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Potential of Deep Sea Offshore Wind Energy

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Affidavit

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master thesis.

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Abstract

As climate change intensifies countries all over the world are introducing and trying to accomplish ambitious emission and renewable energy targets in order to retaliate. Reaching those goals will only be possible with a lot of large-scale projects. Deep sea offshore wind energy is very suited to play a big part by being quite versatile. This energy source has a high capacity factor which gives it the capability of providing baseload energy and being flexible at same time. Deep sea offshore wind energy has the ability to produce energy 24 h a day and use excess power to create green hydrogen contributing to bringing down emission in the building and transportation sector. The aim of this thesis is to analyze where the most preferable sites for the energy source in Europe and Africa are located. The method is based on the Levelized Cost of Energy (LCOE) using a multi-criteria decision-making process. The factors included in the model are wind speed, water depth, distance to grid and distance to shore. While nature reserves, under water cable, locations with wind speeds smaller than 5 m/s and regions with a water depth less than 60 m and more than 1000 m create a Boolean mask in order to remove those areas from the simulation. Factor weights are calculated from the LCOE shares of the factors. After standardization factors, factor weights and Boolean mask are multiplied resulting in the potential in form of a scale. Most of northern Europe is very suitable for deep sea offshore wind energy including large parts of the Gulf of Bothnia, costal area around Iceland and Ireland as well as North and Baltic sea. The waters in the south of Europe only have a few hot spots in the Bretagne, South of France, North of Spain and between Greece and Turkey. The potential of Africa consists mostly of small preferable sites in many different areas of the continent like Morocco, Madagascar, Mauritania, Senegal and Eritrea. Over South Africa and Namibia spreads the only large high potential area. In order to validate the functionality of the process it was compared to the potential calculations from the 2018 IEA Offshore Wind Outlook and to commissioned and planned wind farms. Since no project have been conducted yet in Africa this last comparison was only performed in Europe. As a result of this evaluation it can be concluded that the model is functional. The simulation outputs are very similar to the outlook and most of the projects are situated in areas with high deep sea offshore potential.

Kurzfassung

Mit der Zuspitzung des Klimawandels führen Länder auf der ganzen Welt ehrgeizige Ziele zur Reduktion der THG-Emissionen und verstärkter Nutzung erneuerbarer Energien ein und versuchen, diese mit geeigneten Maßnahmen zu erreichen. Das Erreichen dieser Ziele erfordert die Umsetzung zahlreicher Großprojekte. Die Offshore-Windenergie in der Tiefsee ist sehr gut dafür geeignet, eine große Rolle zu spielen, da sie äußerst vielseitig ist. Diese Energiequelle hat einen hohen Kapazitätsfaktor, der ihr die Fähigkeit verleiht, Grundlast-Energie zu liefern und gleichzeitig flexibel zu sein. Tiefsee-Offshore-Windenergie kann über längere Zeiträume Energie produzieren und überschüssige Energie kann zur Erzeugung von grünem Wasserstoff genutzt werden, was zur Senkung der THG-Emissionen beitragen kann. In dieser Arbeit wird analysiert, wo sich die bevorzugten Standorte für diese Energiequelle in Europa und Afrika befinden. Die Methode basiert auf den Energiekosten (Levelized Cost of Energy, LCOE) unter Verwendung eines Multikriterien-Entscheidungsprozesses. Die in das Modell einbezogenen Faktoren sind Windgeschwindigkeit, Wassertiefe, Entfernung zum Netz und Entfernung zur Küste. Während Naturschutzgebiete, Unterwasserkabel, Standorte mit Windgeschwindigkeiten von weniger als 5 m/s und Regionen mit einer Wassertiefe von weniger als 60 m und mehr als 1000 m eine Boolesche Maske bilden, um diese Gebiete aus der Simulation zu entfernen. Faktorgewichte werden aus den LCOE-Anteilen der Faktoren berechnet. Nach der Standardisierung werden die Faktoren, die Faktorgewichte und die Boolesche Maske multipliziert, was das Potenzial in Form einer Skala ergibt. Der größte Teil Nordeuropas eignet sich sehr gut für die Offshore-Windenergie in der Tiefsee, einschließlich großer Teile des Bottnischen Meerbusens, des Küstengebiets um Island und Irland sowie der Nord- und Ostsee. Die Gewässer im Süden Europas haben nur einige wenige Hotspots in der Bretagne, Südfrankreich, Nordspanien und zwischen Griechenland und der Türkei. Das Potenzial Afrikas besteht hauptsächlich aus kleinen bevorzugten Standorten in vielen verschiedenen Gebieten des Kontinents wie Marokko, Madagaskar, Mauretanien, Senegal und Eritrea. Über Südafrika und Namibia erstreckt sich das einzige große Gebiet mit hohem Potenzial. Um die Funktionalität des Verfahrens zu validieren, wurde es mit den Potenzialberechnungen aus dem IEA Offshore Wind Outlook 2018 sowie mit in Betrieb genommenen und geplanten Windparks verglichen. Da bisher noch kein Projekt in Afrika durchgeführt wurde, fand dieser letzte Vergleich nur in Europa statt. Als Ergebnis dieser Bewertung kann festgestellt werden, dass das Modell funktionsfähig ist. Die Simulationsergebnisse sind dem Outlook sehr ähnlich, und die meisten Projekte befinden sich in Gebieten mit hohem Tiefsee-Offshore-Potential.

Contents

1 Introduction

In this chapter it is elaborated why deep sea offshore and wind energy development in general is important. Furthermore advantages of the technology and the current status are explained.

1.1 Climate Change

Climate change forces the world to shift its energy production from fossil fuels to renewable energy. In order to deal with this challenge, the EU has set up climate and energy targets for 2020, 2030 and 2050. On a lower level in the Renewable Energy Directive every member country has set its individual binding renewable energy target. The goals of the EU for 2020 were emitting 20% less Greenhouse Gas (GHS) emission compared to 1990, 20% of renewable energy in its energy-mix and 20% increase in its energy efficiency. The emission target was accomplished two years early [1]. For 2030 those numbers were increased to 40%, 32% and 32.5%. The ultimate goal is the reach net-zero greenhouse gas emissions (GHG) in 2050. The energy mix and emission reductions needed to reach that target are shown in Figure 1.1 and 1.2.[2] For that kind of rapid increase of renewable energy production large scale project with a lot of capacity will be needed. The energy source most suited for such projects are offshore wind farms.

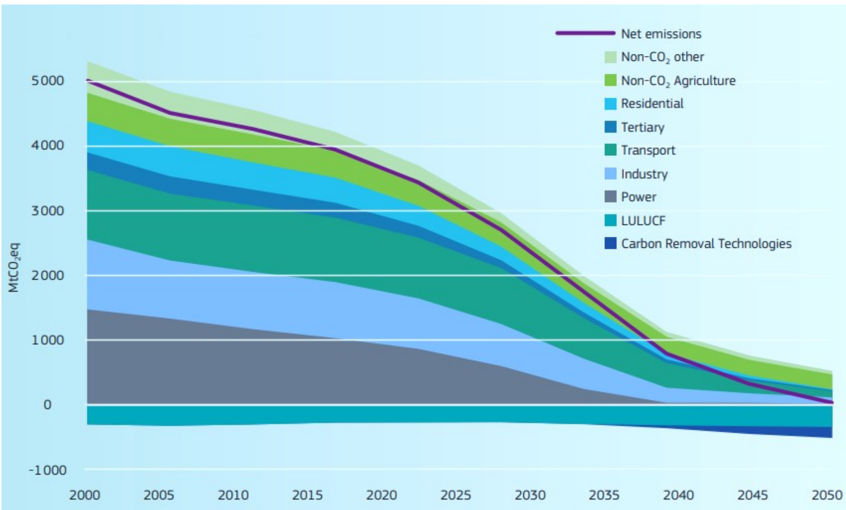

Figure 1.1: GHG emissions trajectory in a 1.5 °C scenario [3].

On an international level the Paris agreement was reached in 2015 to show commitment and hold each other responsible. The 55 countries that ratified it produced more than 55% of the global CO^2 emissions at that time. It was negotiated by 195 parties and by today 189 ratified it. The agreement set the goal of a maximum increase of 2 $°C$ compared to pre-industrial levels with the addition of trying to stay under 1.5 $°C$. Global peaking is supposed to happen as soon as possible followed by climate neutrality in the second half of the century. For climate change mitigation every participating country had to come up with NDCs (National Determined Contributions), which are reviewed every 5 years.[4],[5]

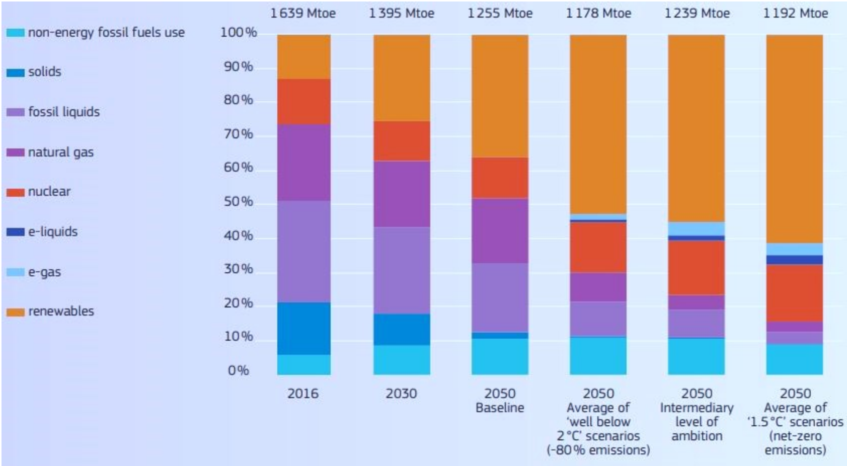

Figure 1.2: Gross inland consumption of energy in the EU [3].

Most African countries do not emit a huge amount of GHGs compared to European countries. One reason for this is that a lot of people do not have access to electricity yet. The African governments and international organizations are working on changing that. With the electrification rate rising it is important that the developing countries do not make the same mistake industrialized ones made. Research has shown that for a many parts of Africa renewable energy even is the more economical option. Since this continent already has to face harsh impacts of climate change the leaders of its countries are very aware how important clean energy development is and already reached an agreement in 2009 at the African Union Assembly of Heads of States and Government on a renewable energy strategy. In the renewable scenario that IRENA developed for Africa wind energy has the second biggest share of the 800 GW supposed to be build till 2050 just a few Gigawatt less than photovoltaic.[6]

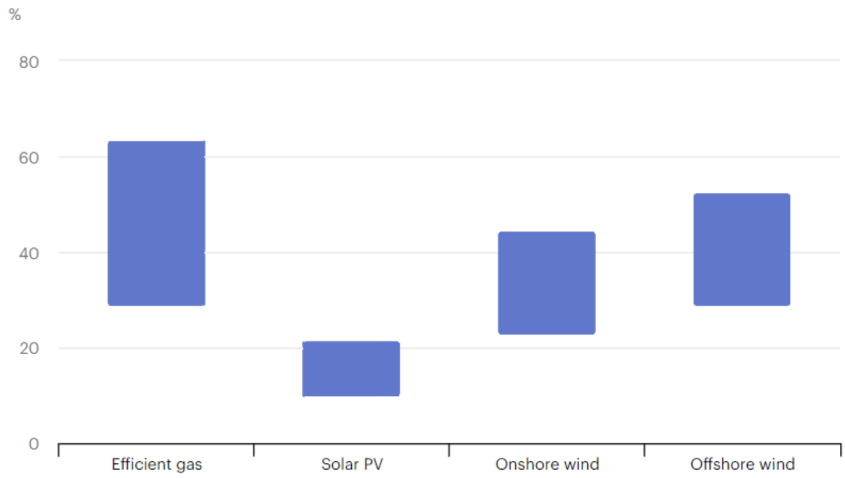

Figure 1.3: Average annual capacity factors by technology, 2018 [7].

1.2 Advantages of Offshore Wind Energy

Offshore wind energy has a high capacity factor compared to photovoltaics and onshore wind. A capacity factor is the average of the power it actually produces divided by the power it is supposed to generate without down time etc. meaning the rated power [8]. The capacity factor of offshore wind is similar to that of efficient gas, see Figure 1.3. Wind is an intermittent energy source as is solar. Looking at the fluctuations it can be said that the later varies twice as much with up to 40% from hour to hour than offshore wind with 20%. The seasonal production peak differences of the two energy sources complement each other with wind energy producing more in the winter and photovoltaic having a peak in the summer months. But wind also has the ability to generate power all day and night. Having a relatively high capacity factor and somewhat low fluctuations makes it a variable baseload technology since enough energy is produced to cover the baseload while still being intermittent. The power production during off-peak demand hours can be used to generate hydrogen which will play a big part of getting emissions down in the building and transport sectors.[7] When comparing offshore with onshore wind energy the later has a lot of benefits except for being more expensive. It does not have to compete with other alternative uses of the land it is build on and public acceptance issues are a lot smaller. Most of the time offshore wind is so far away from the coast that negative impacts like noise pollution, visual impacts and shadow flicker (effects where the shadow of the blades can inflict photo-induced seizures or photosensitive epilepsy) do not affect people.[9]

1.3 Current status

An overview of the development of offshore wind capacity in Europe so far is given in Figure 1.4 and Table 1.1. When the 1 GW line of global annual installed capacity was first crossed almost all of it was built in Europe. When that number more than quadrupled in 2018 only around 60% were contributed by it with China making up almost 40%. The frontrunners in offshore wind development in Europe are by far the UK and Germany.[7]

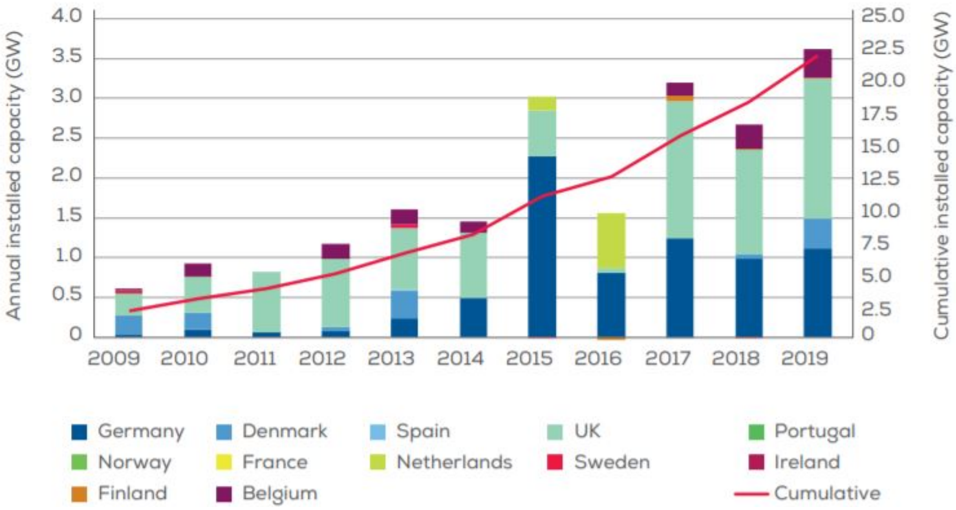

Figure 1.4: Annual and cumulative installed wind energy capacity in Europe [10].

Country	No. of wind farms connected	Cumulative capacity in MW	No. of turbines connected	Net capacity connected in 2019 in MW	No. of turbines connected in 2019
UK	40	9,945	2,225	1,760	252
Germany	28	7,445	1,469	1,111	160
Denmark	14	1,703	559	374	45
Belgium	8	1,556	318	0	44
Netherlands	6	1,118	365	0	0
Sweden	5	192	80	0	0
Finland	3	70.7	19	0	0
Ireland	1	25.2	7	0	0
Spain	2	5	2	0	0
Portugal	1	8.4	1	8	1
Norway	1	2.3	1	0	0
France	1	2	1	0	0
Total	110	22,072	5,047	3,623	502

Table 1.1: Overview of grid-connected offshore wind power projects at the end of 2019 [10].

Over the last decade the average turbine capacity increased from 3 MW to almost 8 MW and wind farm size from 200 MW to more than 600 MW. Out of necessity the water depth and distance to shore of the site grew with them over the years as illustrated in Figures 1.5 and 1.6. Suitable shallow water sites that are close to shore are the cheapest therefore were utilized first. Those locations will get scarcer in the decades to come. Deep sea offshore (water depth deeper than 60 m) and innovative transmission technologies will be needed for the sector to grow in order to reach the targets set for the decades to come. [10]

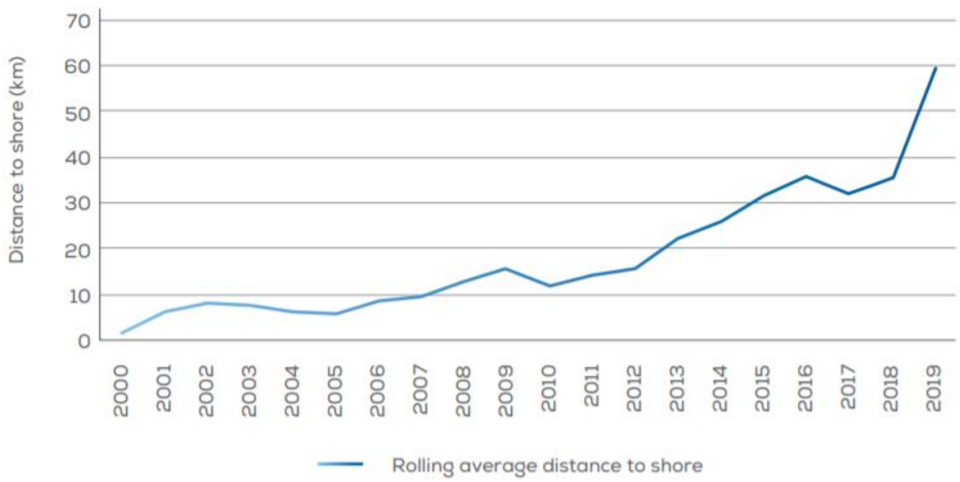

Figure 1.5: Development of the average distance to shore for offshore wind power plants [10].

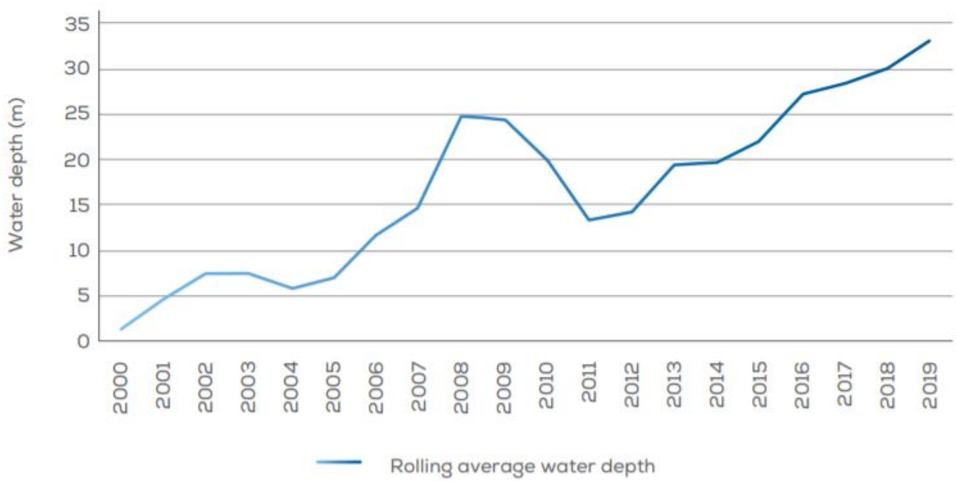

Figure 1.6: Development of the average water depth for offshore wind power plants [10].

2 Wind Energy Technology

In this chapter the technology behind wind energy is discussed. First a short overview of its history is given. Then the different parts of a wind turbine and their functions are explained.

2.1 History

The first driver of renewable energy sources happened decades before climate change even became a topic: The first and second oil crisis. The first was the Arab Oil Embargo in 1973 where the Arabic member states of OPEC raised the oil price and stopped exporting oil to the USA, Japan and parts of Europe because those countries supported Israel during the Yom Kippur War. The second oil crisis in 1979 was a result of the Islamic Revolution in Iran where the social conflicts seriously impaired the Iranian oil industry.[11] The issue of energy security was suddenly very important and a lot of public funds from western countries poured toward *R&D* for alternative energy sources where wind energy was also a part of. The idea of producing electricity with the help of wind by powering an electric dynamo first appeared in the early 1880s. It is not clear who invented and built the first wind-driven machine. Prof. James Blyth is somebody who is often declared to have done that in July 1887 in Scotland. He supplied his vacation cottage with electricity using a wind-powered generator. The first record that can be found establishing wind energy offshore was in Germany in the early 1930s. After that nothing happened for a long time because the rest of the technology involved in offshore wind power was not ready yet like submarine cables. All the ideas and concepts before the oil crisis stayed theoretical. After the first oil crisis the first wind energy *R&D* program was set up in the USA in 1975 operated by NASA in the name of the US Department of Energy and Department of Interior. The program was a success just five years after the first land-based wind farm was constructed with 20 x 30 kW turbines in New Hampshire. In the years to come the wind power industry was kept afloat by entrepreneurship and policy incentives. E.g. a production tax credit enforced in 1992 by the USA to push innovation in the industry instead of just incentivizing the installation of wind turbines.[12] Europe was a lot slower than the USA. The first onshore wind farm was commissioned in 1982 in Greece on the island of Kynthos with 5 x 20 kW turbines[13]. Followed by the first offshore wind farm worldwide in Denmark in 1991. This wind park had a water depth of 2 to 6 m with a gravity-based foundation and a distance to shore of 1.5 to 3 km of the cost from Lolland island. It contains a total rated power of 4.95 MW and construction costs of about 10 million Euros. The wind farm is operational to this day.[14]

The reason why Europe was quicker in offshore development is the availability of suitable land for onshore projects. The sheer abundance of land usable in the USA resulted in less land-use issues as well which was a big problem in Europe. So, in the USA the need to go offshore was a lot smaller.[12] The first large-scale offshore wind farm is called Middelgrunden and was commissioned 2000 in Copenhagen, Denmark. The wind farm has 20 x 2 MW turbines, a water depth of 5 m and a distance to shore of 5 km.[13], [15]

2.2 Wind Turbines

The concept behind a wind turbine can be seen as a reversed fan. Wind is producing electrical energy and in a fan electrical energy is producing wind. How mathematically speaking the power is generated can be described with the Rankine-Froude theory in equation 2.1. It shows the high dependency of the generated power on the relative wind velocity where a 10% rise produces 33% more power. The composition of a wind turbine with all its components is depicted in 2.1.[16]

$$P = \frac{1}{2}\rho_{air} C_P A_S V_{Rel}^3 \tag{2.1}$$

P .... Power in W
ρ_{air} .... Air density in kg/m^3
C_P .... Power coefficient
A_S .... Swept area of the wind turbine rotor in m^2
V_{Rel} .... Relative wind velocity in m/s

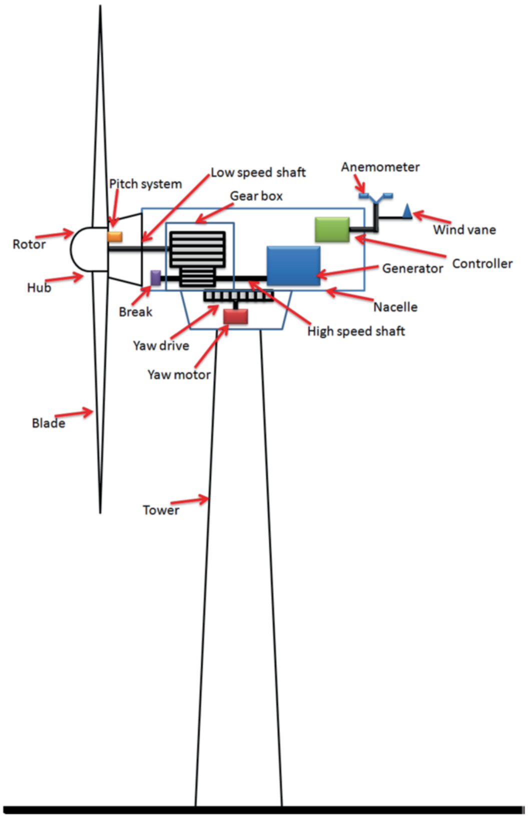

Figure 2.1: Components of a wind turbine [16].

In the following paragraphs the components that a wind turbine is made of are explained:

2.2.1 Nacelle

The nacelle is the big rectangle above the tower that contains many other components. In larger turbines (MW range) the nacelle is spacious enough that a helicopter is able to land on it. Inside the nacelle the conversion of kinetic energy to electricity is completed, which makes it the most crucial component of the turbine. The hub and the blades are attached to the nacelle by the main shaft. On the inside the main shaft is linked with the gearbox.[16]

2.2.2 Hub, Blade and Pitch System

The hub connects the blades with each other and the pitch system is placed inside of it. These days most wind turbines have pitch-controlled variable-speed generators, where in order to enhance power production the pitch angle of the blades is adjusted. The blades of a wind turbine are usually airfoil shaped. The classic wind turbine has a three-bladed horizontal-axis. Downwind turbines with two blades though less common are also sometimes employed. The concept of the blades is that the airfoil creates a difference in airflow streamlines which results in a divergence of pressure over the blade. This leads to a lift force that develops a torque in the rotor.[16] The material most used nowadays for rotor blades is glass fibre reinforced plastics. But for the bigger turbines (3-6 MW) carbon fibre or aramid has to be used for reinforcing material. This is relevant for offshore applications since bigger turbines are used.[17] Together the hub and the blades are called rotor. They can be arranged as up wind where it is directed towards the wind or downwind rotor where it is aimed away from the wind. The pitch system turns the blades more and more horizontal when the wind is faster than the rated wind speed. To what degree the blades have to be turned is determined by the controller. At this point the three important wind speed values should be mentioned. At the cut-in wind speed the turbine starts to produce power which rises with wind speed till the rated wind speed is reached. From this point on the amount of generated power stays the same as the wind speed rises. When the cut-out wind speed is attained the turbine shuts down for safety reasons. This is shown in Figure 2.2. With the help of the active pitch system lower wind speeds can already produce energy and the cut-off wind speed can be increased. The downside is that the servomotor used in such a system needs energy as well, but the consumption is always smaller than energy won by the active control. For turning the blades electric or hydraulic systems can be used but the latter is employed more often.[16]

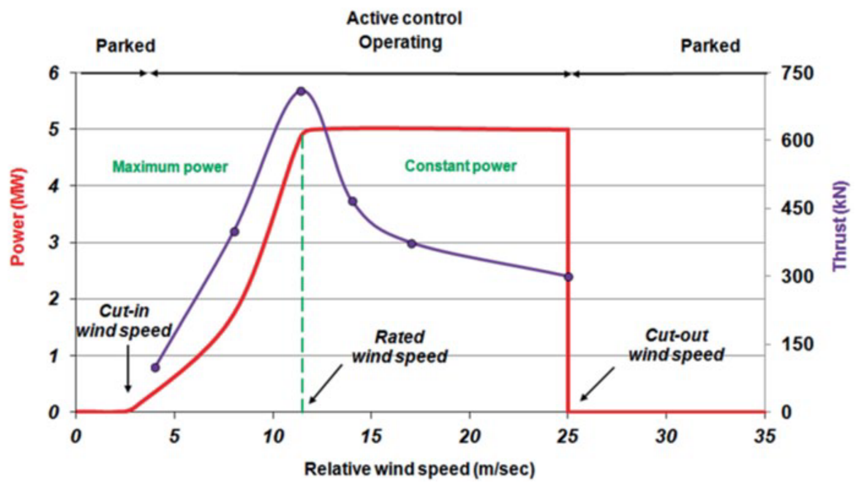

Figure 2.2: Power and thrust curves [16].

2.2.3 Main Shaft, Gearbox and Generator

The main shaft can also be called low-speed shaft because it is on the side of the gearbox with slower speed. As already mentioned, it is attached to the rotor on the one side and to the gearbox on the other. The first connection is not only for transmitting the torque from the rotor but also supporting its weight. The gearbox on the other side of the main shaft accelerates the rotational speed and drives the high-speed shaft with that speed. The gear of a wind turbine should not be imagined like the one used in cars. The main purpose for both is to change the speed of the rotation, but the ratio is constant in a wind turbine and does not need to be able to change as in a car gear. What kind of gearbox with what ratio gets used is dependent on the type of chosen generator. This ratio lies between 30 and 200. It is not uncommon that heating and cooling of the lubricant is creating problems in the gearbox. In extremely low winter temperatures and very high summer temperatures the lubricant can freeze or become to hot respectively and loose its functionality because of it. Depending on the site of the wind turbine adjustments have to be made for heating or cooling. The most common generator used for wind turbines is an ordinary induction machine. The purpose of a generator is to produce 60Hz AC electricity from the mechanic energy. In order to do that most electric machines need a rotational speed a lot higher than the slow one produced by the rotor. This explains the need of the previously described gearbox. The atypical aspect of wind turbine generators unlike most other generators used to produce power for the electrical grid is that it is powered with quite a varying torque. In order for the generator to work properly a cooling system has to be added. Often the generator is encased and cooled with a fan sometimes hydraulic cooled generators are used instead but the downside to this approach is that a radiator is needed in the nacelle.[16],[17]

2.2.4 Converter and Transformer

A converter is used to regulate the generator by managing the voltage at the stator or rotor of the generator. Current and rotational speed are measured and with that information the torque is computed. With voltage, current, rotational speed and torque the electrical and mechanical power of the generator are estimated and adjusted afterwards if needed. After the converter the transformer is used to convert the voltage of the turbine to the one of the collector grid (33 or 36 kV).[16]

2.2.5 Controller and Sensors

The controller observes the state of every part with sensors in and around the turbine. It uses that data to optimize the power production by managing the yaw system, the generator and the pitch system. Many different sensors are needed to do that correctly. Rotational speed of rotor and generator as well as the voltage/current of the generator to limit the loads if necessary. In case of a hydraulic cooled generator the hydraulic pressure is measured. In order to monitor the state of the gearbox sensors check its oil, windings and bearings temperature. For the operation of the pitch and yaw systems the pitch angle at each of the rotor blades, yaw angle, number of power cable twists and thickness of the brake linings are monitored. There is also a sensor to verify whether the tower door is shut or not. Sensing the size and frequency of vibrations in nacelle and rotor is also very important since that is one most hazardous reasons for a wind turbine to break down because it leads to fatigue loading of components as well as creating noise. A vibration sensor is made up of a ball sitting on a ring. Attached to the ball is a chain, that again to a switch which turns the turbine off in case of too much vibration. Parameters around the turbine that can have an impact to its functionality as well as lightning strikes and their charge, outside temperature, wind direction and wind speed are also monitored. For measuring the last two anemometers are used. Either a simple cup anemometer consisting of three cups around a vertical axis with a wind vane or an ultrasonic anemometer where phase shifts of high frequency waves are used. The electronics needed for all of this monitoring should be in a particular temperature range. For the oversight of staying in that range another temperature sensor is employed.[16],[17]

2.2.6 Yaw System and Tower

Upwind turbines have a yaw drive in place to be able to always turn in the direction the wind comes from. This is not the case with downwind turbines where a yaw system is not needed at all because the nacelle follows the wind passively. Occasionally it happens that the yaw drive turns the turbine in the same direction for a long time because of the way the wind changes direction. In that case the cables inside get more and more twisted till the cable twist counter reaches a certain number and signals the yaw system to unwind. The gears used to turn the turbine have to be greased for the system to work properly. The second aspect of the yaw system is that it functions as the link between the nacelle and the tower. There are three options for the tower material: tubular steel, concrete or steel lattice. The first is used the most and is cone shaped. The second is most suited for very high hub heights (>100 m). The third needs the least amount of material but this advantage can be outweighed by the amount of labor required in the manufacturing process. Therefore it is just used in countries with low labor costs.[16],[17]

2.3 Floating Substructures

For the first concepts of floating substructures the offshore oil and gas industry was used as an example. In its design a lot of very different aspects have to be kept in mind compared to its bottom-fixed counterpart. Floating substructures have six degrees of freedom and in order to keep it in place mooring lines have to be applied.[16] For this usually chains or cables are used. Those need to be fixed to the ground by some kind of anchoring. The only component listed above that has a price dependency on the water depth are the mooring lines. There are a few different kinds of loads a floating foundation has to be able to endure. They are illustrated in Figure 2.3. The rotor of the turbine has to withstand loads induced by the wind. The floating structure itself gets loads induced from waves, the ocean currents and the sea-level e.g. from tides. Other loads from the environment e.g. icing will be experienced from the turbine and the substructure. Failures of any component can also lead to loads as well as other incidental and miscellaneous loads from something else like the export cable. In order to resist those loads design measures are in place. Either the ballast, the buoyancy or mooring are stabilized with a slender vertical structure, hydrostatics or taut lines. The design will found on the strategy elected from above.[18]

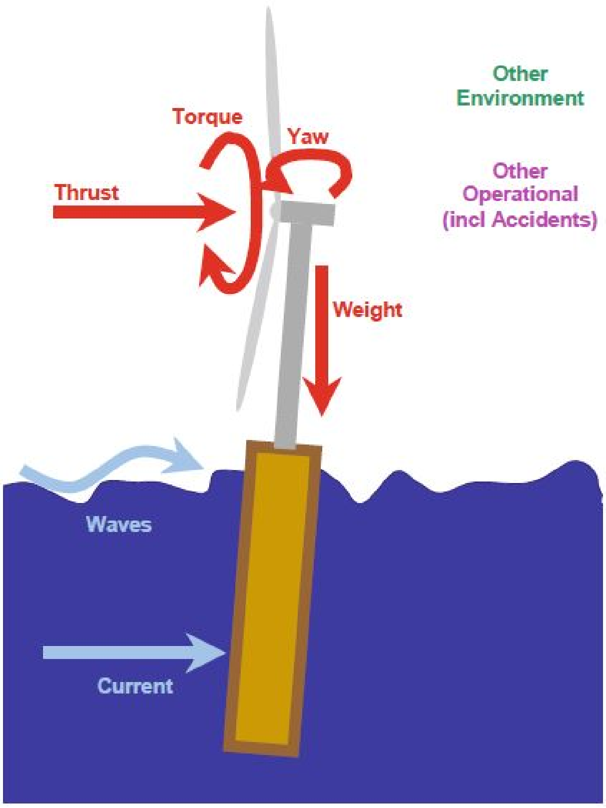

Figure 2.3: Loads on floating substructure [18].

2.3.1 Spar

A Spar is a ballast stabilized platform. This concept was first adopted in the offshore oil and gas technology. It was created to be used as a buoy to collect oceanographic data in the 1990s. Its composition and components can be seen in Figure 2.4. A spar substructure looks like a thin cylinder and contains ballast in the bottom made out of water, metal or concrete. Therefore, the center of gravity lies quite low this contributes to the stability of the structure and prevents pitch and roll rotations. The tower is either placed above the spar or they are one in a seamless transition. The main contributors to yaw motion are the aerodynamic loads that produce moments at the blades. The yaw motion at the lower part of the spar can be seen as trivial because of the symmetry of the design. The spar substructure design has a very small water plane area which leads to very little corrosion at water level.[19],[16]

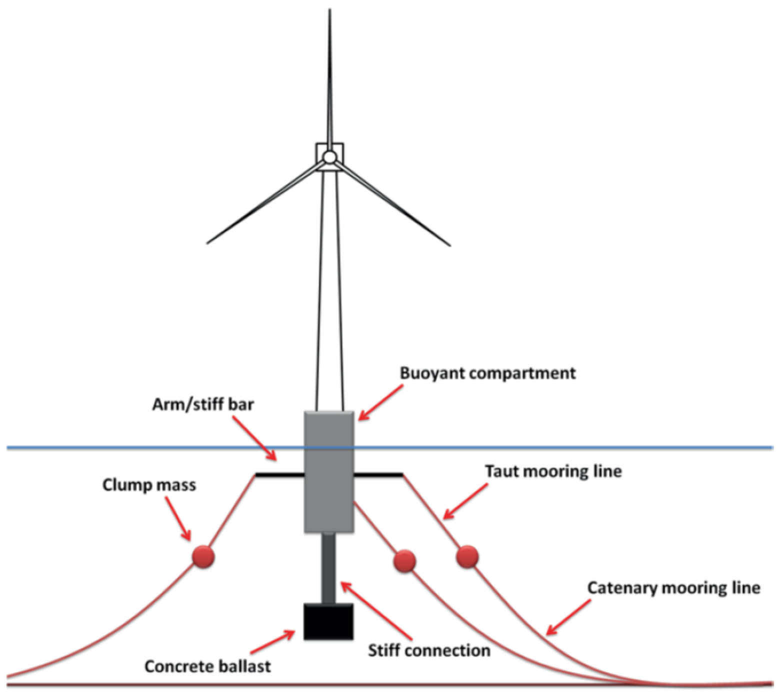

Figure 2.4: Spar substructure [16].

How long and how wide the spar should be for an optimal function depends on a few parameters: stability, vertical motion, pitching motion, cost and fatigue criteria. After taking all of those into account a small design window of width and length is left as illustrated in Figure 2.5. Attaching this kind of substructure to the turbine is rather difficult since very deep waters are needed. Therefore, the assembly needs to happen on-site most of the time which includes a horizontal tow-out and upending.[18]

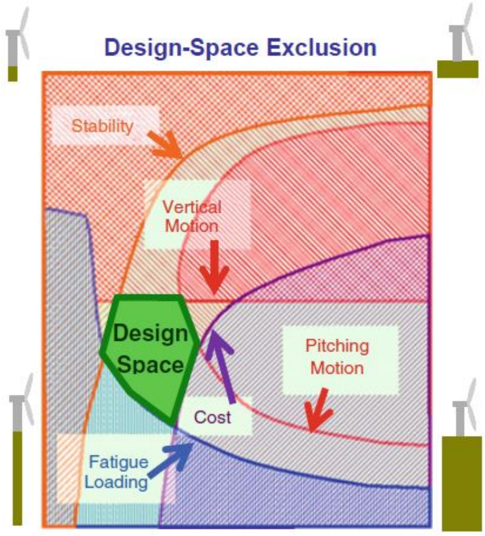

Figure 2.5: Design criteria for a spar substructure [18].

2.3.2 Tension-Leg Platform

A tension leg platform (TLP) is mooring stabilized with the help of the tension forces from the tendons used as mooring lines. This design was created for the oil and gas industry and was used to move into deeper waters with a rather cheap cost starting in the 1980s. A TLP substructure is made of a cylinder in the center where the turbine is placed on top and three to four arms where the tendons are connected to create some distance to the center column. The diameter of this column should be kept rather small because it decreases hydrodynamic loads. In order to do this, pontoons can be used instead of hard and rigid arms. The structure of a typical TLP is illustrated in Figure 2.6. This design does not have any buoyancy instead the tight tendons give the structure stability by pulling the platform further under water. It also limits the platforms movements which also decreases roll, pitch and heave but surge, sway and yaw movements do still occur. This makes the platforms behavior similar to a fixed structure and unable to adjust its vertical position which can be very problematic in case of high waves and tides. In areas with a lot of sea-level change a TPL platform is neither reliable nor save. The system cannot stay afloat on its own if the water level overreaches the design limit or a mooring line breaks the whole turbine will drown which results in catastrophic damage.[18],[19], [16]

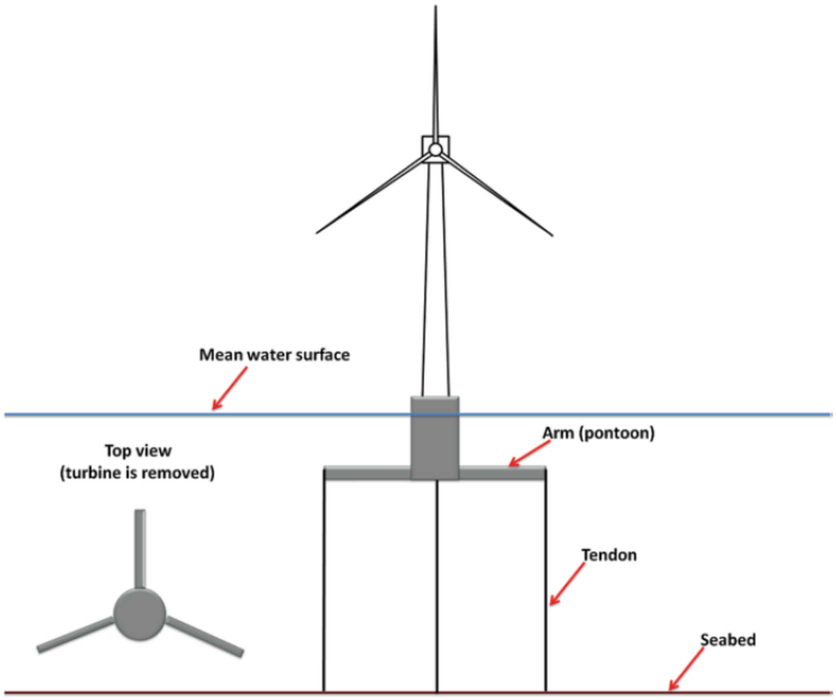

Figure 2.6: TPL substructure [16].

Because of the high importance of the mooring lines a special thought goes to the method of anchoring during the design process. Tension piles, gravity anchors or suction buckets can be used. The fact that it cannot stay afloat without its mooring lines make the installation more complicated. Usually the platform is ballasted while towed to the site and de-ballasted on site before its installation. All this makes some kinds of maintenance also more difficult. This design is cheap and light weighted but is rather suited for shallow water than deep sea.[19],[18]

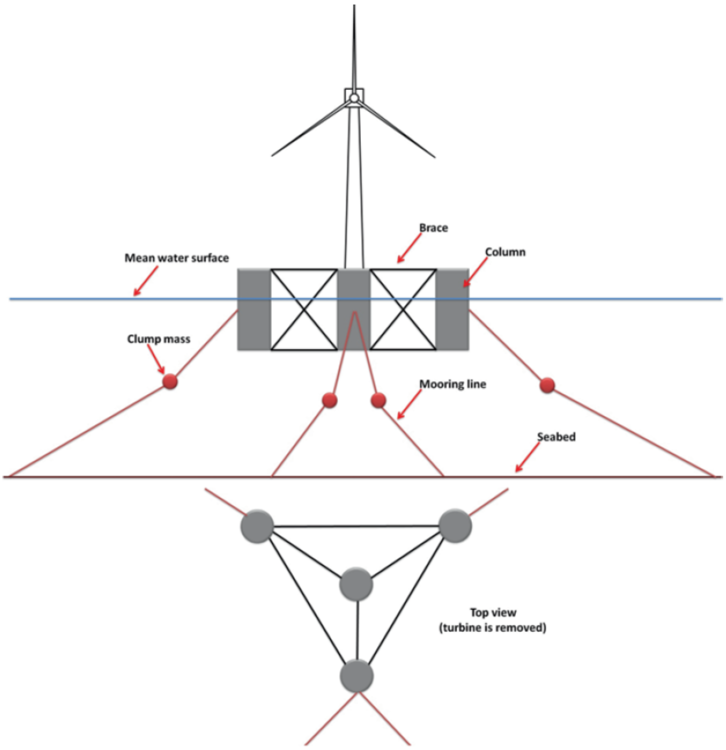

Figure 2.7: Submersible braces substructure [16].

2.3.3 Semisubmersible

The semisubmersible substructure is buoyancy stabilized. It is the oldest of the three types and was already used in the 1960s also in the oil and gas industry. This type of substructure is made up of columns linked with pontoons and braces. Its structure is illustrated in Figure 2.7.[19] The design gains its stability with the help of the Archimedes' law where the buoyancy force keeps it stable. According to Archimedes' law, buoyancy is equal to the weight of the liquid being displaced [20]. There are few design parameters that can be changed in this type of substructure. The number of columns can be chosen to be three or four and its shape can be rectangular or cylindrical. The position of the turbine which can be placed in the middle or on top of a column. There is also the possibility to add heave suppression discs at the base. The arrangement of the mooring lines can be differed in number and placement. An important role for the mooring lines is the structure in place in terms of yaw, surge and saw motion and at the same time not to stiff to avoid problems like at a TPL platform. The installation of a turbine with a semisubmersible substructure is a lot less problematic than in the other two designs since the structure can be towed to its destination. Which means that the whole structure can be assembled onshore which saves costs. But the construction itself is rather complicated to the point where the fabrication cost is higher than the cost of material.[16],[19],[18]

3 Floating Wind Farm Projects

In Europe many floating wind farm projects are already commissioned or planned. Most of them are demos. In this chapter three of them are analyzed. The first is Hywind which has a demo version in Norway and a full scale wind farm in Scotland. The second is WindFloat which also has a prototype and a full scale wind farm. And the third one is Seatwirl which is a project for small scale application.

3.1 Hywind

The origin of this project lies with the company Statoil which is a Norwegian oil and gas company. They changed their name in 2018 to Equinor to represent their move from oil and to include wind and photovoltaics production. They used their knowledge from floating offshore oil and gas platforms for their floating wind platform design.[21]

3.1.1 Hywind Demo

From having the idea for the project till its commission in 2009 it took almost a decade. The turbine was deployed with a distance to shore of 10 km in Norway close to Karmøy in a water depth of 200 m. This design uses a spar substructure with steel as material. The ballast used in the spar is gravel and water. The used turbine was from Siemens and has 2.3 MW. The dimensions of the other parameters of the structure are displayed in Table 3.1. The diameter of the spar is smaller above than below the water surface in order to have less wave action. The mooring system consists of three mooring lines with drag embedded anchors. The third mooring line is for redundancy reasons the system would still be held in place by two mooring lines in case of one breaking. The deep-water fjords of Norway are perfect for the assembly of wind turbines with a spar substructure. Such a fjord was used for the construction of the nacelle and the rotor. The turbine was towed by tugboats to the destination site. The wind turbine is still generating power for the grid even though the test program was just supposed to run 2 years. In 2011 it reached a capacity factor of 50.1% after predictions for the project were 39%. It was prognosed for the turbine to have an annual production of 7.9 GWh. Between 2009 and 2014 it reached 7.6-10.1 GWh. Over the years it endured many extreme weather situations where the fastest wind speed measured was 40 m/s and the highest wave height was 19 m with no major incidents. It also did not need more unscheduled maintenance than fixed turbine structures. Now it is used as a testbench for high-voltage underwater cables after being sold to Unitech in 2019 while still producing enough energy equivalent to 400 households each year for the grid.[21],[18],[16]

Description	Hywind Demo	Hywind Scotland
Turbine nameplate capacity	2.3 MW	6 MW
Hub height	65 m	98 m
Rotor diameter	82 m	154 m
Operational draft	100 m	78 m
Displacement	5 300 m^3	11 200 m^3
Water depth at site	200 m	95-129 m
Substructure diameter submerged	8.3 m	14.5 m

Table 3.1: Comparison Hywind Demo and Hywind Scotland [18].

3.1.2 Hywind Scotland

After the success of the Hywind Demo the next step was to move up in scale for the first commercial floating wind farm Hywind Scotland which went operational in 2017. The concept of the wind farm is illustrated in Figure 3.1. It consists of 5 x 6 MW turbines in order to power 20,000 households. Its distance to shore is 25 km with a water depth of 95-120 m near Peterhead. The average wind speed at this location is 10 m/s. The design principle is the same but the dimension of the turbines are a lot bigger than in the demo version which can be seen in Table 3.1. The concept of one turbine is shown in Figure 3.2. The material used for the mooring lines was steal. For stability 60 tonne weights were used at each of the mooring lines.[21],[18]

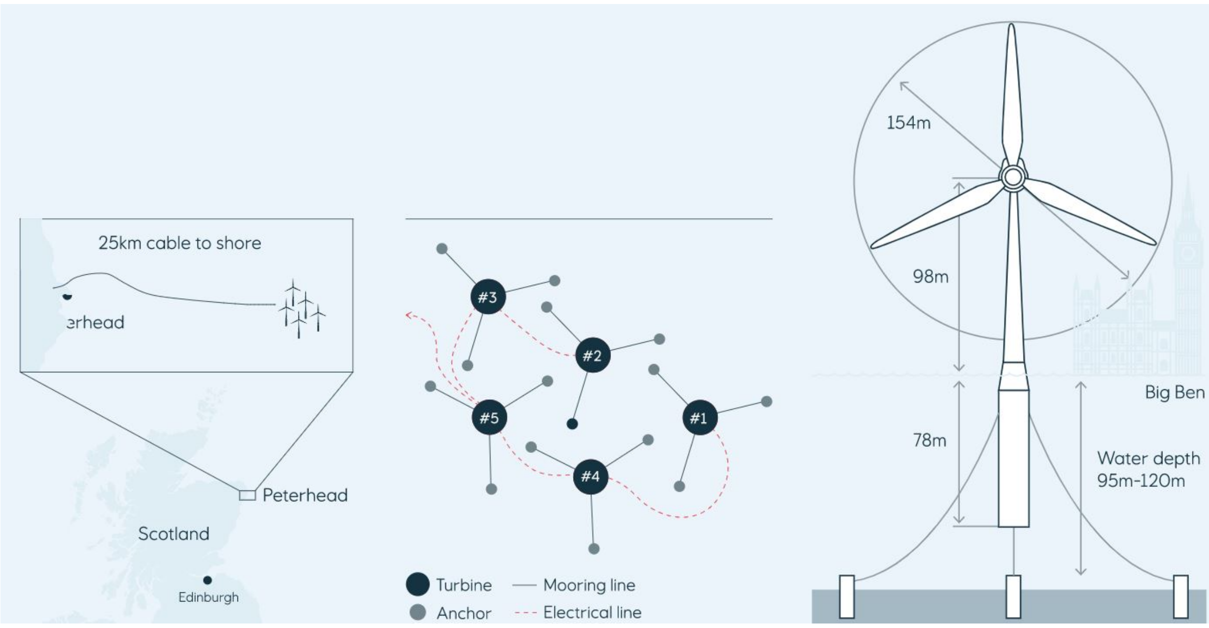

Figure 3.1: Concept of the Hywind Scotland wind farm [21].

Equinor was able to reduce the cost compared to Hywind Demo by 60-70%. Both projects benefited a lot by the offshore expertise in oil and gas of Equinor. It enhanced reliability of components and made marine vessels and electrical infrastructure cheaper and more efficient. Some problems on the other hand are very specific for deep-sea offshore wind turbines like maintenance on site, mass production of substructures and finding the right anchoring systems. At winds faster than the rated wind speed problems with resonant pitch motions can occur in the tower this is counter acted by a control algorithm with active damping as well as with an active floater control system. Like at the demo project the turbines can be towed to shore for maintenance but a deep enough dock at the port is needed. This decreases downtime and makes maintenance cheaper but at this point in time is still quite more costly than for bottom-fixed structures. The problem with mass production is not solved as well. Currently the logistics are not figured out yet in order to produce spar substructures at large quantities. But despite having a few "Childhood diseases" the commission of the first floating wind park was a success after having a capacity factor of 65% in its first three months. It had to shut down twice due to two heavy storms hurricane Ophelia and storm Caroline during that time but still managed to have such a great capacity factor.[21],[18],[22]

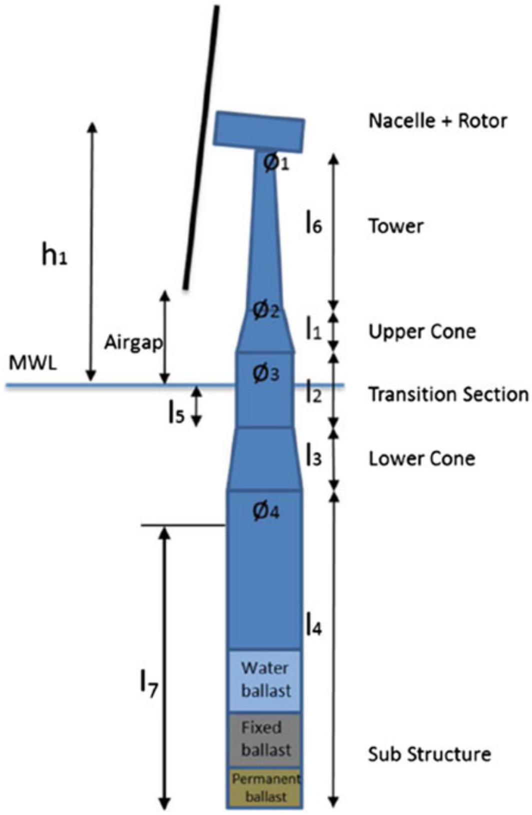

Figure 3.2: Structure of a turbine in the Hywind wind farm [18].

3.2 WindFloat

The WindFloat turbine has a semi-submersible substructure with three columns. The turbine is placed on top of one of them. The idea of the design is to decrease the cost by making the structure less complicated and having a simple fabrication process. At the base of the columns water entrapment plates are used to decrease the turbines movement in the waves while making the structure itself lighter. This design detail shows the commitment to get the best power to weight ratio possible. The mooring system is kept quite simple as it consists of drag embedment anchors, offshore grade chains and cables. Those are conventional mooring components which makes them inexpensive and accessible. The installation process of the mooring system is rather simple and only involves surface vessels which makes the price of this system not very dependent on water depth. The turbine with its substructure is very stable which makes it possible to compile the structure onshore or at a port. Therefore, no specialized lifting cranes are needed. When assembled the turbine can be towed to its destination. It is also rather simple to remove mooring lines and electric cables after installation in order to tow it back to shore for maintenance. This process has a lot of advantages it decreases the OPEX and increases the overall production and capacity factor. The WindFloat project has three phases which can be seen in Figure 3.3. In the following paragraphs Phase 2 and Phase 3 are elaborated.[18]

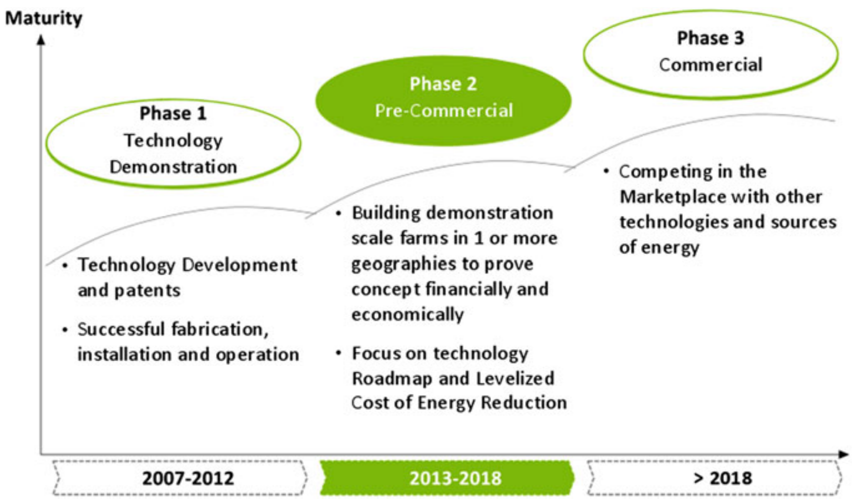

Figure 3.3: WindFloat plan [18].

3.2.1 Windfloat Prototype

The WindFloat prototype is called WF1 and can be seen as schematic and in a photograph in Figures 3.4 and 3.5. It has a distance to shore of 5 km and a water depth of 45 m. The prototype was deployed of the coast of Aguçadoura, Portugal in 2011. The turbine has a capacity of 2 MW. The prototype generated energy uninterrupted till 2016 operating through storms with a wave height up to 20 m. It was the first full-scale wind turbine of its substructure kind to go on grid and first offshore wind turbine in the open Atlantic waters. Compared to a reference turbine with a fixed substructure the energy output was the same which leads to the conclusion that the floating substructure does not have an impact on the power production.[23],[18]

Figure 3.4: Prototype schematic [18].

Figure 3.5: WindFloat prototype [18].

3.2.2 Windfloat Atlantic Wind Farm

The Windfloat turbines are able to resist waves up to 17 m high and wind speeds to 30 m/s. The windfarm consists of three turbines which are 50 m apart from each other. Owned by the Windplus consortium is deployed at a distance to shore of 20 km and a water depth of 100 m in Viana do Castelo. It has a total height of 190 m which consists of the base, the tower and the rotor. The rotor itself has a diameter of 164 m. The wind turbine is designed to be towed by a standard towing craft which helps to decrease installation and maintenance costs. The three turbines were assembled in July 2019 by standard onshore cranes at the port on land. The first turbine was towed and installed in October 2019 followed by the second in December. The first was connected to grid at the end of the December. Its capacity is 8.4 MW which makes it the world's largest installed on a floating platform. The third turbine was towed to its destination in May 2020. A picture of the whole wind farm is illustrated in Figure 3.6. When all three turbines are on grid the wind farm will have a capacity of 25 MW.[23],[24]

Figure 3.6: WindFloat wind farm [24].

3.3 SeaTwirl

The design of the SeaTwirl wind turbines has a vertical axis which makes it different than all the other wind turbines discussed so far. It is linked to the substructure by a tower. The substructure itself is similar to a normal spar like structure with a keel at the bottom filled with ballast. The generator is placed in its own shell around the tower close to the water surface beneath the turbine which makes it easily accessible therefore decreases maintenance costs. The whole structure is held in place by several catenary mooring lines. The whole concept of those turbines is shown in Figure 3.7 taking the S2 as example. Vertical turbines do not need a yawn system because for power production it does not matter from which direction the wind blows. At a wind farm where turbines with a horizontal axis are used the spacing is very important in order for them not to decrease each other's power output. This is not the case with vertical axis wind turbines. Close spacing has the opposite effect the flow interaction can increase the energy production. Another aspect of SeaTwirls design is the ability to store rotating energy which helps to have less intermittent energy production.[25]

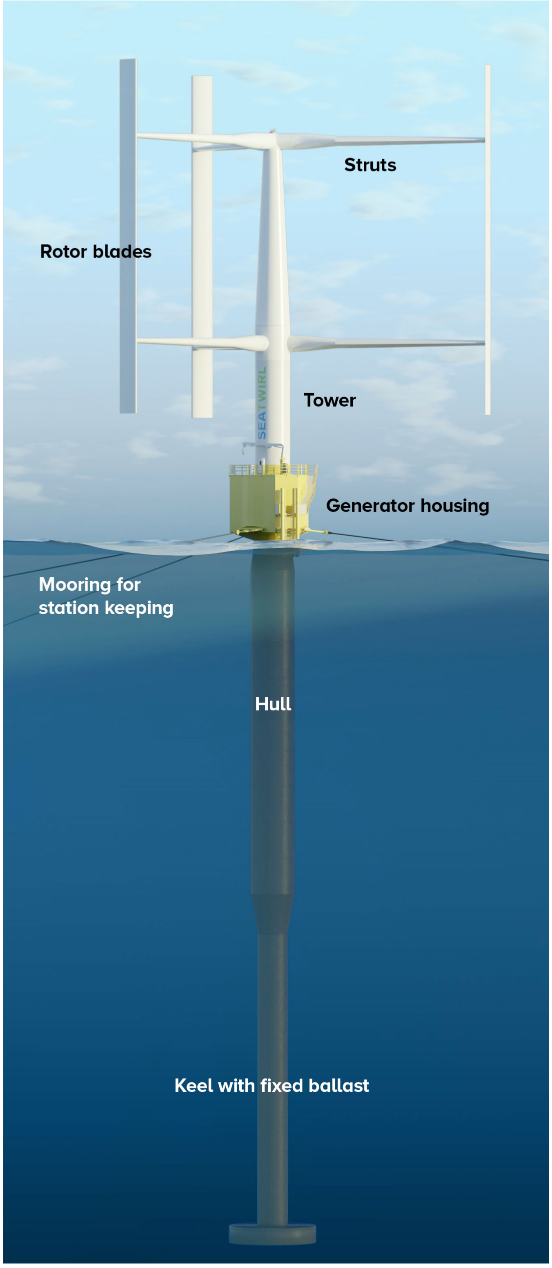

Figure 3.7: SeaTwirl concept with the S2 as example [25].

3.3.1 Sea Twirl S1

In 2015 the SeaTwirl concept model S1 was deployed of the coast off Lysekil, Sweden at a water depth of 35 m. It is shown in Figure 3.8. The turbine has a capacity of 30 kW. Its height is 13 m above and 18 m below water. The S1 has a turbine diameter of 10 m. The prototype resisted wind speeds at hurricane level. The idea behind this concept was to create a wind turbine for harsh weather conditions and a low budget. The small-scale design was thought to be a good alternative to diesel generators in remote areas.[25]

Figure 3.8: Seatwirl prototype S1 [25].

3.3.2 Sea Twirl S2

The S2 wind turbine is meant to be a version of the S1 with more capacity. It is supposed to be launched in 2021 with a capacity of 1 MW. It is a lot bigger with a height of 55 m above and about 80 m below water level. The diameter of the turbine is going to be 50 m and the height of the rotor blade about 40 m. The plan is to deploy it in water depth of 100 m or deeper. The turbine is going to have a cut-off wind speed of 25 m/s but is able to withstand wind speeds up to 50 m/s. An illustration of the S2 is shown in Figure 3.9.[25]

Figure 3.9: Seatwirl type S2 [25].

4 Specific Investment Costs

The measure used to analyze the specific investment costs of deep sea offshore wind farms is the Levelized Cost of Energy (LCOE). Equation 4.1 describes the precise version of the formula including cost of capital [26]. The simplified form of it is depicted in Equation 4.2 [27]. The LCOE can be divided in three parts: capital expenditure, operating costs and decommissioning costs.

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}} \tag{4.1}$$

$LCOE$ .... Levelized cost of energy in €ct/kWh
I_0 .... Capital expenditure (CAPEX) in €ct
A_t .... Annual operating costs (OPEX) in year t
M_{el} .... Produced electricity in the corresponding year in kWh
i .... Weighted average cost of capital (WACC) in %
n .... Operational lifetime in years
t .... Individual year of lifetime (1,2,... n)

$$LCOE = \frac{CAPEX + OPEX + DECEX}{AEP} = \frac{\text{cost over lifetime}}{\text{produced energy over lifetime}} \tag{4.2}$$

$LCOE$ .... 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

4.1 Capital Expenditure

The capital expenditure (CAPEX) are all the costs that occur before the wind farm is commissioned. The different cost components it is made of are shown in Figure 4.1. The methodology of the potential simulation is based on Cavazzis 2016 paper [28]. In Table 4.1 its CAPEX breakdown of offshore wind farms in general is compared with Maienzas 2020, [27] paper that analyses deep sea offshore in particular.

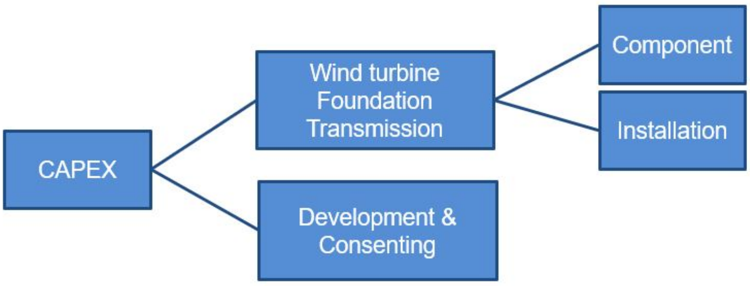

Figure 4.1: Capital costs of an floating wind farm [27].

4.1.1 Wind turbine

The turbine cost in a wind farm is proportional to the rated power per turbine and the number of turbines. This means as turbine sizes grow with 12 MW turbines supposedly getting on the market next year the capex grows with it. Since a lot of other cost components are dependent on the turbine size as well e.g. foundations. The upside to this is that larger turbines lead to a smaller number of turbines per wind farm which decreases O&M and installation costs. Overall an increasing turbine size results in a decrease in LCOE. The wind turbine market is not very competitive. With Siemens and Vestas holding the vast majority of the market share as is shown in Figure 4.2. For this reason, the price of offshore wind turbines is not going down as fast as it would have with more competition in the market. This however seems to change as more companies mostly Asian start gaining market share.[7],[29],[12]

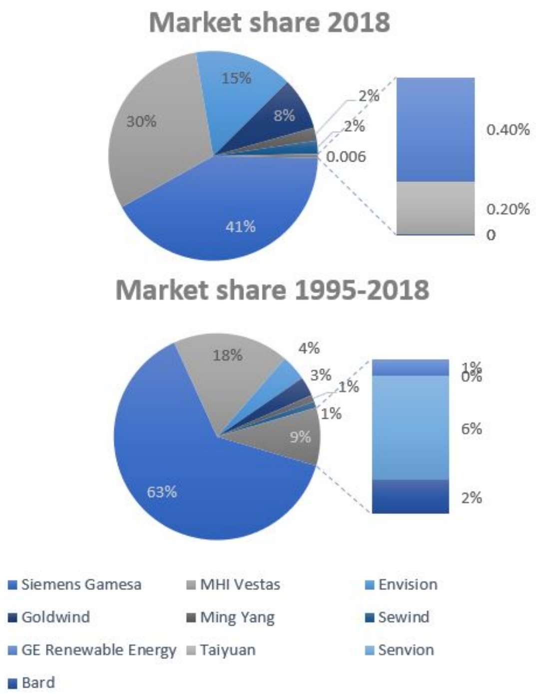

Figure 4.2: Market share of offshore wind turbine producers [7].

4.1.2 Foundation

The most expensive part of floating foundations is the floating platform (see Table 4.1). The cost of a floating platform depends on the type with semisubmersible being the cheapest and the tension-leg platform the most expensive. Spar type platforms are just a little bit cheaper than tension-leg. The expenditure for mooring lines is dependent of the substructure as well because this determines the number of mooring lines needed. Other price factors are the number of turbines the wind farm has and the water depth. The price of anchoring is also dependent on the number of mooring lines and turbines but also on its own weight.[27] The overall price dependency of the whole foundation on the water depth can be seen in Figure 4.3. Here the calculation from Cavazzi in 2016 and Bosche in 2020 are illustrated. In the newer estimation its dependency is smaller as is the price itself.

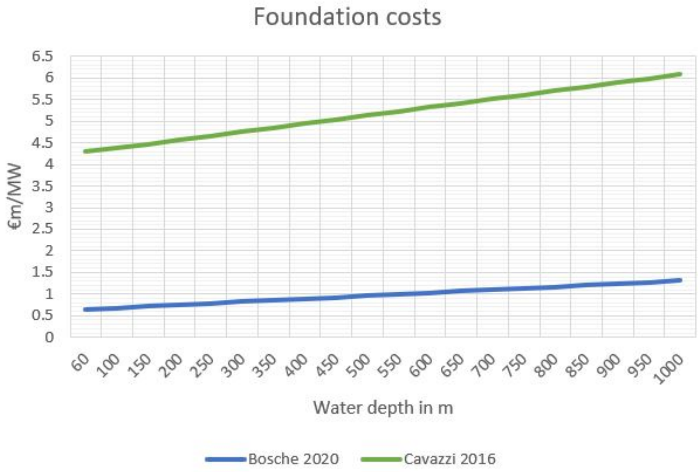

Figure 4.3: Foundation cost comparison [30],[28] .

4.1.3 Transmission

The transmission system can be seen as all electrical components between the wind turbines and the connection the grid onshore. Figure 4.4 gives an overview of its structure. The wind turbines are connected by array cables to the offshore substation. The price of these cables is determined by spacing and number of the turbines. Depending on whether the chosen export cable technology is HVAC or HVDC the substation is a DC/AC or DC/DC converter that transforms the voltage to a higher level. This is necessary in order to stabilize the voltage and decrease electrical losses. The expenditure of an offshore substation depends on the total installed power of the wind farm.[31],[28],[27]

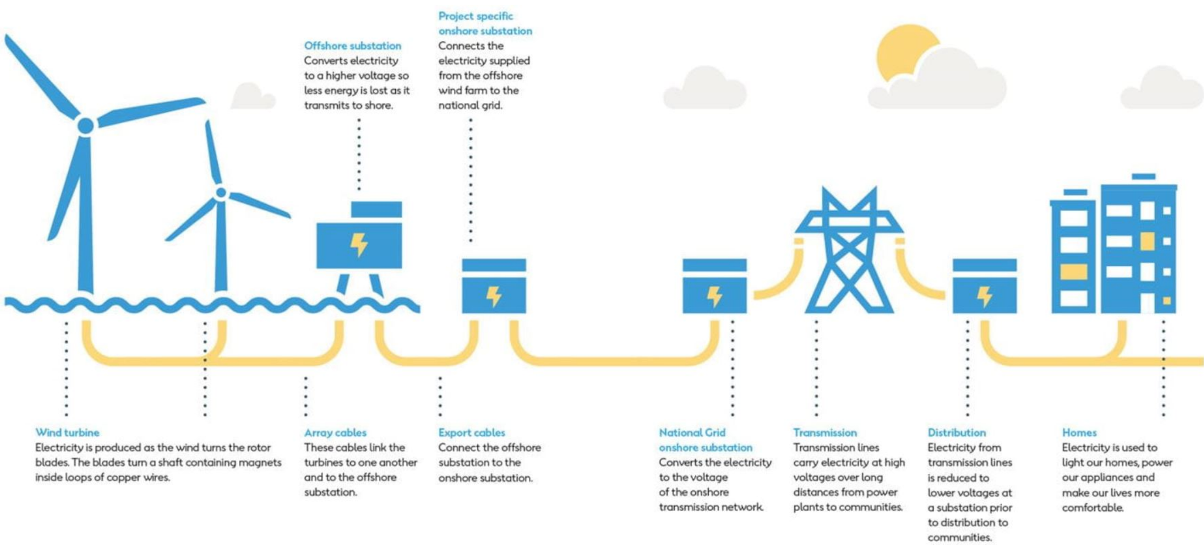

Figure 4.4: Transmission system of an offshore wind farm [32].

The export cable technology is contingent on the distance to shore. The capability of HVAC decreases due to dielectric losses but is cheaper for wind farm closer to shore. The particular distance it is more inexpensive to use HVDC is project dependent and determined by the capacity of the farm, the number of cables needed, converter costs and technology. This is usual around 50km as illustrated in Figure 4.5. The export cable leads to an onshore substation where the voltage is transformed to the voltage of the local grid and in case of an HVDC cable from DC to AC. The cost of the onshore substation is about half of the offshore counterpart. The last step is the connection from the onshore substation to the local grid. How much has to be paid to the TSO to integrate the farm to the grid depends on regional regulations.[7],[27],[30]

Figure 4.5: Comparison of transmission costs HVAC vs. HVDC [30].

4.1.4 Installation

Installation cost is tough to calculate because it is determined by many factors with quite fluctuating values. The transportation of the components is dependent on distance to shore. The turbine installation depends on the number of lifts needed to place hub, nacelle and rotor on top of the tower. This is contingent on the installation tactic which in case of a floating substructure usually done in one lift. The installation process of the different floating foundation types has already been discussed in Chapter 2.3. The most expensive substructure type is TLP which costs almost four times more to install than the other two. Spar is just a little more expensive than semisubmersible. When it comes to placing mooring lines and anchoring TLP is again the most costly. This time the semisubmersible is just a little cheaper and for a spar substructure it is more than halve as expensive than for a TLP. The installation for the array and export cable uses cable laying vessels or combination of tugboats. The cost of this depends on the distance to shore, the number turbines that need to be connected by the array cable and the installation rate. For the whole installation expenditure the day rates of vessels and equipment, labor cost of the crew and the fuel cost fluctuations play a part as well.[27],[12]

4.1.5 Development and Consenting

Development and consenting costs start with an environmental and seabed survey. Then a met mast is installed in order to measure the wind conditions on site. More than half of the cost goes towards project management and development services. And the rest are expenses for front-end engineering and design. Altogether this part of the CAPEX is mostly dependent on the number of turbine in the wind farm which is illustrated by Figure 4.6.[31]

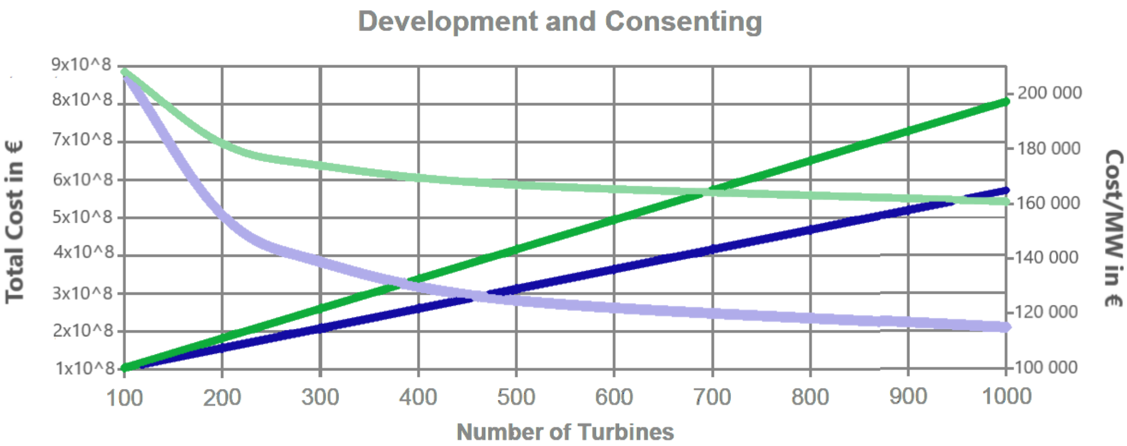

Figure 4.6: Cost of Developement and Consenting: total cost Bottom-fixed(dark green) and Floating(dark blue) on the left y-axis and cost per MW Bottom-fixed(light green) and Floating(light blue) on the right y-axis [31].

	Cavazzi 2016	Maienza 2020
Turbine	**33%**	**41.4%**
Nacelle	11%	
rotor	22%	
Foundation	**16%**	**34.7%**
Floating platform		26.2%
Mooring lines		8.3%
Anchoring		0.3%
Cables	**5%**	**3.5%**
Array cables		1.8%
Offshore export cable		1.5%
Onshore cable		0.2%
Substation and electrical	**10%**	**5.7%**
offshore substation	7%	3.8%
onshore substation		1.9%
other electrical	3%	
Installation Turbines	**9%**	**0.2%**
Installation foundation	**7%**	**3.5%**
Floating platform		1.2%
Mooring lines & Anchoring		2.3%
Installation cables	**9%**	**9.6%**
Array cables		5.5%
Offshore export cable		2.5%
Onshore cable		1.6%
Installation substation and electrical	**1%**	**1.5%**
offshore substation	1%	1.2%
onshore substation		0.3%
Tower	**6%**	
Development	**4%**	
environmental survey	0%	
met mast	0%	
seabed survey	1%	
developement services	3%	

Table 4.1: Comparison of CAPEX percentage distribution between Cavazzi,2016 and Maienza,2020 [28],[27].

4.2 Operational Expenditure

Operational expenditures are costs that have to be paid during the time the wind farm is operational. A major part of it consists of labor, vessel and port costs and is dependent on location (country), distance to shore or suitable port respectively but also on the meteorological ocean climate at the site. The cost can be split between operational and maintenance cost as illustrated in Figure 4.9.[33],[30]

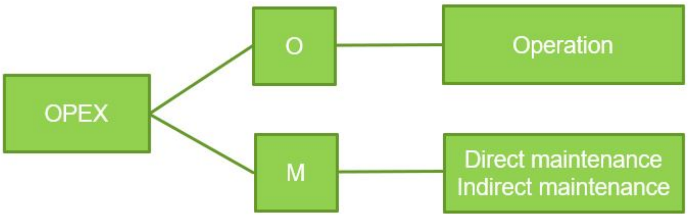

Figure 4.7: Operational cost of a floating wind farm [27].

4.2.1 Operation costs

The operational costs can be divided between seabed rental, insurance and Grid access fees. The first factor is very different for every site. The user rights for the area is usually auctioned off to the highest bidder which makes excellent sites quite expensive. The cost for insurance depends on the project size. Grid access fees have to be paid to the grid owner for feeding-in in their grid.[12]

4.2.2 Maintenance costs

The first part of maintenance cost is direct maintenance. This can be divided in preventive and corrective procedures. Preventive measures are to evade breakdown of components and therefore downtime. It involves planned maintenance like scheduled replacement and inspection of components. Corrective maintenance becomes relevant when something is already broken and needs to be fixed. Since preventive measures are a fixed cost but cheaper than corrective maintenance the risk of some part breaking always needs to be evaluated. This comparison is illustrated in Figure 4.8. Indirect maintenance is the second part which are all the costs around the actual maintenance activities including port fees for putting aside spare parts, vessel hiring as well as planning and managing the maintenance.[27],[12]

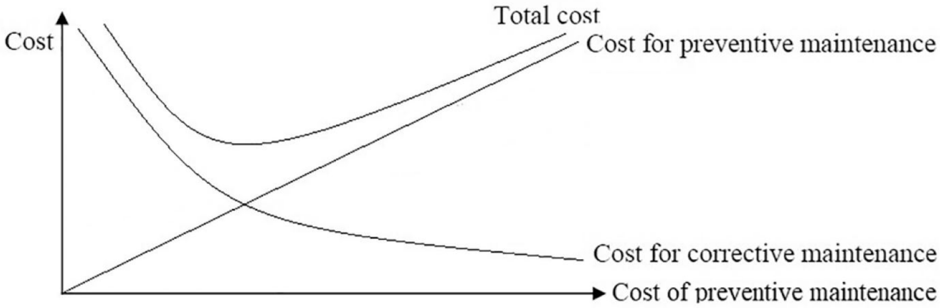

Figure 4.8: Preventative vs. corrective maintenance in cost [27].

4.3 Decommissioning Expenditure

The decommissioning expenditures include all the cost at the end of the lifetime of a wind farm after it went out of operation. The wind farm and its components have to be removed in a fashion that conforms with local regulations. The decommissioning expenditures can be described as a percentage of the installation costs:

- Floating system 70% of installation cost
- Cables 10% of installation cost
- Substations 90% of installation cost
- Mooring and anchoring 90% of installation cost

The cost of clearing a floating turbine from the site is a lot cheaper than at a bottom fixed structure because the effect on the seabed is much lower. After taking down the wind farm the scrap materials can be sold.[27],[30]

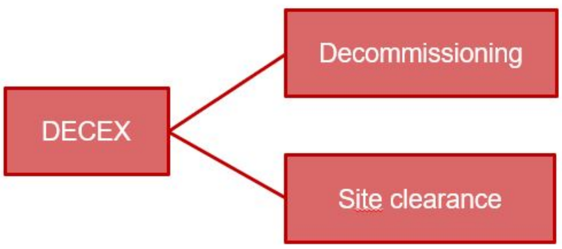

Figure 4.9: Decommissioning cost of a floating wind farm [27].

4.4 Levelized Cost of Energy - Literature Comparison

After analyzing the different cost components of a deep sea offshore wind farm Figure 4.10 shows the LCOE comparison to a bottom fixed structure. The cost of both types is illustrated as a function of water depth and distance to shore. It clearly depicts the strong dependency of the bottom fixed wind farm on both factors compared to small dependency of floating platforms.

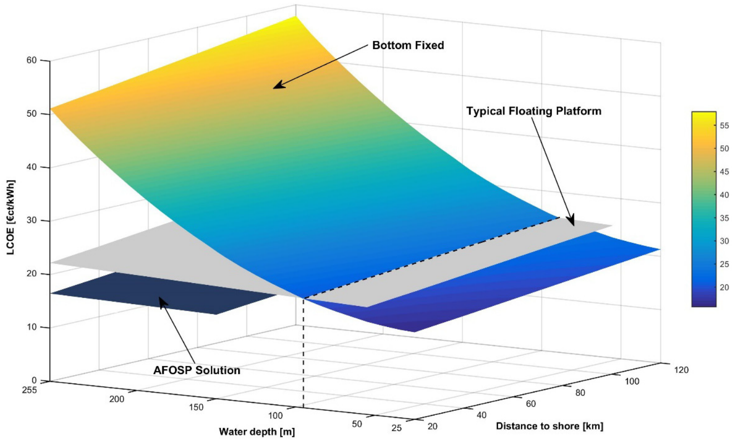

Figure 4.10: LCOE of bottom fixed and floating wind turbines as a function of water depth and distance to shore [29].

In Figure 4.11 a overview of LCOE calculations in literature was established. The turbine used in the reference wind farms was around 5 MW with the exception of Bosch,2020 [30] who used an 8 MW turbine which probably plays a big role why it is the lowest calculation with 6.26 €ct/kWh. In general can be said that the overview shows the price decrease over the years because the more recent literature computed the lower LCOEs.

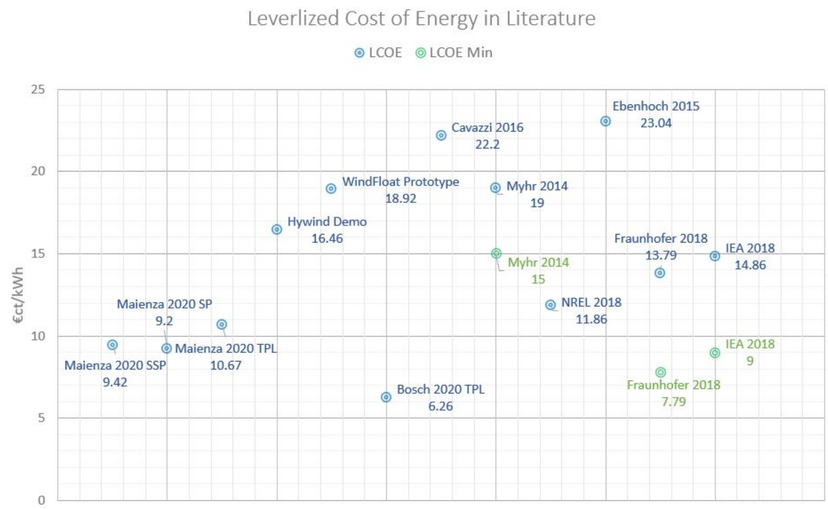

Figure 4.11: LCOE in Literature [27],[30],[28],[31],[29],[26],[33],[7].

Offshore wind energy is still more expensive than energy produced from other source with the exception of gas and biogas as can be seen in Figure 4.12. The marked purple area is the LCOE range of floating offshore found in literature from 2018 and younger.

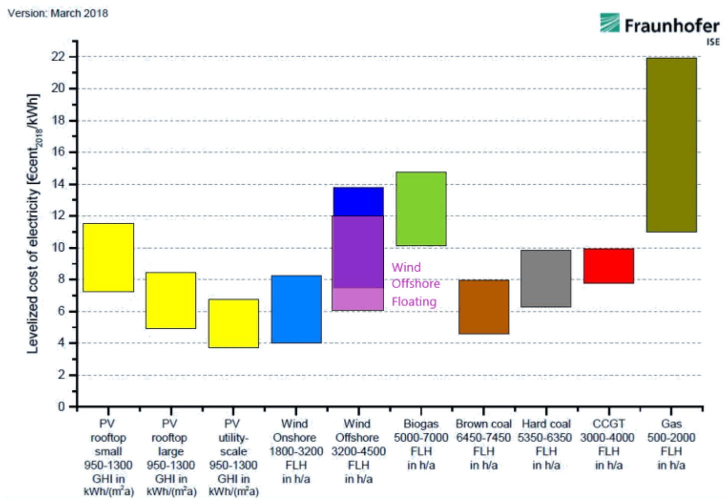

Figure 4.12: LCOE of different energy sources [26].

Figure 4.13 shows the cost differences between the three types of floating substructure conducted in 2020 by Maienza. The platform type with the highest CAPEX is TLP due to the price of the floater itself. The OPEX is the same for all three. TLP has the most expensive decommissioning cost as well because of the high installation expenditure. In conclusion this makes TLP the most expensive and semisubmersible the cheapest type.[27]

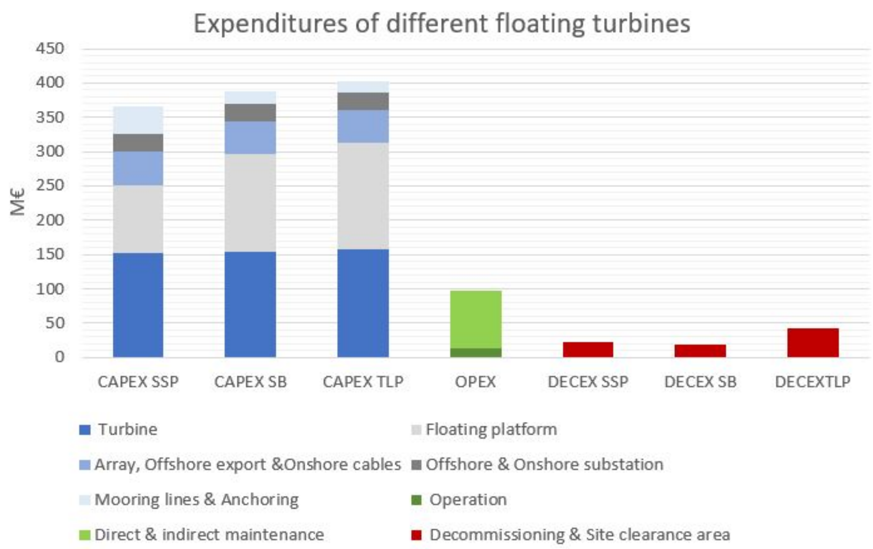

Figure 4.13: Comparison of expenditures from floating turbines with different substructures [27].

5 Outlook

In offshore wind industry is expected to continue to grow in the coming years. New markets will emerge, and new companies will enter them. An increasing number of oil and gas companies will enter the industry in order to stay relevant in a time where fossil fuels are cut back as much as possible. This will help with getting the cost down since it makes the market more competitive. Investing in offshore wind energy will become decreasingly risky and more often done by private investors. The wind turbines continue to grow in capacity. While today the offshore wind sector is still heavily subsidized the need for this will decrease in the next couple years making the industry more self-sustaining. Offshore wind has the chance to more and more compete with nuclear energy and fossil fuels.[7],[12]

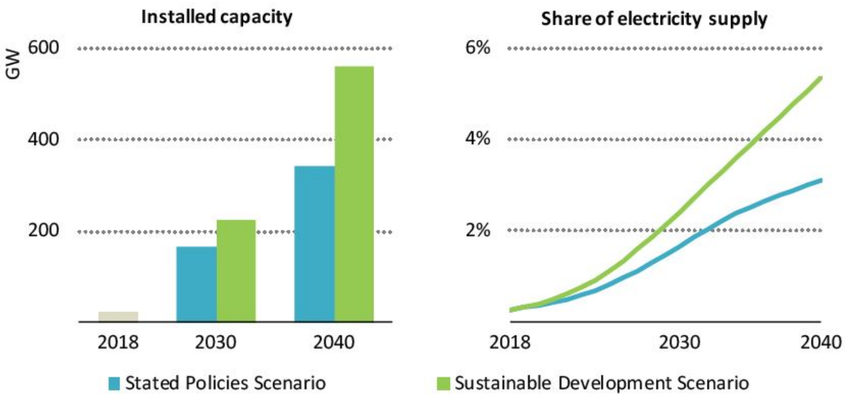

Figure 5.1: Predicted installed capacity and share of electricity supply [7].

The capacity factor is predicted to rise to 60% in Europe till 2040 while the LCOE is supposed to decrease. The forecast for capital expenditure is a price fall to 1.71 M€/MW by 2040. O&M costs are assumed to drop from 81 k€/MW in 2018 to 45 k€/MW in 2040. Digitalizing parts the O&M process like new monitoring techniques or visual inspections via drones makes it cheaper. The global average LCOE is supposed to decrease 60% in 2040 compared to 2018. Offshore wind energy will become a bigger part in the energy mix of many countries with the prediction of 560 GW installed capacity in a sustainable development scenario and more than 300 GW in the stated policies scenario. This would result in 5% and 3% respectively of the global electricity supply as illustrated in Figure 5.1.[7],[12]

5.1 Challenges

Despite the great predictions for the next few decades the sector still has some challenges to overcome.

5.1.1 Public Acceptance

For decades the wind energy industry just neglected public acceptance in the wind farm developing process. The reason for this was when renewable energy was emerging in the 1980s a survey determined that the public is in favor of wind energy. After that approval was just always assumed but this had to change in recent years. Public acceptance issues resulted in projects getting delayed or not being realized at all in the past. This is a bigger problem with onshore development, but the offshore wind industry had to learn as well that the public opinion has to be considered. The research on this topic showed that consent towards renewable energy in general often does not correlate with support to a specific project that is nearby. The cause mostly made responsible for this is "not in my back yard" theory where people support technologies as long as they are not developed close to them. But in the last couple years more and more experts suggest that this over simplified opposition in the public. Experience has revealed that there is less opposition if the public is well informed and invest in the project themselves. This is implemented in most wind energy projects in Denmark where a large percentage of offshore wind farms are partially or fully owned by private cooperative. This financial profit for the local communities increases the general public acceptance. There are also other approaches to get the public on the side of the development like including the local community from the early planning stage and also implementing some of their recommendations. In all strategies with a lot of public involvement there is a chance that all the attention on the project turns into a big discussion. This could lead to the strict opposition using it to stall the project. In general can be said that public acceptance improves once the wind farm is installed given that no major incidents happened until that point.[12],[34]

5.1.2 Environmental Impacts

Offshore wind energy needs less fossil fuel than most energy sources and almost no water during the production process [35]. The negative effect it has on the environment around it is not fully understood yet but seen as possible. A positive impact that has been observed by researchers in Denmark is that foundations are used as refuge from fish which had a positive effect on its population. The risk of endangering birds by them colliding with the rotor blades has been a concern of wild live protection groups for a while. The actual number of birds dying due to wind turbines has to be seen in relation. Taking Denmark as example: The country produces a large percentage of its electricity with wind energy and because of that about 30 000 birds die each year. Comparing this number to the one million bird deaths caused by traffic it seems less critical. The greatest cause of bird deaths however are cats where in the UK 55 million birds get killed by cats each year.[7],[36] Nevertheless, researchers are trying to reduce death rate caused by wind turbines. It seems in general that the reason for birds crashing into the rotor is that it spins to fast for the birds to spot the blade in time. In Norway where a study showed that painting one of the blades black helps the birds to detect it results in 70% less deaths [37].

5.1.3 Supply Chains and Component Failures

A problem in the offshore wind industry has yet to overcome is the issue of efficient supply chains which decreases project risk and cost. In order for this to happen the different supply chain links have to be brought together. By setting ambitious renewable energy targets and actually executing them on time governments are able to ensure enough projects are realized for the faster supply chain to be economic. The last element needed for more efficiency is standardization of equipment and production process. This would decrease production cost as well. Another challenge is component failure which occurs most often in subsea cables making up 77% of the total losses in the sector. A cable failure leads to no or decreased energy production in addition to the maintenance cost for the cable itself. Research for cable technology improvement and better maintenance strategies could decrease the losses.[7],[12]

5.1.4 Onshore Grid and Intermittency

The grid infrastructure needed for large scale offshore wind development is perhaps the biggest challenge the industry has to face in the future. Without reinforcing and/or expanding the grid soon it might not be strong enough to deal with the production peaks of the windfarms. To soften the impact of intermittency on the grid storage technologies like batteries or power to X will be needed. The creation of hubs between countries will be a part of the solution for some areas as well. This connection is beneficial for involved countries in many ways like sharing the cost and more security of supply while saving on grid expansion somewhere else. Research even suggest that the financial and technical advantages exceed the investment costs. Such a hub is supported from the countries neighboring the North Sea but no actual project is on its way so far.[12], [38]

6 Potential Calculations with ArcGIS

In this chapter the practical part of the thesis is explained and its results analyzed. With the help of ArcGIS the potential areas for deep sea offshore wind energy for Europe and Africa were conducted.

6.1 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"[9], and is explained in this section.

6.1.1 Analytic Hierarchy Process

The Analytic Hierarchy Process is a multi-criteria decision-making process developed by Thomas L. Saaty in the 1970s based on psychology and mathematics. It is used in a variety of fields from resource allocation to conflict resolution. The first step is a firm definition of the problem and find out what information is needed. Next the criteria and sub-criteria are defined, here also called factors. It is important for the process that the problem can be arranged in a network-structure or hierarchy. They are compared in pairs to determine their importance. This is done by establishing a pairwise comparison matrix with all criteria on both axis and using Table 6.2. The comparison itself can be based on measurements but also on inclinations and feelings. The appointed order is applied to weight their criteria. This all can also be done with sub-levels of the criteria. All of these steps and claims established during the process need to be consistent in order for the process to work properly. The consistency can be verified with a few calculations using the eigenvalue λ of the pairwise comparison matrix and the number of factors n. The final indicator for consistency is the consistency ratio which has to be smaller than 0.10 otherwise the decisions in the pairwise comparison have to be edited.[39], [40]

$$CI = (\lambda_{max} - n)(n - 1) \tag{6.1}$$

CI .... Consistency Index
λ_{max} ...... Principal Eigenvalue
n .... Number of factors

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

Table 6.1: Random Consistency Index [40].

First the consistency index CI is determined with Equation 6.1. Then the random consistency index from Table 6.1 is needed. This index was developed by Saaty in using a sample size 500 and generated a reciprocal matrix randomly with the whole importance range 1 to 9 and 1 to 1/9 with the goal of achieving a CR of 0.10 or less. The last step is to calculate the consistency ratio itself with Equation 6.2.[39],[40]

$$CR = \frac{CI}{RI} \tag{6.2}$$

CR .... Consistency Ratio
CI .... Consistency Index
RI .... Random Consistency Index

Intensity of Importance	**Definition**	**Explanation**
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Table 6.2: Importance Index scale [39].

6.2 Analytic Hierarchy Process - Application

Bahaj used the Analytic Hierarchy Process to develop a simple and robust method to calculate to potential of deep sea offshore energy for different sites. In addition to the Importance Index he adopted a new value the Representative Cost Ratio (RCR) which is calculated by the LCOE share of one factor divided by the other. Bahaj used already established Important Indexes from onshore wind studies and calculated their RCR in order to establish a relationship between the two values. The result of this is illustrated in Figure 6.1.[9]

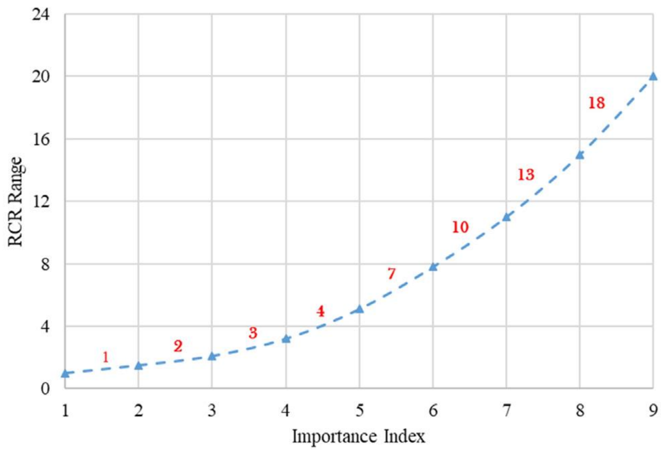

Figure 6.1: RCR range vs. Importance Index [9].

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". Then the corresponding Important Indexes can be entered in the pairwise comparison matrix according to Figure 6.1 resulting in Table 6.3. In order to normalize the matrix every element is divided by the sum of the column it is in. The outcome of each calculation is put into the normalized matrix as illustrated in Table 6.4. The Factor weigh is determined by computing the average of every row. The sum of all factor weights is one.[9]

	Wind Speed	**Water Depth**	**Distance to Shore**	**Distance to Grid**
Wind Speed	1	3	7	9
Water Depth	1/3	1	5	6
Distance to Shore	1/7	1/5	1	3
Distance to Grid	1/9	1/6	1/3	1
Total	1.59	4.37	13.33	19

Table 6.3: Pairwise comparison matrix [9].

	Wind Speed	**Water Depth**	**Distance to Shore**	**Distance to Grid**	**Factor Weight**	λ_{max}
Wind Speed	0.63	0.69	0.53	0.47	0.58	0.93
Water Depth	0.21	0.23	0.38	0.32	0.28	1.23
Distance to Shore	0.09	0.05	0.08	0.16	0.09	1.23
Distance to Grid	0.07	0.04	0.03	0.05	0.05	0.84
Total	1	1	1	1	1	4.23

Table 6.4: Normalized matrix, factor weights and λ_{max} [9].

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. The number of factors is four which results in an RI of 0.9 and an CI of 0,077. With an CR of 0.085 the model is consistent. The last step of the method is to compute the potential with equation 6.3.[9]

$$P = \sum_{i=1}^{n} W_i X_i \cdot \prod_{j=1}^{l} C_j \tag{6.3}$$

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

6.3 Factors and Constraints

Research for this thesis showed that the common denominator of various offshore wind energy potential calculation methods is the idea of factors and constraints. A factor can be seen as criteria on which the potential is dependent on in calculations. As a constraint can be seen all the areas that are excluded from the calculations. Possible factors and constraints are shown in Table 6.5 as well as markers for the ones used by the IEA in its 2019 offshore wind outlook, Bahaj in his 2020 paper on which the model for this thesis is based on and the actual ones used in the model. The four factors from Bahaj were all adopted in this model but not every constraint. A minimum wind speed, maritime protection areas and submarine cables were implemented as unsuited areas. The minimum and maximum distance to shore were adjusted. Lastly water depth restrictions were implemented because other than a needed upper limit a lower one was need in order to just look at deep water suited for floating turbines. Major shipping lanes were not included due to the lack of implementable maps and the question of how frequent shipping traffic has the be in order for the area to be excluded. Existing oil and gas installations were not omitted. The reason being the idea that oil and gas platforms need a lot of energy and a wind farm next to it could be beneficial.

		IEA 2019	**Bahaj 2020**	**This model**
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
	Fishing zones			
	Protected wrecks and tunnels			
	Military exercises areas			

Table 6.5: Comparison of factor and constraint selection [9],[7].

6.3.1 Factor Maps

The next step after identifying the factors and constraints was to find maps to use for the calculations. The bathymetry data was acquired from the General Bathymetric Chart of the oceans which is a project from the International Hydrographic Organization and the Intergovernmental Oceanographic Commission with the goal of making correct bathymetry easily accessible for the public [41]. The wind speed data used is from the global wind atlas a project from the World Bank and the Department of Wind Energy at the Technical University of Denmark which makes a high-resolution global wind map accessible for free [42]. The grid size of the map is 250 m and the wind speed data used for the model is at a height of 100 m. The data for every country in Europe and Afrika with sea access was downloaded rather than the whole continents in order to keep calculation time down. This approach resulted in having a data gap in the north-west of Africa. The reason for this is the political controversy about Western Sahara being a part of Morocco or not. It seems like the global wind atlas wanted to be diplomatic because the area of Western Sahara is not part of the Morocco dataset, but it is also not possible to download the data of Western Sarah by itself resulting in a data gap. The only way to get around that would be to use the dataset of the whole continent. For the third factor the grid structure for the two continents was needed. For Europe the grid structure from ATLANTIS was used. The nodes were imported to ArcGIS as XY-Data and then connected according to the existing grid lines. The grid map for Africa was developed from the UNHCR with 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 [43]. The last factor is the distance to shore to calculate this factor the coast outline from Europe and Africa was needed. For this continent and country shapes from the ArcGIS database were used. All the factor maps can be seen in Figures 6.2 and 6.3.

6.3.2 Contraints Maps

For wind speed and water depth constraints the maps from the related factors were used. The underwater cable paths are from a map developed by TeleGeography a research platform for telecom data funded by Huawei Marine Networks and Equinix [44]. The map for reserved maritime natural park is from Protected Planet a site run by United Nations Environment World Conservation Monitoring Centre with data from governments, non-governmental organizations, landowners and communities and updated every month [45]. The maps of all constraints are illustrated in Figures 6.4 and 6.5.

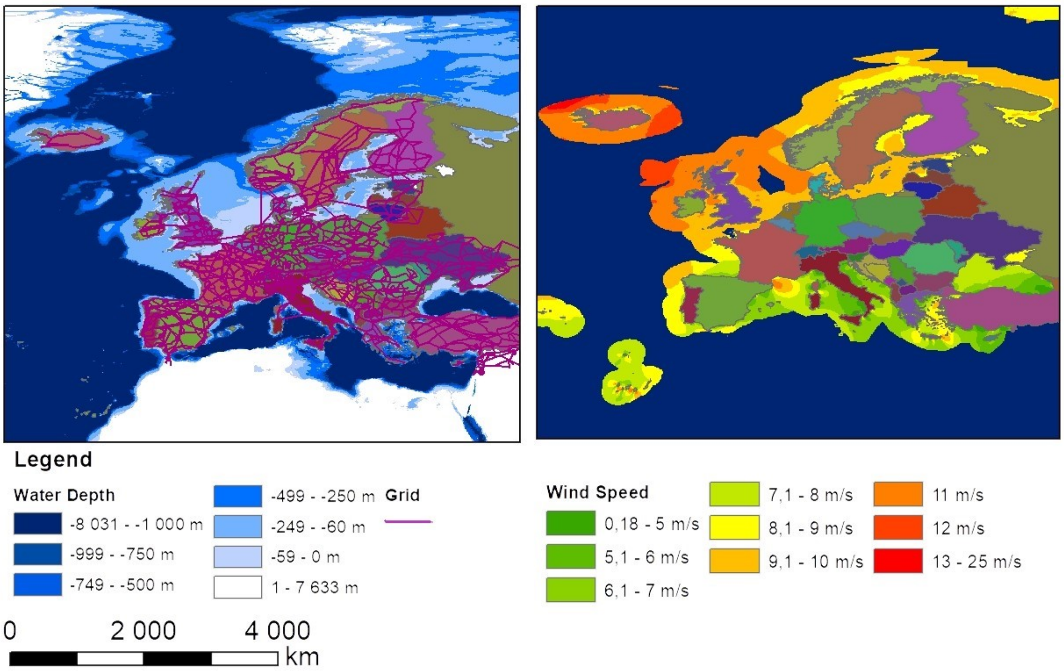

Figure 6.2: Water depth (left) and wind speed in Europe (right).

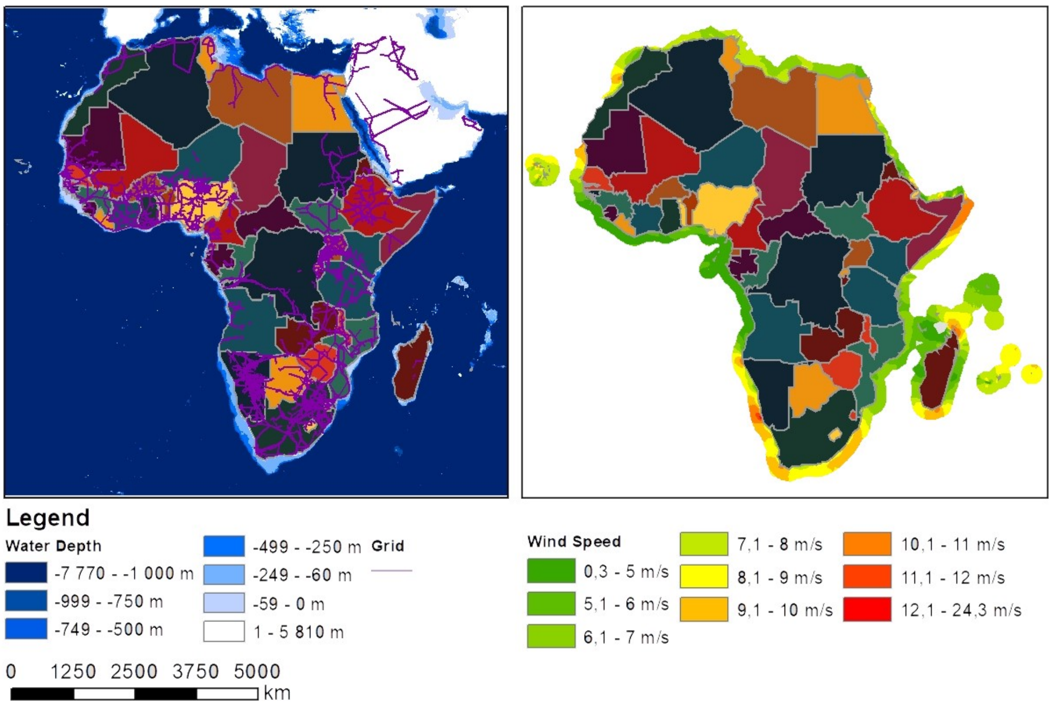

Figure 6.3: Water depth (left) and wind speed in Africa (right).

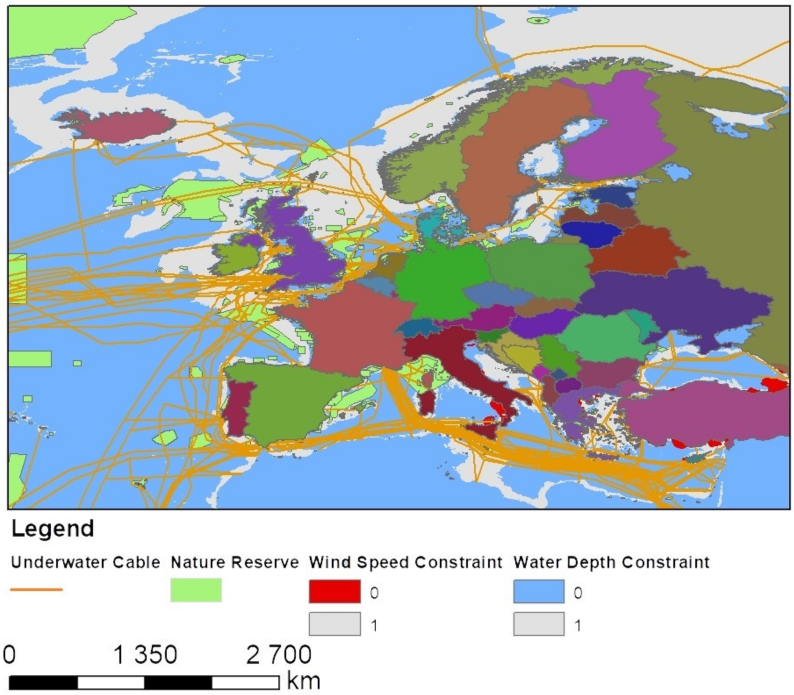

Figure 6.4: Constraints in Europe.

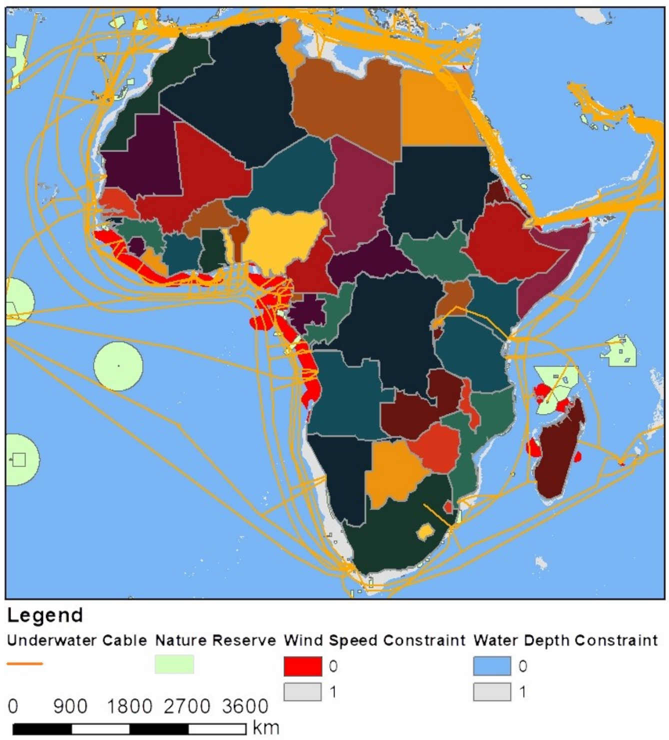

Figure 6.5: Constraints in Africa.

6.4 ArcGIS Tools

In this section all the ArcGIS tools used in the potential calculation are described. Figure 6.6 shows an overview of the model itself and the tools used at the different steps. The calculations with the factors start at the top and the ones with the constraints on the bottom.

6.4.1 Mosaic to New Raster

The fist step is to merge the wind speed data from the countries of one continent together in one layer. This is done with the Mosaic to New Raster tool which is part of the Data Management toolbox. Other than input and output sources the number of bands was set to zero because it has to be set to the number of bands of the input raster. The grid size was set to 250 m. It is the grid size from the wind speed datasets and is going to be used for the whole model. The rest of the setting were left on the preset parameters.

6.4.2 Clip

The maps for water depth, nature reserves and submarine cables are global maps that still needed to be cut in the shape that is interesting for the calculations in Europe and Africa respectively. For this reason shapes were created with the size and the location of the so called study area. The tool Clip which is part of the Analysis toolbox only needs the factor/constraint map in question and the study area as inputs. The result is only the area of the map that is in the same location as the study area.

6.4.3 Euclidean Distance

Before getting into the tool description itself it should be discussed what a euclidean distance is. In an Cartesian coordinate system it is the line segment between two points. It can be seen as the hypotenuse of an right-angled triangle with the x and y distance between the two points being the adjacent and opposite. The euclidean distance is then calculated with the Pythagorean theorem. In the ArcGIS tool it is computed the same way by taking the midpoint of each cell as the starting point. The tool counts the number of cells that the starting cell is apart from the cell in question in x and y direction and than calculates the euclidean distance from that. This is done for every cell of the raster. The input sources for this tool in the model were the coast line and the electricity grid to calculated distance to shore and grid. The other two input parameter were the maximum distance and the grid size. An extra setting to be set was the processing extent to the study areas because otherwise it is possible that the auto-setting does not have the same extend. The output of those calculation are shown in Figures 6.7 and 6.8.

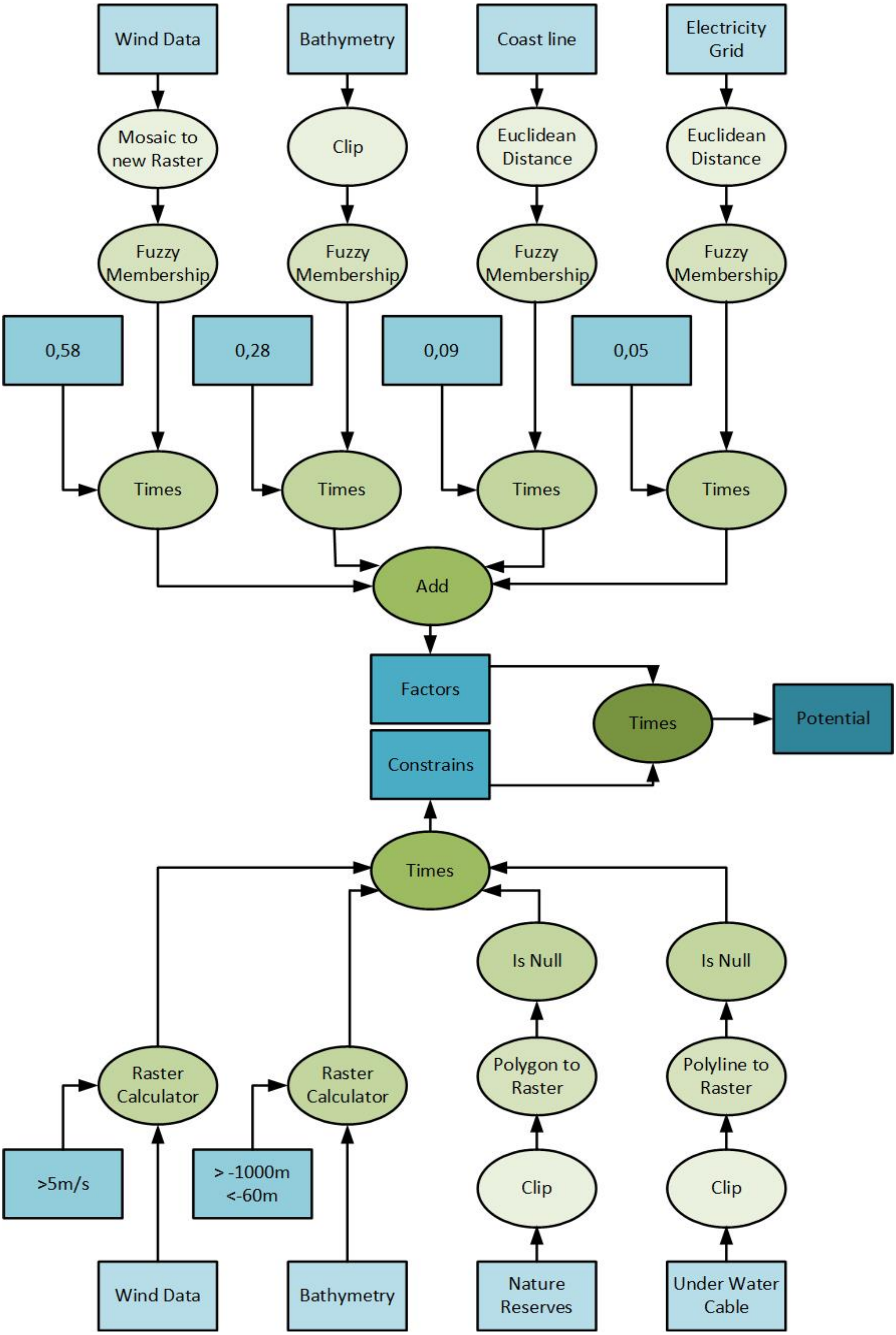

Figure 6.6: Flowchart of the model.

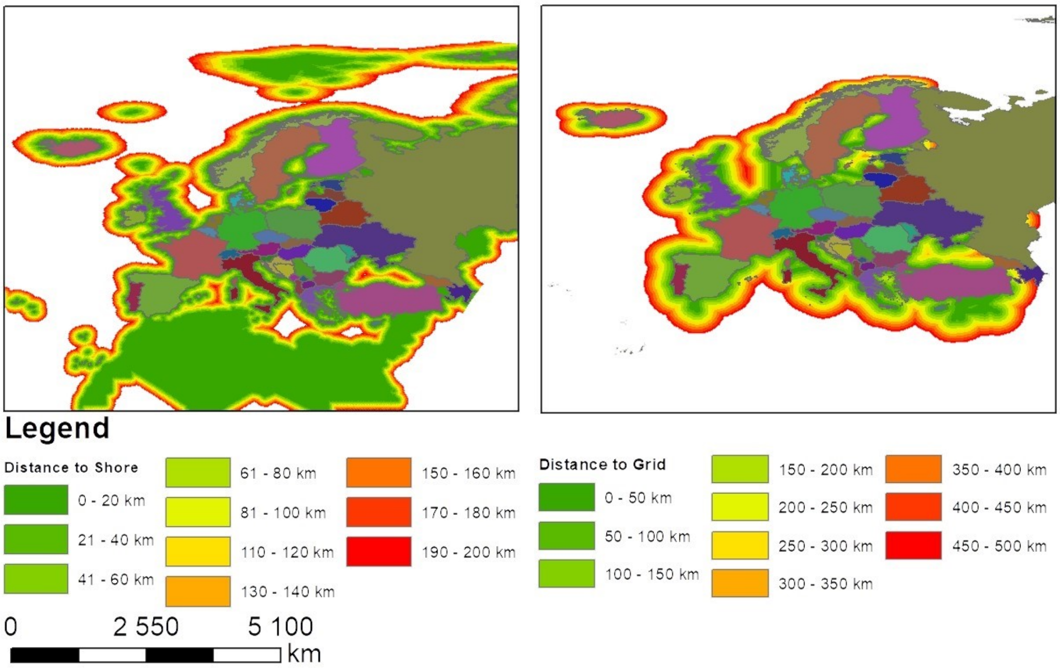

Figure 6.7: Distance to shore (left) and grid in Europe (right).

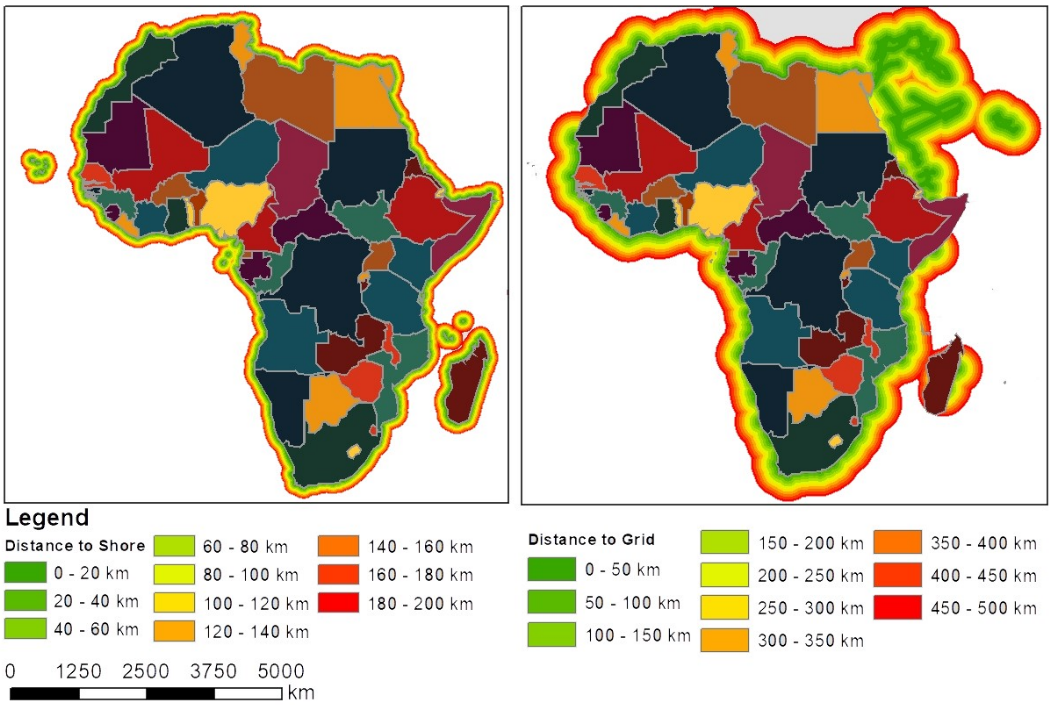

Figure 6.8: Distance to shore (left) and grid in Africa (right).

6.4.4 Polygon/Polyline in Raster

This tool is part of the Conversion toolbox and used to convert the maps of maritime protection areas and submarine cables. Both layers are a polygon and polyline respectively type maps. The format categories are just shapes not divided in a grid and therefore it is not possible to carry out calculations with them. But the layers still contain values. Every polyline for example represents a submarine cable and has parameters like an object ID number, the name of the cable or its capacity. Therefore, when converting the layers one parameter has to be chosen as the value assigned to the raster cell. In both cases the FID was selected but this value is not from importance because further on it is only going to be differentiated of a grid cell has a value or not. For that reason, the cell assignment parameter of the tool is also not relevant because it determines which value is given to the cell in case of two values occurring in one cell. The cell size is selected to be 250 m like in the whole model.

6.4.5 Is Null

The Is Null tool is very simple: all the values in the input raster are set to zero. This only applies to cells that have a value. The constraints are used as a Boolean mask therefore a cell that is part of a constraint should be zero and all the others one. The Is Null tool is applied to the nature reserve and submarine cable raster layers. This is the reason why the value given to the cell in the tool above is irrelevant because it is overwritten anyway.

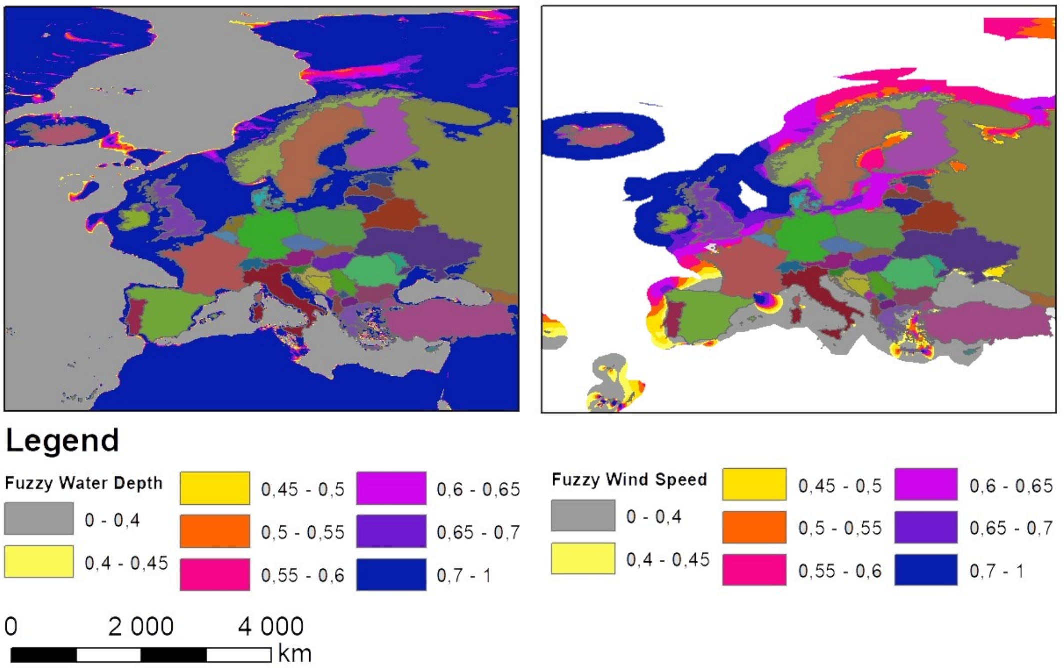

Figure 6.9: Fuzzy Factors water depth (left) and wind speed (right) in Europe.

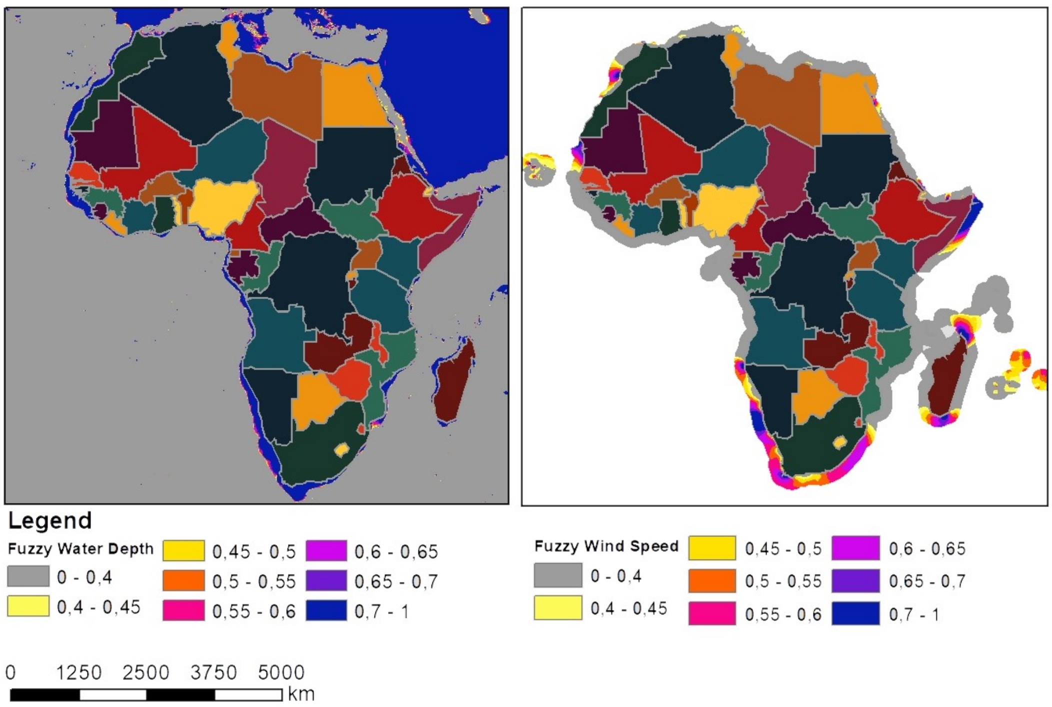

Figure 6.10: Fuzzy factors water depth (left) and wind speed (right) in Africa.

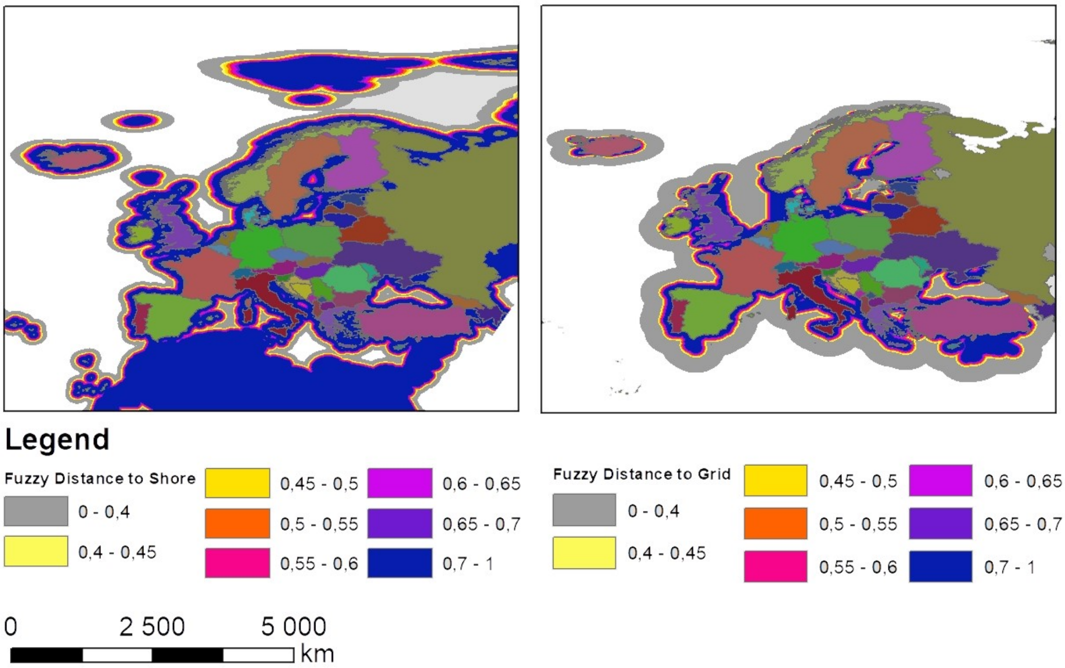

Figure 6.11: Fuzzy Factors distance to shore (left) and grid (right) in Europe.

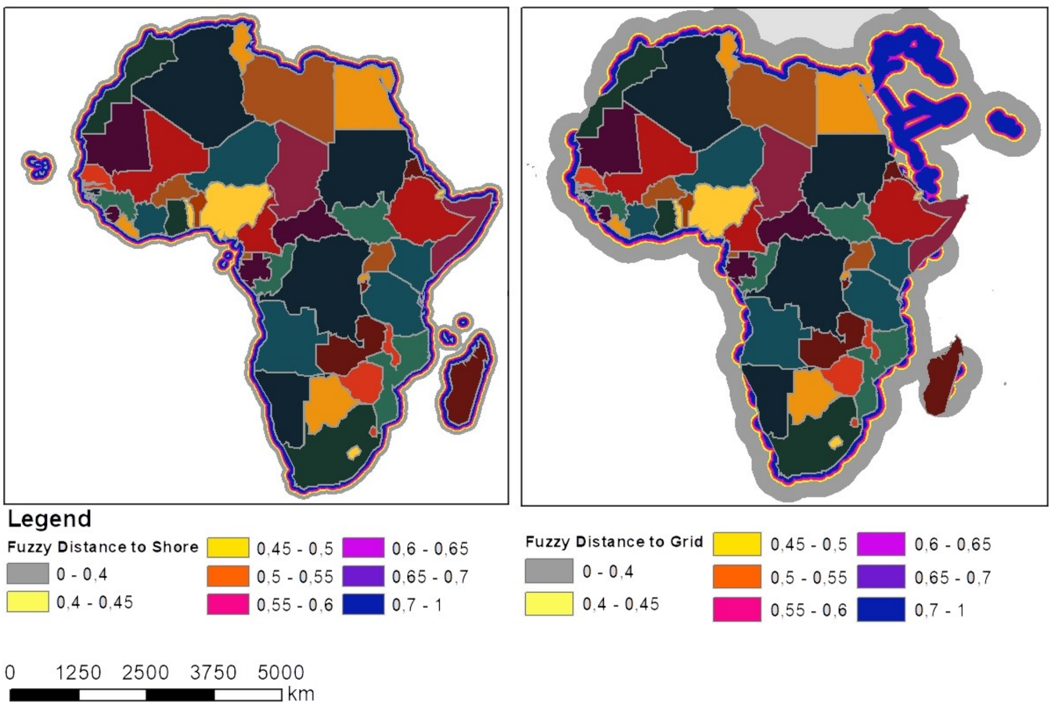

Figure 6.12: Fuzzy factors distance to shore (left) and grid (right) in Africa.

6.4.6 Fuzzy Membership

The Fuzzy membership tool is part of the spatial analyst toolbox and used to standardize the four factors to values between zero and one. The factors all have different scales and not the same units. This step is carried out to scale them in ways that they are comparable. There are different ways this tool can be used to scale the values of a raster between a minimum and a maximum. In this case the values were standardized linearly. The chosen limits are shown in Table 6.6. The wind speed boundaries are the rated and cut-in wind speed of an average 8 MW turbine [46]. The maximum grid distance was chosen to be 300 km because it is almost half of 580 km which is the length of the longest underwater power cable installed so far [47]. At this point it should be mentioned that just because a cell has the value zero for one of the factors it doesn't mean it is excluded like a constraint. It just means a smaller overall score. The output of this standardization is illustrated in Figures 6.9, 6.10, 6.11 and 6.12.

Factor	Max	Min	Condition	Value	Condition	Value
Wind Speed	12 m/s	5m/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 6.6: Fuzzy Membership Inputs [9].

6.4.7 Raster Calculator

The tool Raster Calculator form the toolbox Spatial Analyst can be used to make a variation of calculations with raster. In the model it was used to compute the areas with an average wind speed smaller than 5 m/s and with a water depth deeper than 1000 m but also shallower than 60 m. In the tool the concerned layer has to be selected and wanted formula needs to be typed. The output of this was already illustrated in Figures 6.4 and 6.5. The Raster Calculator could have also been used to implement Equation 6.3 but this would have made debugging harder. Therefore its simpler versions the tools Times and Add were implemented. Those just have two input raster and calculate the mathematical operation that they are named after. The result of the tiles Factors and Constraints in Figure 6.6 are illustrated in Figures 6.13 and 6.14.

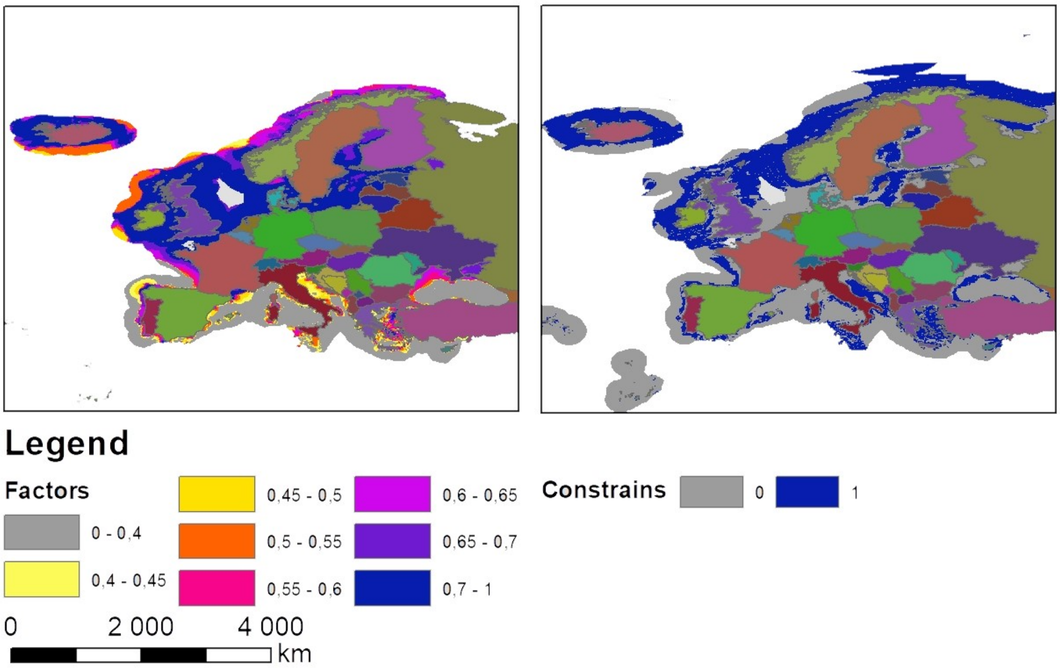

Figure 6.13: Factors (left) and constraints (right) in Europe.

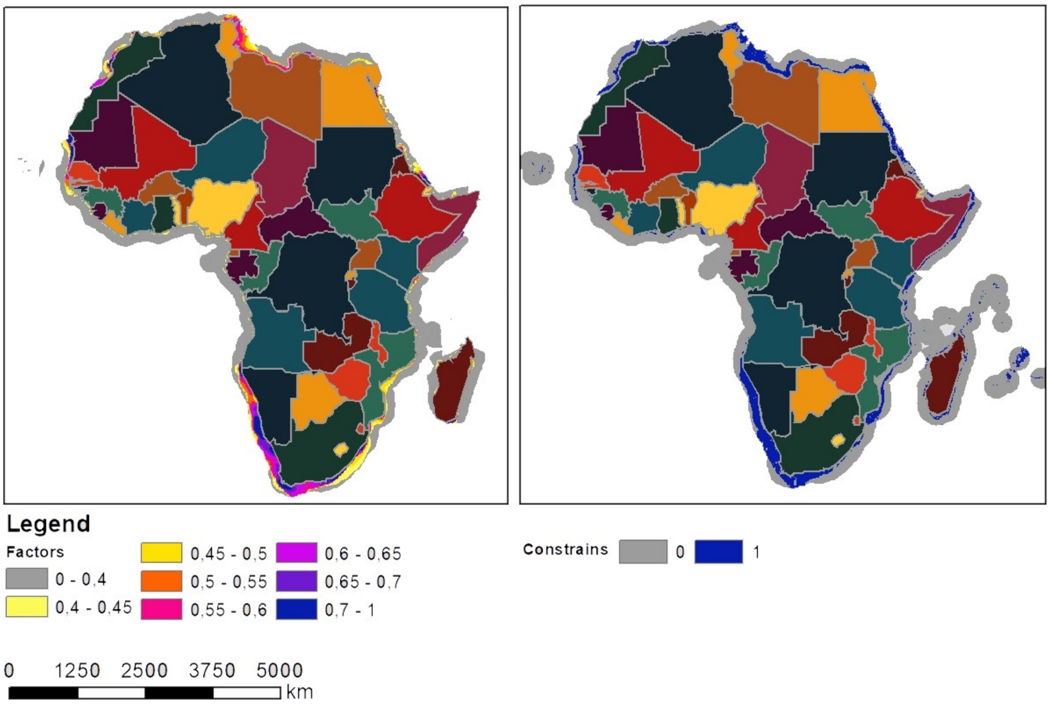

Figure 6.14: Factors (left) and constraints (right) in Africa.

6.5 Deep Sea Offshore Wind Energy Potential Results

The last step of the model was to multiply the factors with the constraints in order to obtain the potential which is pictured as a potential scale between zero and one. A score below 0.4 was considered unsuited and one higher than 0.7 as the highest potential category.

6.5.1 Results Europe

The simulation results for Europe's deep sea offshore wind energy potential is illustrated in Figure 6.16. The calculations showed that the waters around Iceland and Ireland are very suited as well as the northern part of the North Sea between the UK and Norway. The Baltic sea has a high potential starting with Poland towards the east and also the southern part of the Gulf of Bothnia. In the south of Europe small areas have such a great score like in France the Bretagne and the coastline between Marseille and Perpignan or the North Aegean islands and the Cyclades in Greece. For the comparison of these results with the calculations of the IEA in Figure 6.15 all the areas with a score higher than 0.4 are considered because that simulation only differentiated between suitable and unsuitable. While getting similar results it can be said that the simulation for this thesis is a more conservative approach. Another way to validate the results is to look at current and future project sites which are also plotted in Figure 6.16. Most of them actually are in high potential areas.

Figure 6.15: Geospatial analysis for Europe conducted by the IEA [7].

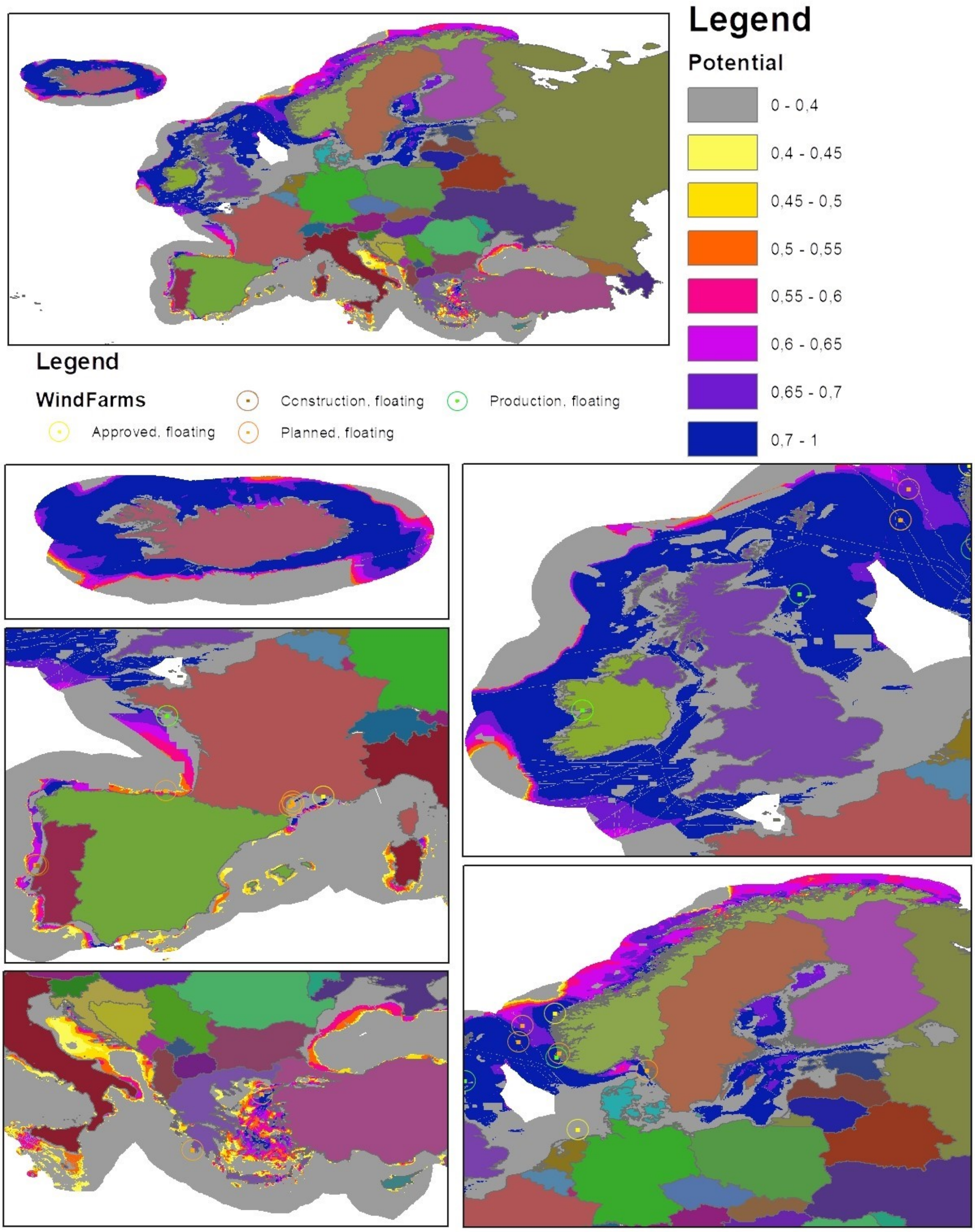

Figure 6.16: Potential in Europe.

6.5.2 Results Africa

The largest high potential area in Africa can be found in Namibia and on the west coast of South Africa. The other very suited areas consist of 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 cost of Somalia and Eritrea. This is illustrated in Figure 6.18. As for the comparison to the IEA calculations in Figure 6.17 can be said the same as for the European results. There are no offshore wind farms commissioned from African countries yet to compare the results to.

Figure 6.17: Geospatial analysis for Africa conducted by the IEA [7].

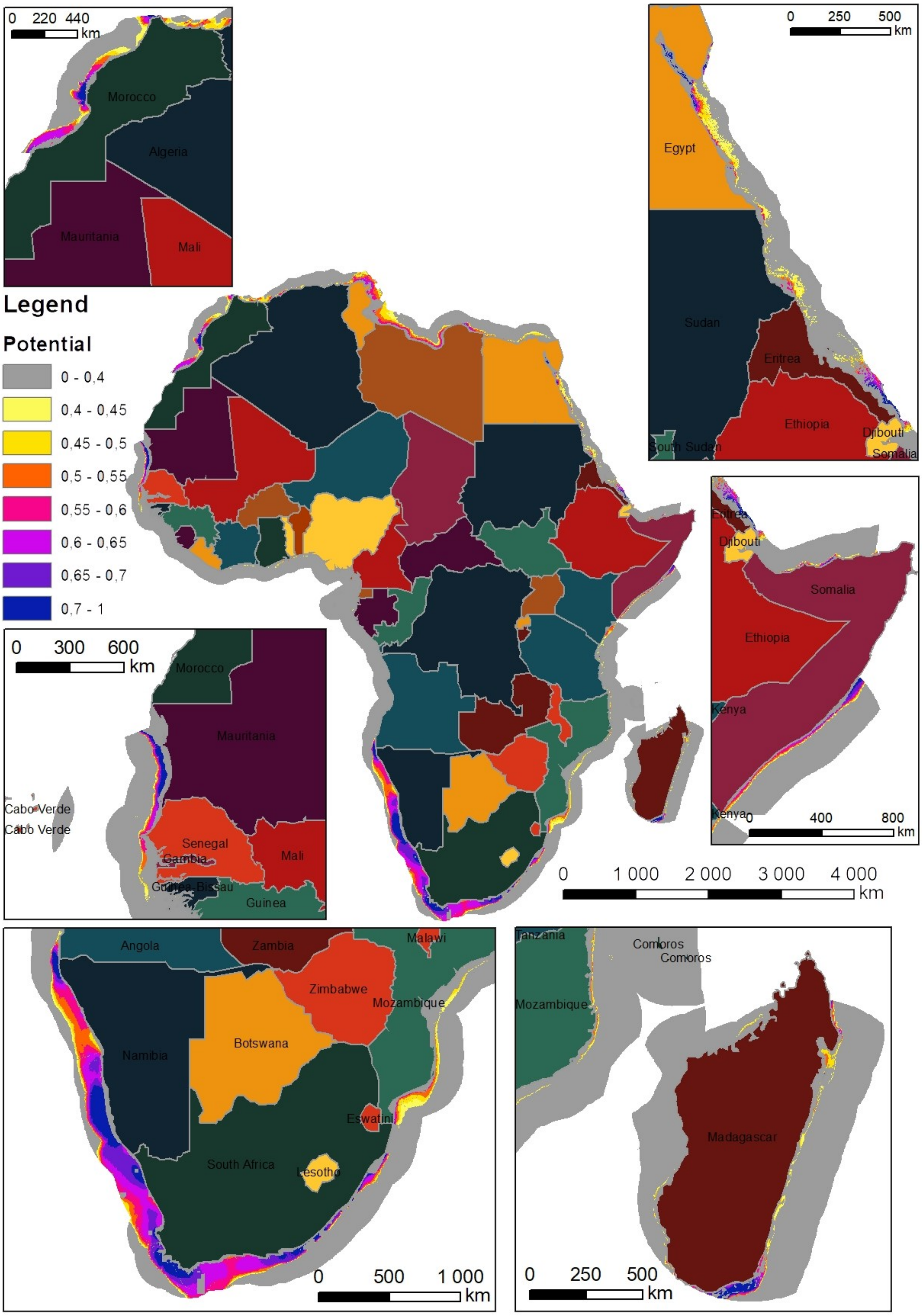

Figure 6.18: Potential in Africa.

6.6 Known Weaknesses

The model still has a lot of room for improvements. The first point is closing the data gaps resulting from the country specific wind maps like in the North Sea, between France and the UK, Monaco, a small area in the Black Sea, Western Sahara, most eastern tip of Somalia and its border to Kenya. It should be mentioned that most of them are in low potential areas therefore not very important. The second flaw is Cavazzis outdated LCOE distribution. It was not possible to recalculated them because it was not described how to do it. The factor weights of wind speed and water depth will probably come closer together due to more percentage of cost going towards the foundation. Another point is the obscurity of the RCR to Importance Index conversion. While trying to comprehend the method some decisions seemed not straight forward like wind speed vs. distance to shore having the same RCR but not the same Importance while wind speed vs. water depth and distance to shore having the same RCR and Importance Index. Changing both to seven or to six makes the model a lot less consistent, see Table 6.7. While conducting those calculations it became apparent that my computation of the factor weights and the eigenvalues with the original Important Indexes doesn't lead to same numbers as stated in the paper resulting in a less consistent model. I tried contacting the Author about how the LCOE shares are calculated, the thoughts behind deciding on the better Importance Index and the eigenvalue calculations. Unfortunately I did not get an response from Bahaj and therefore couldn't improve my calculations. Since the model stated in the paper is the one with the best consistency it is very feasible that I missed a decision or assumption that is important and not mentioned in the paper.

	Bahaj 2020		Gruber 2020		Gruber 2020 II=7		Gruber 2020 II=6	
	Factor weight	λ_{max}	**Factor weight**	λ_{max}	**Factor weight**	λ_{max}	**Factor weight**	λ_{max}
Wind Speed	0.58	0.93	0.58	0.92	0.57	0.91	0.57	0.91
Water Depth	0.28	1.23	0.28	1.23	0.29	1.27	0.29	1.26
Distance to Shore	0.09	1.23	0.09	1.23	0.09	1.20	0.10	1.20
Distance to Grid	0.05	0.84	0.05	0.88	0.04	0.89	0.05	0.89
Total	1	4.23	1	4.26	1	4.27	1	4.26
CR		0.085		0.0977		0.0997		0.0966

Table 6.7: Calculation comparison.

7 Conclusion

Offshore wind energy will become an increasingly important part of the global electricity generation. With the rapidly increasing climate change, industrialized countries have to switch to clean energy and developing countries have to find a sustainable way for their electrification process. This thesis 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. An elaboration of necessity of this energy source is conducted. All the components required in this technology and its history are discussed. Three different lighthouse projects and their prototype are analyzed. As a base for the potential calculations the Levelized Cost of Energy consisting of CAPEX, OPEX and DECEX was determined. In order to not have a one sided few on this, a few particular approaches from the last couple of years were evaluated and compared. The predictions for next few decades and the challenges the sector still has to face are discussed. For the potential calculations, a method using an Analytic Hierarchy Process as developed by A. Bahaj at the University of Southampton with the aim to create an approach that is simple and robust, was used. The factors that the potential is dependent on in this method are wind speed, water depth, distance to grid and distance to shore. The area excluded from the calculations are nature reserves, under water cables, locations with wind speeds smaller than 5 m/s and regions with a water depth less than 60 m and more than 1000 m. 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 2018 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. Therefore the model can be deemed as functioning despite having a few weaknesses to be sorted out in the future.

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