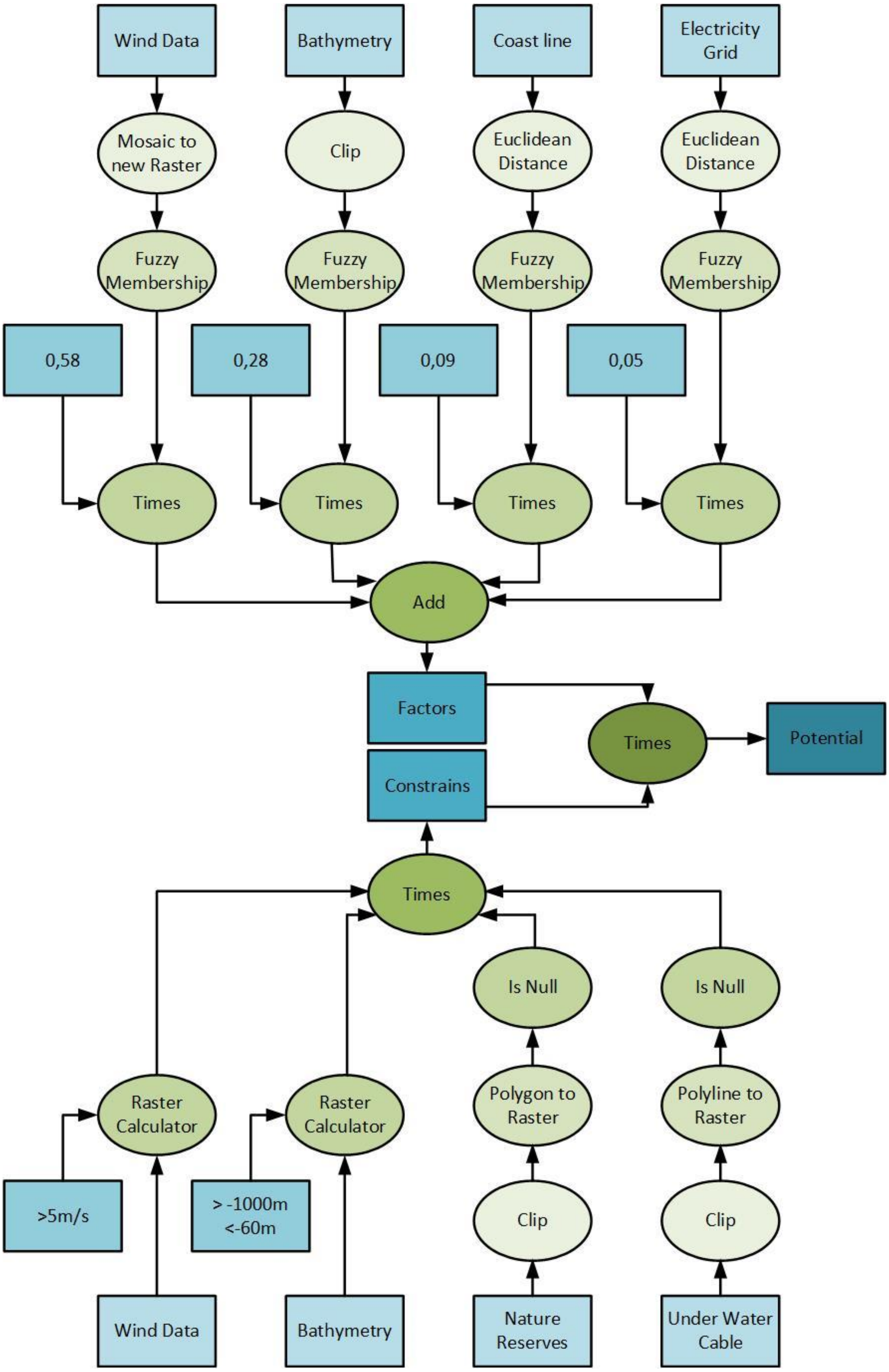

Figure 1: Flowchart of the wind potential calculations

3 Results

Figure 2 depicts the simulation results for Europe's deep sea offshore wind energy potential. The calculations revealed that the waters around Iceland and Ireland, as well as the northern part of the North Sea between the United Kingdom and Norway, are ideal. The Baltic Sea has a lot of potential, starting with Poland in the east and going all the way down to the southern part of the Gulf of Bothnia. Small areas in the south of Europe have a very high score, such as Bretagne and the coastline between Marseille and Perpignan in France, or the North Aegean islands and the Cyclades in Greece. All areas with a score greater than 0.4 are considered for comparison with the IEA calculations because that simulation only differentiated between suitable and unsuitable. While the results are similar, the simulation for this work is a more conservative estimate. Another method for validating the results is to examine current and future project sites, which are also plotted in Figure 2. The majority of them are in high-potential areas. Namibia and the west coast of South Africa have the most high scoring areas in Africa. Small stripes in the south of Madagascar, the west coast of Mauritania, Senegal, and a small part of Morocco, as well as tiny parts of the east coast of Somalia and Eritrea, are also very suitable. This is depicted in Figure 3. The same can be said for the comparison to the IEA calculations as for the European results. There have yet to be any offshore wind farms built in African countries to compare the results to.

4 Conclusion

This paper focused on determining the role of offshore wind energy in water depths deeper than 60 m with floating turbines and estimated the potential in Europe and Africa. As a base for the potential calculations the LCOE consisting of CAPEX, OPEX and DECEX was determined. The factors and constraints for the potential calculation are defined. The LCOE shares of the factors are compared and their factor weights computed. In order to calculate the potential, the factors are standardized before multiplying them with their factor weights and the Boolean mask established from the constraints. The simulations that were conducted for Europe show a lot of high potential in most of the North and Baltic Sea area also including the Gulf Bothnia. Iceland and Ireland are completely surrounded by regions with a high potential score. France, Spain and Greece show a few small hot spots as well. In comparison, the outcome of the Africa simulation was not so preferable with only one big high potential area around Namibia and South Africa. The other areas with excellent site conditions are very small and being spread over Morocco, Madagascar, Mauritania, Senegal and Eritrea. The approach was compared to the calculations executed by the IEA in 2019 and in Europe to the sites of existing and planned floating wind farms. The correlation is strong even though this model being a rather conservative estimate. The findings of this paper provide a potential starting point of locations for investing in deep sea offshore wind energy. This is made possible by the rating system as opposed to simply knowing whether or not there is potential.

Future research should look into data gaps caused by country-specific wind maps, such as those in the North Sea, between France and the UK, Monaco, a small area in the Black Sea, Western Sahara, the most eastern tip of Somalia, and its border with Kenya. It should be noted that the majority of them are in low-potential regions and hence are not particularly relevant. Further studies should be conducted to update Cavazzis LCOE distribution, as there has been significant technological progress since the paper's publication.

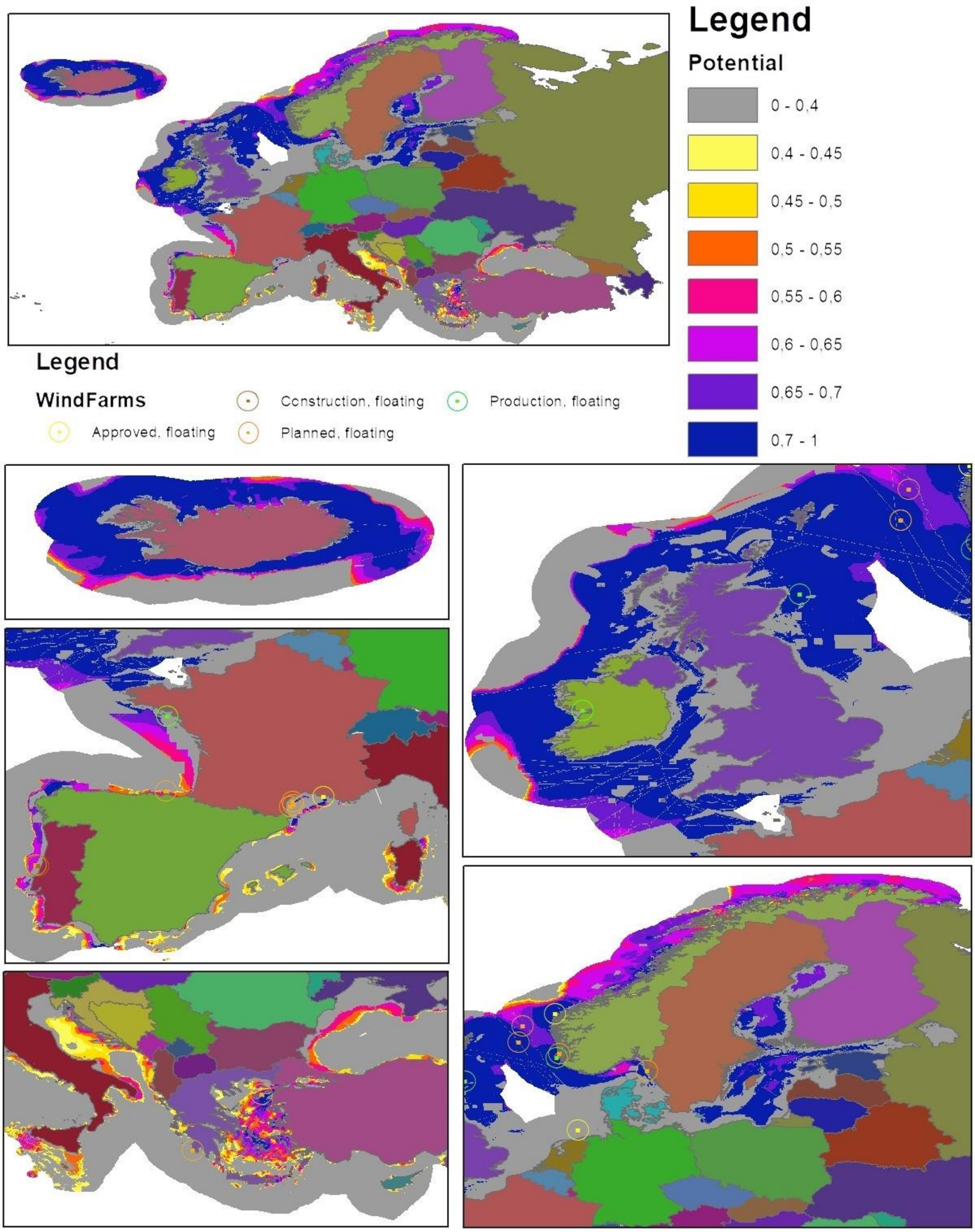

Figure 2: Potential in Europe

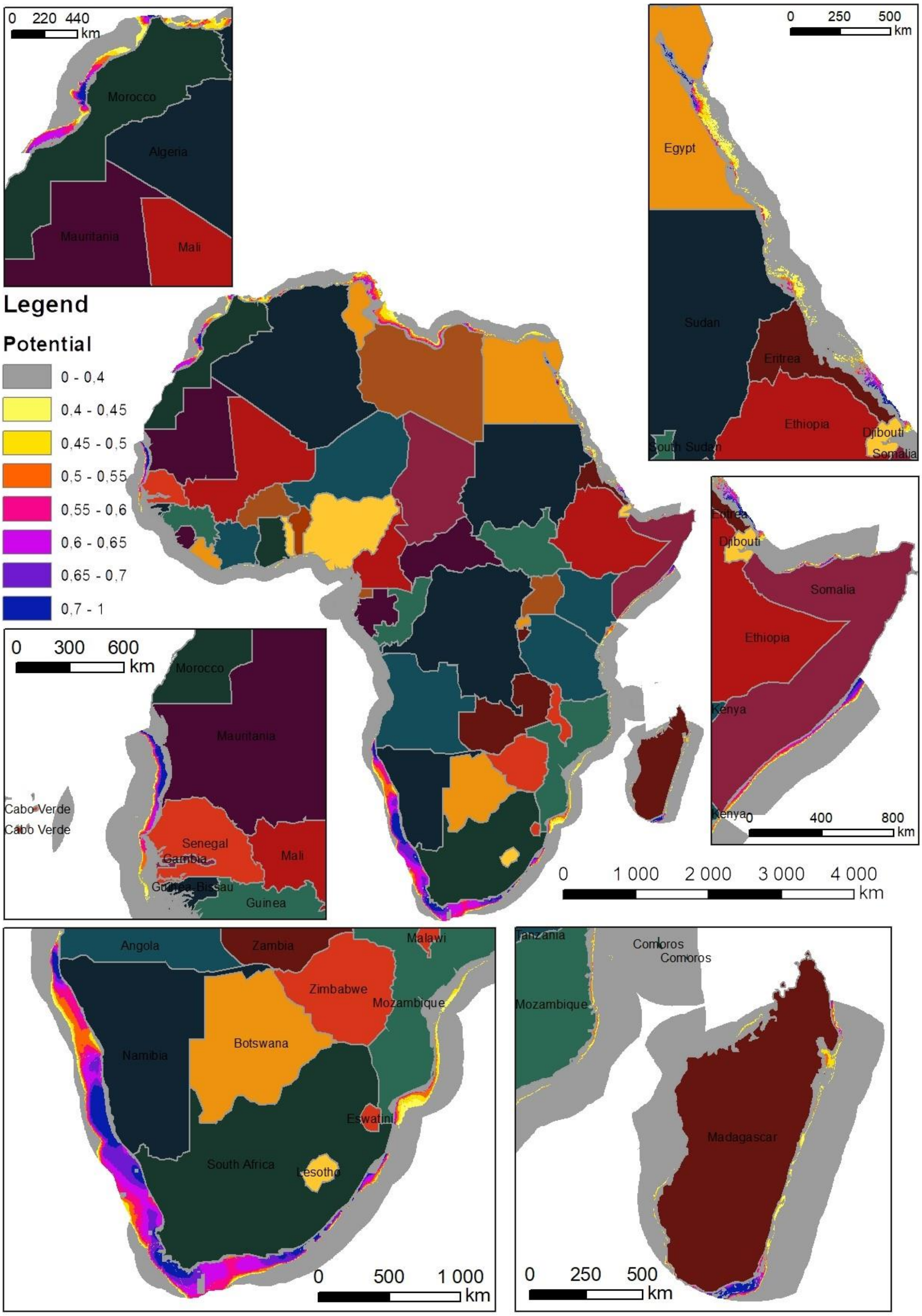

Figure 3: Potential Africa

Literatur

[1] A. S. Bahaj, M. Mahdy, A. S. Alghamdi, and D. J. Richards, "New approach to determine the Importance Index for developing offshore wind energy potential sites : Supported by UK and Arabian Peninsula case studies," *Renew. Energy*, vol. 152, pp. 441–457, 2020, doi: 10.1016/j.renene.2019.12.070.

[2] L. Cozzi, B. Wanner, C. Donovan, and E. Al., "Offshore Wind Outlook 2019," Paris, 2019. [Online]. Available: https://www.iea.org/reports/offshore-wind-outlook-2019.

[3] L. Ramírez, D. Fraile, and G. Brindley, "Offshore wind in Europe," Brussels, 2019. [Online]. Available: https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2019.pdf.

[4] S. Cavazzi and A. G. Dutton, "An Offshore Wind Energy Geographic Information System (OWE-GIS) for assessment of the UK's offshore wind energy potential," *Renew. Energy*, vol. 87, no. 2016, pp. 212–228, 2016, doi: 10.1016/j.renene.2015.09.021.

[5] L. Gruber, "Potential of Deep Sea Offshore Wind Energy," Graz University of Technology, 2020.

[6] R. W. Saaty, "The analytic hierarchy process—what it is and how it is used," *Math. Model.*, vol. 9, no. 3–5, pp. 161–176, 1987, doi: 10.1016/0270-0255(87)90473-8.

[7] T. L. Saaty, "Decision making with the analytic hierarchy process," *Int. J. Serv. Sci.*, vol. 1, no. 1, p. 83, 2008, doi: 10.1504/IJSSCI.2008.017590.

[8] GEBCO, "What we do," 2021. https://www.gebco.net/about_us/overview/ (accessed Aug. 24, 2021).

[9] DTU Wind Energy, "Global Wind Atlas," 2021. https://globalwindatlas.info/ (accessed Aug. 24, 2021).

[10] H. Stigler, U. Bachhiesl, G. Nischler, and G. Feichtinger, "ATLANTIS: techno-economic model of the European electricity sector," *Cent. Eur. J. Oper. Res.*, vol. 24, no. 4, pp. 965–988, 2016, doi: 10.1007/s10100-015-0413-8.

[11] ArcGIS, "Africa - electricity transmission and distribution," 2020. https://www.arcgis.com/home/item.html?id=b844d9ecb24c422e8cd9707bb52ee409 (accessed Aug. 24, 2021).

[12] PriMetrica, "We've got the telecom intel you need," 2021. https://www2.telegeography.com/ (accessed Aug. 24, 2021).

[13] ProtectedPlanet, "Discover the world's protected areas," 2021. https://www.protectedplanet.net/en (accessed Aug. 24, 2021).