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A feasibility study of sustanaible offshore wind energy development in Kenya

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Malmö, Sweden

A FEASIBILITY STUDY OF SUSTAINABLE OFFSHORE WIND ENERGY DEVELOPMENT IN KENYA

By

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Kenya

A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the reward of the degree of

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DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

(Signature):

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Supervised by:

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Supervisor's affiliation**…….**

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ABSTRACT

Title of Dissertation: **A feasibility study of Sustainable Offshore Wind Development in Kenya.**

Degree: **MSc**

The energy sector currently accounts for more than 90% of CO_2 emissions. Renewable energy has significant ecological and economic benefits that can help in accelerating the achievement of SDG goal 7: Affordable and clean energy. This research assessed the technical potential, economic viability and environmental benefits of installing a bottom –fixed Offshore Wind Farm in Kenya. The technical assessment involves using Quantum GIS (QGIS) to carry out a spatial study in order to identify an optimal offshore site within Kenya's EEZ with wind speeds of at least 7m/s and above, water depths of at most 50m, falls outside of the marine protected areas, will not opaque ship traffic but is closest to the existing National Grid Transmission network.

An offshore wind farm of 100 MW capacity made up of Vestas's V164-10.0 offshore wind turbines rated 10 MW each was modelled. The estimated energy yield of the plant computed using a python program was found to be sufficient to meet the electricity demand requirements of Kenya's coastal region. The modelled project's LCOE analysis carried out using MS Excel based on Capital, Operation and Decommissioning cost estimates obtained from authoritative publications was found to be marginally impressive since it is lower than Kenya's Feed in Tariff rate for wind. The project was also projected to have significant social cost savings that amounted to about 40% of the estimated capital cost of the project.

Based on the SWOT analysis and the assessments above, Kenya has a huge Offshore Wind potential whose development can be accelerated through a fortified legal and policy framework, adequate planning that would encompass accelerating the development of a Marine Spatial plan, collecting bankable offshore data and an incentivized mechanism.

KEY WORDS: **Offshore Wind Farm, LCOE, Feed in Tariff, Environmental cost.**

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LIST OF ABBREVIATION

CAPEX	Capital Expenditure
DEPEX	Decommissioning Expenditure
EEZ	Exclusive Economic Zone
EPRA	Energy Petroleum Regulatory Authority
EROI	Energy Return on Investment
EU	European Union
FiT	Feed in Tariff
GIS	Geographic Information System
GWC	Generalized Wind Climate File
Gwh	Gigawatt hour
HFO	Heavy Fuel Oil
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy
KenGEN	Kenya Electricity Generating Company
KETRACO	Kenya Electricity Transmission Company
KPLC	Kenya Power and Lighting Company
kWh	Kilowatt hour
LAPSSET	Lamu Port-South Sudan-Ethiopia-Transport
LCA	Life Cycle Analysis
LCOE	Levelized Cost of Energy Agency
LTWP	The Lake Turkana Wind Power project
MSP	Marine Spatial Plan
MW	Megawatt
NH_3	Ammonia

NOx	Nitrogen Oxides
O&M	Operation and Maintenance
OPEX	Operating Expenditure
OWE	Offshore Wind Energy
$PM_{2.5}$	Particulate Matter
QGIS	Quantum Geographic Information System
RE	Renewable Energy
SCOE	Society’s Cost of Energy
SDG	Sustainable Development Goal
SO_2	Sulphur dioxide
TEU	Twenty-foot Equivalent Unit
UNFCCC	United Nations Framework Convention on Climate
VOCs	Volatile organic compounds

CHAPTER 1 - INTRODUCTION

1.0 Background

The energy sector accounts for about two thirds of the global emissions (IRENA, 2021). This is due to the historical overdependence on carbon intensive fossil fuel sources. The United Nations Climate regime – Intergovernmental Panel on Climate Change (IPCC) continues to intensify global action by heightening awareness on climate change causes, consequences and providing scientific input to the Paris Agreement which aims to strengthen global response by limiting the increase in global average temperatures to well below 2°C above pre-industrial levels and to limit the temperature increase to 1.5°C above pre-industrial levels. Renewable energy coupled with energy efficiency gains can help eliminate 92% of CO_2 emissions by the year 2050 according to the Global Warming report of 1.5°C (IPCC, 2018).

Similarly, according to the findings of an impact assessment cited in the amendments to EU's Renewable Energy Directive 2030, the energy sector is responsible for over 75% of the total GHG emissions in the EU. The EU commission has since sort to mitigate against the potential irreversible effects of GHG emissions through the European Green Deal with the ultimate aim of rendering EU climate neutral by 2050. The revised 2030 Climate Target Plan proposes more ambitious steps that among other things reduction GHG emissions by at least 55% below 1990 levels by 2030 up from a previous target of 40%. The European Climate law is set for radical review in what is dubbed as the "Fit-for-55″ package that seeks to amend over ten pieces of legislation among the Renewable Energy Directive. In April 2021 a consensus was reached between the European Parliament and the Council and July 2021 was set as the target date for the commission to review and propose legal mechanisms for achieving the 2030 targets (EU, 2021)

In the package the commission proposed a revision of the renewable energy target to 40% up from 32%. According to Wind Europe this means that the union will have to more than double its current wind capacity of 180 GW to 451GW by the year 2030. The EU therefore needs to build an additional annual capacity of 30 GW between 2021 and 2030 (Wind Europe, 2021). On the other hand, Kenya is a signatory to the United Nations Framework Convention on Climate Change (UNFCCC). Alive to her obligation as a contracting state, Kenya developed The National Climate Change Response Strategy 2010 so as to align her climate change objectives to the global expectations. The highlight of the report is the projected 50% increase in GHG emission by the power generation sector on a business as usual trajectory and emphasizes the need to accelerate investment in wind energy, solar and biofuels which have a significantly low carbon footprint The Climate and Development Knowledge Network [CDKN], (2010).

IRENA's Power Generation Costs 2020 report indicates observes that "renewable power generation is becoming the default economic choice for new capacity" (IRENA ,2020). This is largely due to the fact that the LCOE of renewable energy options such as solar and wind (both onshore and offshore) have fast fallen to the range of fossil fuels and even below as shown in Figure 1.1.

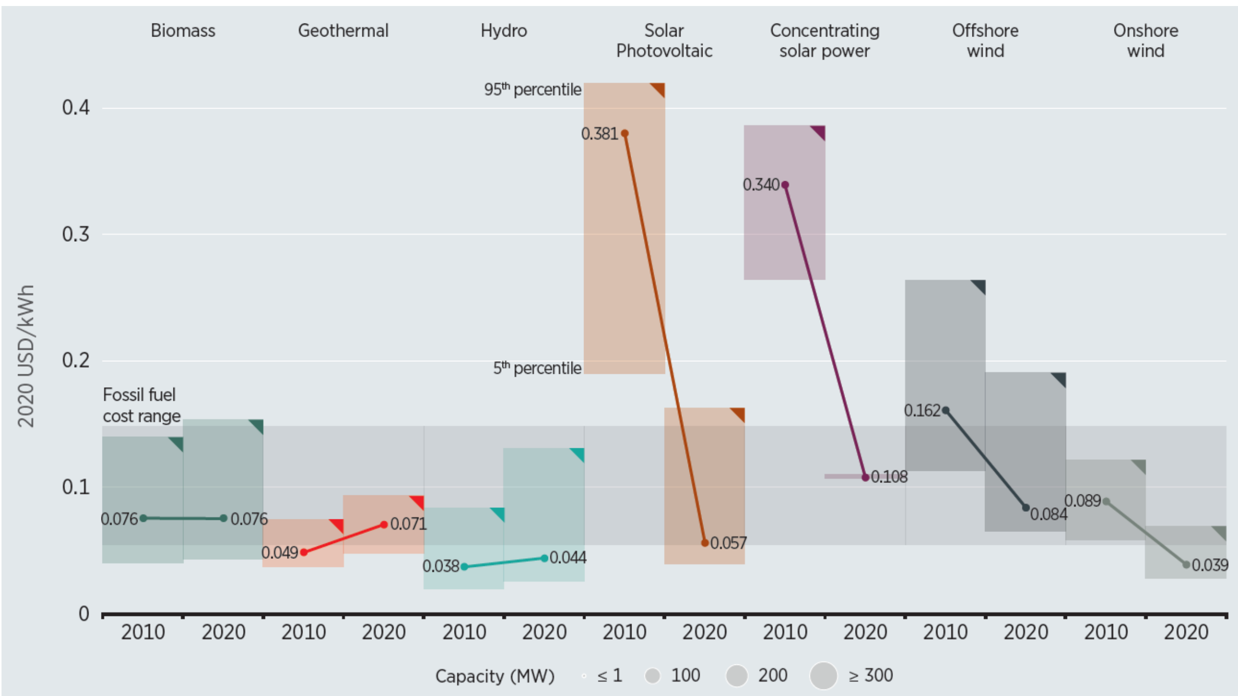


Figure 1. 1 Global LCOEs from newly commissioned. Utility-scale renewable power generation technologies, 2010-2020. Source: Adapted from IRENA's Power Generation Costs 2020 report. (IRENA, 2021, p.15)

Off-shore wind power is a fast growing renewable source of energy especially for economies characterized by high coastal settlement such as the European economies, USA and Asia. Despite its higher initial cost of installation, offshore wind has the advantage of enabling installation of larger turbines and overcoming the disadvantages of land based wind energy generation such as noise pollution and landscape alteration.

1.1 Is offshore wind an alternative?

Kenya' coastal territory spans 640 KM long bounded by Somalia to the North and Tanzania to the South, it is majorly used for maritime transport, recreational activities, commercial fishing and also oil and gas exploration. The region experiences extractable wind resources that would be harnessed for power generation. There is a need to seize the opportunity presented by the blue economy framework and ensure that the potentiality of Offshore wind is adequately considered and proportionately provided for in the Marine Spatial Plan currently being drawn following the 2018 first ever 'Sustainable Blue Economy' conference that was co-hosted by Kenya with Japan and Canada. This conference brought together 184 countries (Nairobi Convention, 2018).

Kenya has the unique opportunity to take advantage of offshore wind resources given the experience gathered from the development of its onshore wind subsector that is fast growing as shown in Figure 1. One key learning point is the need for early feasibility studies and collection of bankable offshore wind resource data similar to what was previously performed in the financial year 2011/12 when the Government of Kenya with the support of The World Bank procured the services of WinDForce, a management services firm that carried out a study of the onshore wind resource potential. The study provided input to the published wind sector prospectus which has been instrumental in enabling decision making by prospective investors (WinDForce, 2013).

This research therefore seeks to assess the potential of OWE in Kenya by identifying potential sites for offshore wind farm development, assessing the ecological benefits of investing in offshore wind and recommend enhancement mechanisms that would foster investor interests.

1.2 Problem Statement

The planetary boundary concept helps define the various ways human activities have negatively impacted the planet. Climate change is one of the nine planetary boundary elements that are today potentially destructive and deleterious to life on earth. The effects of climate change are spontaneously being witnessed world over, from the rise in temperatures, wanton flooding due to sea level rise, prolonged drought cycles resulting in desertification, ecosystem degradation to

loss of biodiversity. This is a consequence of anthropogenic activities that have largely involved perpetual extraction of resources without regard to the long term impacts.
Global action through SDG goal 13 – Climate Action - and SDG goal 7- affordable and clean energy is one of the key global response mechanisms for sustaining the course. Discourse on how to intensify climate action is scheduled to happen in the upcoming Conference of the Parties - COP 26[1] which is set for early November 2021. Power generation is central to climate talks since it is the biggest contributor to GHG emission. Since the demand for power has a positive correlation with the increase in population there is urgent need for engendering circularity and sustainability in power generation. A circular system is one that is regenerative, restorative, involves use of renewable energy and limits wasteful use of materials (Ellen MacArthur Foundation, 2013, p.7).

The demand for electrical power is expected to continue rising given the 2.2% projected average annual growth rate in population. Despite notable mention of Maritime Energy in Kenya's Blue Economy grand plan, there have been inadequate subsequent studies and development plans on its potential. It is important that maritime renewable energy sources such OWE are adequately assessed and provided for in the spatial plan so as to avoid future maritime conflicts with other maritime activities.

OWE is a fast growing maritime renewable energy alternative. Projected trends point to the fact that with the advancements in technology offshore wind's LCOE will free fall below that of fossil fuel which is considered relatively cheaper. OWE overcomes the disadvantages of onshore wind such as noise pollution and being a landscape menace. Comprehensive studies to ascertain and profile the potential of shallow water OWE in Kenya are yet to be conducted.

1.3 Research Objectives

This research sort to assess the viability of bottom-fixed offshore wind in Kenya by:

i. Assessing Kenya's offshore physical dimensions, offshore wind conditions and the scope of use by other marine services.
ii. Analyzing the financial viability of developing an offshore wind farm in Kenya.
iii. Quantifying the environmental cost savings that offshore wind would help mitigate against.

[1] COP 26 is the 26th United Nations Climate Change policy set to be hosted by UK in the period between end of October and November, 2021.

1.4 Research Questions

This research shall be seeking to address the following questions

1. What is the technical potential of Kenya's offshore development based on the offshore wind characteristics, bathymetric dimensions, ship traffic density and power transmission infrastructure?

2. Which are the potential sites for offshore development in Kenya and what is the energy yield for the modelled offshore wind farm at the selected site?

3. What is the likely financial performance and social cost benefit of the modelled offshore wind Farm?

4. What are the barriers to the development of Offshore Wind farms in Kenya and how they can be surmounted?

1.5 Research Limitations

This research relies on online databases that contain information captured by use of remote sensors and other modelling techniques. This data is a mixture of actual and derived data obtained by means of interpolation and extrapolation techniques hence it may have had inherent marginal errors that could have been propagated throughout the study. Therefore, this data should be validated by installing site specific measurement equipment so as to enhance accuracy of the results.

Factors such as geotechnical conditions and Metocean characteristics are not considered in this study but equally merit consideration when assessing OWE potential.

Cost estimates for implementing and running the project were adopted from publications since actual project costs are difficult to secure due to business secrecy issues.

1.6 Research Outline

This research consists of six chapters. Chapter one provides a background of Kenya's electricity generation, demand and impact. This introduction reviews key developments in Kenya's energy sector, the emerging drivers and trends. The problem statement is clearly stated, the research objectives are subsequently enumerated, the limitations of the study and study methods are also subsequently addressed in this initial chapter. Chapter two contains the literature review which highlights the key outcomes of the studies that have already been conducted, the ongoing developments of the sector globally and the projected trends. Chapter three describes the approach used to collect and analyse the data obtained. Chapter four entails a synopsis of the key elements of an offshore wind farm, chapter five involves data analysis. Chapter six encompasses the discussions and conclusion. The approach is as outlined in Figure 1.2.

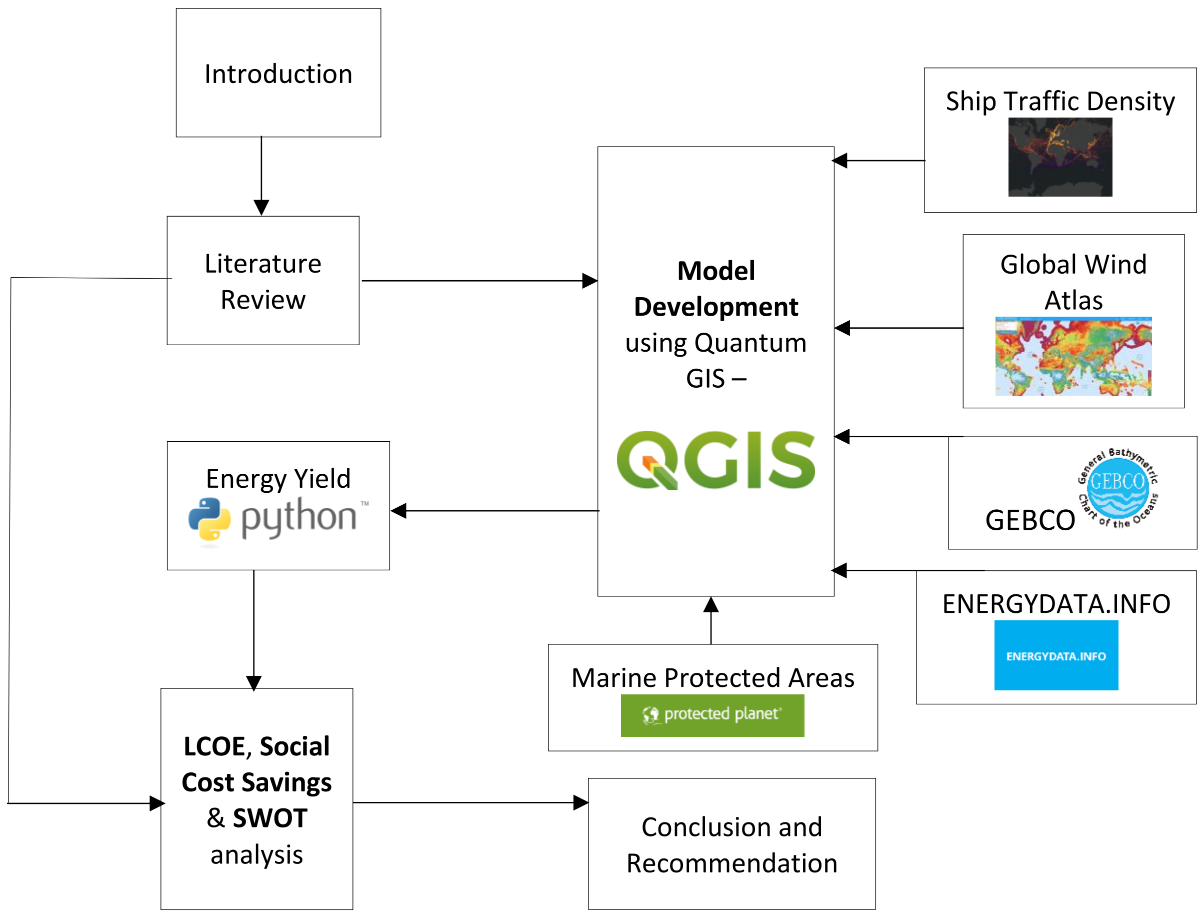


Figure 1. 2 Research outline flowchart. (Author, 2021)

CHAPTER 2 – LITERATURE REVIEW

2.0 Introduction

Offshore wind Energy (OWE) is emerging as one of the most dynamic technologies in the energy sector. From an installed capacity of 3 GW of OWE in 2010, the installed capacity increased to 23 GW in 2018. New installations increased by about 30% annually, a rate higher than all other electricity sources except for solar photovoltaics (PV) (International Energy Agency, 2019). This chapter focused on reviewing global OWE studies with a view to inform the feasibility of its development in Kenya in the days to come.

Wind energy turbines can either be located on land (onshore) or at sea (offshore). The world's cumulative capacity of onshore as at 2020 was 699GW compared to that of offshore wind which recorded 34.4GW. This is attributable to the fact that onshore wind is relatively cheaper and easier to install than offshore wind. Offshore wind on the other hand enables utilization of consistent and higher wind speeds at sea, enables use of higher capacity turbines given the relative abundance of wind offshore, reduces conflicts with other land uses and it mitigates against visual impact and also noise pollution on land (IRENA, 2021).

2.1 The history and milestones of offshore wind.

According to the chronology documented as 'The history of Europe's Wind Industry' by Wind Europe, the world's first offshore wind farm was built at Vindeby, Denmark in the year 1991, it was later decommissioned in 2017 after exhausting its useful life. It consisted of eleven 450 KW wind turbines (Wind Europe, 2021). Commissioned in 2020, Hornsea one offshore wind farm located off the East Coast of the UK in the North Sea is today the world's largest floating offshore wind farm. It is made up of 174 Siemens Gamesa 7MW wind turbines with a hub height of 190 metres tall, it also boasts of the furthest location off the coast spanning 120 km in distance (Orsted, 2021). IRENA observes that offshore wind development has gained momentum in the recent past. The agency predicts a spiral growth from the current 34GW to about 380 GW by 2030 (IRENA, 2021).

Elsner (2019) observes in his study on the 'Continental –scale assessment of the African Offshore wind energy potential: Spatial analysis of an under-appreciated renewable energy resource' that despite OWE's capital intensiveness the recent advances in turbine technology and growing installation experience have led to higher capacity factors and lower capital cost.

This is evidenced by a sharp decline of contracts for difference (CFDs) prices that European governments awarded to offshore wind energy developers in the year 2017. A review of the OWE LCOE trends as an indicator for competitiveness shows that it has continued to consistently decline. Wieslaw et al (2016) cite in their book titled 'MARE-WINT' the approach by Siemens, (2014) that considers a more comprehensive measure of LCOE referred to as Society's Cost of Energy (SCOE). This approach takes into account the other fundamental factors such as jobs created by energy sources, subsidies, variability costs, geopolitical risks and environmental impact, going by this technique the SCOE of OWE is expected to fall from 140 € /MWh in 2013 to 61 € /MWh by 2025 which is reasonably close level to that of commonly used fossil fuels such as coal's which is projected to be 110 € /MWh. IRENA (2021) points to a similar trend whereby the LCOE fell by 48% from 2010 to 2020 thus hitting a new low of USD 0.084/kWh which is equal to about 71 € /MWh.

2.2 Why Europe is a global leader in offshore wind

In terms of the global spatial distribution of OWE, European countries account for about 90% of the world's total installed capacity, this translates to 25,014 MW as of today composed of 5,402 turbines connected to the grid across 12 countries. UK accounts for the largest share (42%) followed by German, Netherlands, Belgium and Denmark in a descending order. Though impressive, this state of affairs falls short of the ambitious targets by the EU to build 300GW of offshore wind by 2050. The ramping up of this OWE deployment is due to the relatively high speed winds in the region, shallow waters, technological advancement, enabling policy mechanisms and financial support through the EU (WindEurope, 2020).

The European market continues to be a global leader in offshore wind because of the political will and enabling policies necessitated by EU's agenda to fully decarbonize its economies by 2050. The electrical infrastructure integration achieved through The Trans-European Networks for Energy (TEN-E) regulation has been useful in pushing for funding towards the electricity sector as opposed to fossil fuels. The Renewable Energy Directive is another instrumental policy item that has provided legal certainty thus making the EU market attractive, the state aid guidelines on energy and environmental protection has helped mobilize funding and incentivized investment in offshore wind (European Commission, 2021). Other policy mechanism such as The EU Emission Trading systems, strengthening of energy auction systems, Energy Taxation directive and the push for easing of permitting procedures have also helped accelerate the shift towards renewable energy options such as offshore wind.

2.3 Sustainability of offshore wind

The global climate change crisis is largely attributed to anthropogenic activities that have led to the direct destruction of biodiversity and also through indirect means such as release of GHG emissions. A big part of the emissions has their origin traced to energy generating activities. Lifecycle analysis of energy projects has revealed zero sum gains in some areas. In order to ensure that energy sector continues to be sustainable it is important to balance ecosystem interests. Environmental impact assessment that entails carrying out Life Cycle analysis (LCA) and Energy Return on Investment[2] (EROI) ranks OWE projects highly compared to other renewable energy sources.

An LCA study of an OWE project at the Taiwan West Coast by Yu-Fong et al (2017) revealed that both topologies (one an OWE project with an offshore substation was considered and the other with an onshore substation). made a business good case with an assumption of adequate recycling. These findings are in concurrence with those of Kubiszewski et al (2010) who carried out a literature review analysis on the net energy return and EROI for electric power generation by wind turbines. The analysis concludes that the EROI of wind turbines compares favourably with those of other renewable sources such as: coal, Hydro and photovoltaic.

In the wake of the alarming consequences of climate change that the world is contending with, there has been deliberate efforts to ensure that new renewable energy deployment processes and post instalment operation have near zero negative impacts on the environment. Offshore wind development should be guarded against degrading both life below and above water. This underscores the need for marine spatial planning in order to insulate marine ecosystems that would be vulnerable to human activities in the ocean. In light of this reality The EU commission for instance directed member states to integrate offshore wind into their national Maritime Spatial Plans and submit to it by March 2021(European Commission, 2021). These efforts will guarantee reduced conflict in marine use and insulate marine protected areas from interference resulting from offshore wind development.

[2] EROI is the ratio between the amount of usable energy delivered by a given source and the amount of energy used to produce a certain amount of energy.

Most wind farms have a useful life of between 2 and 25 years. Conscious of the likely ruinous effects of the offshore wind materials at the end of their life span, it is now best practice to make provision for decommissioning at the design stage of the project. Specialized entities such as NIRAS have gained expertise in this area and have developed tools such as ODIN-WIND to help ease the decommissioning process. The decommissioning process is done both at on and offshore as illustrated in Figure 2.1. Onshore operations include activities such as the treatment of the structural components by decontamination, striping and after waste disposal (MARE-WINT -pg 402, 2016).

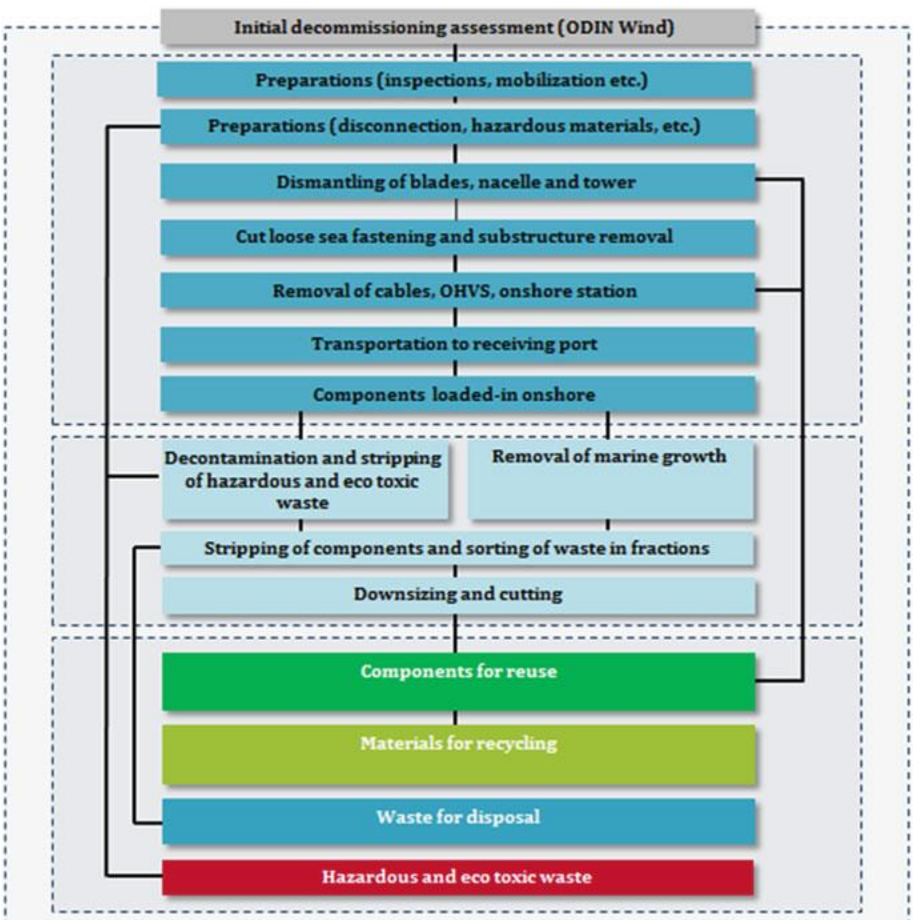


Figure 2. 1 The typical process of decommissioning an offshore wind farm.

Source: Adapted from NIRA's the ODIN-WIND tool (Gjødvad, 2015).

This process is critical since it contributes to sustainability, circularity of the economy hence efficient use of resources and helps mitigate against the planetary boundary issues.

2.4 The unexploited offshore wind potential.

The deliberate ocean data sourcing efforts continue to contribute to the advancement of global OWE studies. The World Bank Funded Energy Sector Management Assistance program (ESMAP) continues to carry out studies on the global OWE potential, it has since reported that 115 of the world's countries are deemed to have technically extractable offshore wind potential amounting to 71,000 GW, of which only 20,000 GW of that is in shallower waters (less or equal to 50 M). At country level the study quantifies Kenya's OWE potential to be at 9.35 GW and 81.72 for fixed foundation and floating foundation respectively (ESMAP, 2021).

Notwithstanding that existing studies indicate a huge potential of the OWE in Africa this resource still remains unexploited, it is not viewed as a priority energy source in Africa because of the perceived immaturity of this technology, availability of unexploited onshore wind resources and lack of robust quantitative analysis that evaluates the OWE potential Elsner (2019). Elsner used modelled satellite-based wind study that involved two criterions: the first scenario considered the existing offshore technology that is constrained to shallow waters while the second assumed availability of new technological developments such as floating wind. The results demonstrate that the small continental shelf of the African continent limits the OWE potential for scenario one. It is hence evident that the availability of floating technologies would significantly increase Africa's OWE technical potential. The study findings indicate that the Western Indian Ocean region has a higher scenario one potential. This includes: South Africa (38.5GW), Mozambique (152 GW), Madagascar (87.9GW), Tanzania (17.6 GW), Kenya (14.4 GW), Somalia (55.6 GW) and Eritrea (14.7GW).

African coastal countries such as Kenya can also learn from recent initiatives such as the Facilitating Offshore Wind Energy in India (FOWIND) with a view to make more accurate estimates and enable investment decision making. FOWIND's purpose was to assist India in OWE development, it was led by Global Wind Energy Council (GWEC) supported by the EU with DNV as a consortium member. DNV's Turbine Architect wind farm modelling tool was used to assess the technical capacity of the OWE resource off the shores of Tamil Nadu and Gujarat states. The consortium also comprehensively carried out: pre-feasibility studies, supply chain, ports and logistics, grid integration and feasibility studies. The outcome of these studies and subsequent data validation exercises are ongoing in earnest for the development of a 1 GW capacity offshore wind farm off the coast of Gujarat (India Ministry of New and Renewable Energy, 2021).

2.5 Why more studies are necessary

Even though extracts from previous global OWE studies above indicate that Kenya exhibits impressive unexploited technical potential both on shallow and deep waters. Both of the above referenced studies on OWE studies considered wind speed potential and bathymetric characteristics of the EZZs. Elsner (2019) factored in marine protected areas as an additional consideration. Neither of the studies incorporated shipping traffic constraint which is an important factor going by the projected growth of the maritime transport sector. Subsequent studies have the advantage of benefiting from the recently launched freely accessible global database of shipping traffic data that has since been deployed with the help of IMF funding (The World Bank, 2021).

In view of Kenya's blue economy sector developments there is need to review and juxtapose the economic potential of OWE against the renewable energy projects being implemented at the coast such as The Malindi solar plant, a 50 Kw, 20 year PPA agreement currently being developed by Globeleq (Globeleq, 2021).

Unlike previous studies, this research sort to specifically focus on Kenya, incorporated competing maritime interests such as ship traffic density and marine protected areas so as to further refine Kenya's bottom-fixed offshore wind technical potential estimates.

CHAPTER 3 – METHODOLOGY.

3.0 Introduction

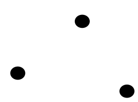
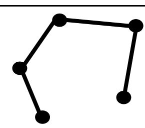
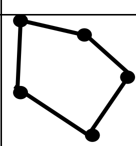
This research was based on quantitative and qualitative research methods. GIS data available on online databases was used as the primary source of quantitative data. The data was visualized, analysed and presented using Quantum GIS (QGIS). Extensive studies based on other secondary sources such as published articles on Science Direct, Google Scholar and reports by IRENA and also Wind Europe were considered so as to establish the key elements of OWE.

Definition of the various types of GIS data acquired (their sources, formats, processing methods), a description of the formulation for the energy yield and also formulation for the LCOE computation and sensitivity analysis are as documented in the subsequent subheadings.

3.1 Data types, sources and formats.

There are three types of GIS data namely: spatial, attribute and metadata. Spatial data can be of either vector, raster, image, Triangular Irregular Networks (TINs) or in Terrain formats. Vector and raster data sets were used for this study. As shown in Table 3.1.1 vector data take various forms.

Table 3.1. 1 Types of vector data.

	Type	**Illustration**
i.	Points	
ii.	Line	
iii.	Polyline	
iv.	Polygon	

Source: (Author, 2021).

A shape file is a spatial vector data format that is used for storing geometric location data that is non-topological together with the corresponding attribute information. Raster data is a spatial data model that is composed of equal cells arranged as an array of rows and columns defining an area on the surface of earth.

Table 3.1. 2 Description of type of data, format and source.

Type	**Format**	**Source**
Mean offshore wind speeds	Raster	Global Wind Atlas, 2021
Bathymetry	Raster	GEBCO, 2021
Shipping Traffic Density	GeoTIFF	The World Bank Data Catalog, 2021
Marine Protected areas	Polygon	The UN Environment Programme World Conservation Monitoring Centre (UNEP –WCMC) - Protected planet, 2021
Power Transmission – 220 kv	Line	World Bank's Energy Data (2021).
EEZ	Shapefile	Flanders Marine Institute, 2019

Source: (Author, 2021).

3.2 Data Analysis

This was largely a desktop exercise which entailed extracting data from online repositories containing measured and extra/interpolated data sets of: mean offshore wind speeds, bathymetric characteristics, marine traffic density and marine protected areas in the formats and sources explained **in Table 3.1.2.**

GIS is a computer based system used for generating, storing, analyzing and visualizing data related to a given location or surface of the earth. This system facilitates understanding of what is present, where it is geographically located, spatial patterns and relationships between different data sets.

The GIS data obtained was analyzed and visualized using Quantum GIS (QGIS) version 3.18.3 which is a free, open source GIS system that is used for the analysis of geospatial data. Subsequently, the limits for each data set were defined and for each potential site the constraints are compared with the standard thresholds. The sites were then ranked and the one with the most favorable conditions was selected. The approach is as illustrated in Figure 3.1.

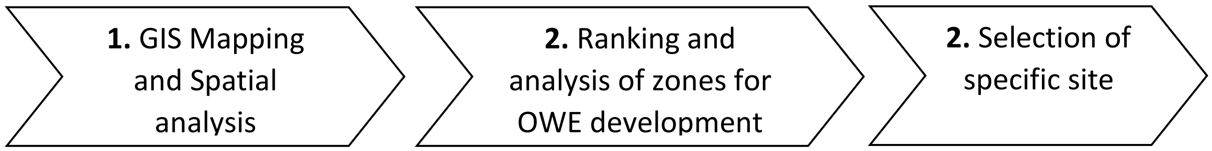


Figure 3. 1 Selection of site sequence of activities.

Source: (Author, 2021).

3.2.1 GIS Mapping and Spatial Analysis

In GIS each data set is managed as a layer of a given data type. A popular example of GIS is Google Maps however it is not suitable for carrying out complex data analysis. QGIS was used in carrying out this study because it is freely available and has advanced capabilities that are equivalent to those of advanced systems such as ArcGIS.

GIS mapping is the act of loading data layers into the GIS system so as to generate a map showing the spatial spread of the data on the surface of the earth. On the other hand, spatial analysis involves graphically merging more than one GIS layer into a hybrid layer that is further evaluated by way of computer processing so as to effectively evaluate the geographic suitability of certain locations for specific purposes.

For the purposes of this study as a rule of thumb all the GIS data sets were converted into a uniform format and resolution before commencing spatial analysis. In order to identify the most suitable OWE site, all the data layers were processed against the minimum thresholds set under Table 2.

3.2.2 Zone ranking and site selection

Upon performing spatial analysis, the area that met the criteria set out in Table 3.2.1 was considered to be appropriate for OWE development. The criterion considers the most critical constraints that relate to the technical potential of the offshore wind development. For instance, water depths directly affect the type of foundation to be used for a certain project, wind speed has an undisputable link to energy yield while transmission distance has a proportional relationship with electrical energy losses.

Further analysis involved splitting the appropriate area into zones based on their proximity to transmission substations. The zones were evaluated based on each element set out in the criteria and then ranked.

Table 3.2. 1 Criteria for selecting an OWE site.

Type Constraint	**Limit/ Range**	**Explanation**
Bathymetry	Consider areas of less than 50m depth	50 m is the average maximum depth for fixed bottom OWE projects.
Wind Speed	At least 7 m/s	Best practice according to DNV. Higher speeds equals higher energy yields
Distance to transmission substation	Should be minimized	The shorter the distance the lesser the transmission losses
Marine Traffic Density	>1 km from shipping route	Avoid disrupting shipping and for safety considerations
Marine Protected Areas	Exclude from suitable zone including a 10 km buffer	Minimize impact

Source: (Author, 2021).

3.3 Energy Yield

A conventional turbine of 10MW, 100m hub height and a blade diameter of 80m was selected. Offshore wind has a varying speed and assumes random directions as dictated by other natural occurrences.

In order to account for the dynamic nature of wind, the Weibull distribution probability model[3] was used to estimate wind speed frequency distribution (Justus, 1978). The probability function of a certain wind speed over a certain duration can be computed using Weibull parameters: A and k in the expression:

$$p(v) = \frac{k}{A} * \left(\frac{v}{A}\right)^{k-1} exp\ (-\ (\frac{v}{A})^{k})$$ .... (Equation 1)

Where $p(v)$ – Probability at a given speed v

The wind turbine's conversion factor is described by its Betz limit value; this is also referred to as the turbine’s power coefficient. The higher the Betz limit value the higher the efficiency of the turbine.

The instantaneous power of a wind turbine is defined by the following expression:

$$P = \frac{1}{2} A * C_p * \rho * V^3$$ .... (Equation 2)

Where: P - Power

A - area

C_p – Conversion factor

ρ – Density of air

V – Wind speed

The energy generated by a turbine was then arrived by using the expression;

$$E = P * t$$ .... (Equation 3)

Where: E – Energy

[3] Weibull distribution probability model is a continuous distribution used in the analysis of life data, failure frequency and reliability

t – time

The annual total energy per turbine was then obtained by summing up all the energy values as shown in the expression below;

$$E_{Annual} = Prob(Sector\ 30^0)\{\sum_{V0}^{vn} \quad P\ (V_1)E_{V0} + P(V_2)E_{V2} + \cdots P(V_n)E_{Vn}\} + Prob(Sector\ 60^0)\{\sum_{V0}^{vn} \quad P\ (V_0)E_{V1} + P(V_2)E_{V2} + \cdots P(V_n)E_{Vn}\} - - - - + Prob(Sector\ 330^0)\{\sum_{V0}^{vn} \quad P\ (V_0)E_{V1} + P(V_2)E_{V2} + \cdots P(V_n)E_{Vn}\} \text{...........(Equation 5)}$$

Where:

Prob (Sector) – proportional duration of occurrence of wind in a given direction (sector)

$P(V_x)$ – proportional duration of occurrence of wind at given speed

E_{VX} – Energy generated at a given speed at a given time and direction

The total energy of a wind farm is obtained by multiplying the number of turbines by the annual energy per turbine on assumption that there are no wake losses.

A python software programming language version 3.9 was used to perform the energy yield calculation so as to simplify the process. The script code for the program was developed based on the formulation provided under the energy yield formulation illustrated under 3.3.

3.4 LCOE and sensitivity analysis

In order to reliably approximate the total cost of construction of the model wind farm in this study, information on capital expenditure (CAPEX), operating expenditure (OPEX) and decommissioning expenditure (DEPEX) was adapted from published estimates from IRENA, NREL, QBIS and Wind Europe. The LCOE computation and sensitivity analysis was carried out using Oracle's crystal Ball software.

3.5 SWOT analysis

SWOT analysis is an acronym for the process of assessing the Strengths, Weaknesses, Threats and Opportunities of a certain project or activity. An assessment of the proposed offshore wind farm based on the results of the study was carried out so as to help form the basis of the conclusion as to whether offshore wind development is feasible in Kenya.

CHAPTER 4 – OFFSHORE WIND FARM DESIGN

4.0 Introduction.

Offshore wind farm design is a process carried out in two stages. The first stage is initiated by the government through the responsible ministry or agencies such as The Danish Energy Agency and UK's The Crown Estate while the second stage is investor led.

4.1 Identification of offshore wind development zone.

The first stage entails the demarcation of offshore zones that have been found to be favorable for offshore wind development because of the adequate wind resources in the area. The proposed zones are situated in areas not utilized for other marine services such as marine protected area, fishing grounds, shipping routes, oil and exploration sites, submarine cables, marine settlement and offshore military operations., this is mostly carried out by state agencies The success of Offshore Wind Farm development is dependent on a number of external factors that can be largely analyzed using the PESTEL[4] strategic framework illustrated in Table 4.1.

Table 4. 1 Factor Affecting OWE Development.

P	E	S	T	E	L
Political	Economic	Social	Technological	Environmental	Legal
- Political will - Security situation	-Demand for power - Availability and cost of capital	-Visual impact and noise	- Offshore wind characteristics -Bathymetric dimensions -Distance offshore -Metocean characteristics	-Marine protected areas	-Policy mechanism

Source: (Author, 2021).

[4] PESTEL is helpful in analysing all the external factors that are likely to affect the success of a project. It is simply a strategic management tool used to study the macro-environment factors.

4.2 Design and Development

Wind farm design and development is the second stage; it is commenced once the tender has been awarded to a specific developer by the state. The awardee proceeds to carry out a detailed design that involves of the wind characteristics, metocean conditions, the geotechnical, appropriate foundation type and wind turbine and also the most optimal wind farm layout with a view to limit wake effects, cable lengths and consequent operation and maintenance costs (MARE-WINT, 2016, p. 337).

The principle elements of a typical offshore wind farm are: The wind turbine(s) and the balance of plant, they are illustrated in the subsequent subheadings.

4.2.1 Wind turbine

A wind turbine is the principle element for generating wind energy, it converts the rotational motion of a rotor into electrical wind energy. The rotational energy is a result of air flow which causes a lifting force on the wind blades which are in turn linked to the generator via a shaft and gear mechanism as shown in Figure 4.2.1.

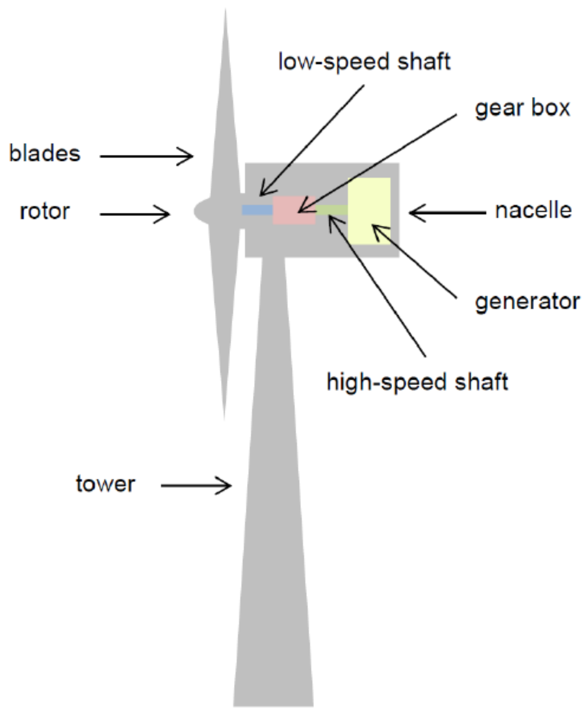


Figure 4.2. 1 A typical wind turbine. (hopgoodganin, 2021).

The choice of an Offshore Wind Turbine

A side from size, design and type, class is a key consideration when selecting a turbine. For instance, class I, II or S turbines are recommended if the wind farm location is expected to be located in an area with extreme typhoon conditions. Accurate selection of an offshore turbine requires adequate consideration of other parameters such as the mean wind speed of the site, the turbine's power curve, hub height, cut-in and rated wind speeds (Dangar et al. 2011). Modern approaches to turbine selection entail use of automated software such as DNV's Turbine Architect.

As shown in Figure 4.2.2, the average turbine rating for wind farms installed in 2020 was 8.2 mw which is a 5% increase compared to 2019's 7.8 MW average. Studies indicate that the turbine rating of projects going live in 2022 range from 10MW to 13MW (Wind Europe, 2020).

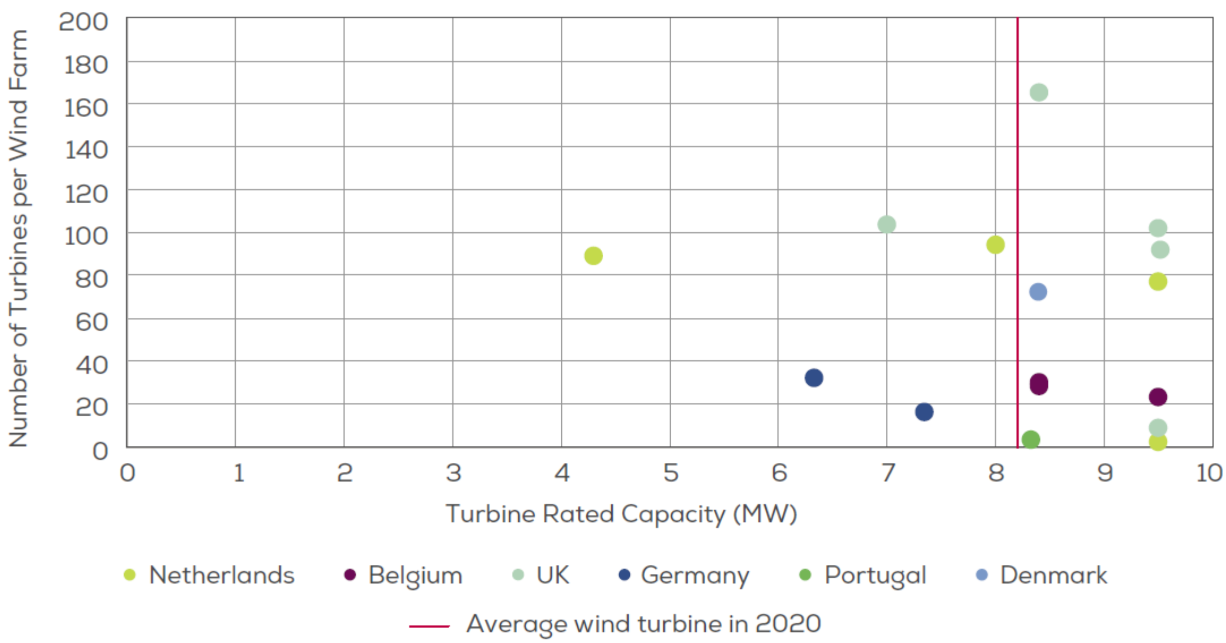


Figure 4.2. 2: Average turbine rated capacity and average number of turbines at wind farm in 2020. Source: Offshore Wind in Europe - Key trends and statistics 2020 by Wind Europe, 2020, p.17.

The design and the length of the rotor blades defines the capacity of a turbine. The larger the rotor diameter the higher the capacity. However, a maximum of 59.3% of the wind's kinetic energy can be theoretically extracted going by the Betz law limit. Due to technological advancements and ongoing research, offshore wind turbines of higher ratings continue to be manufactured

4.2.2 Balance of Plant

Refers to design and supply of towers, foundations, cables, buildings, electrical systems that include: array cables, export cables and substations (both on and offshore) which make up the wind farm except wind turbines.

i. Towers

This is the part that supports the turbine blades and nacelle (the part that houses the generator, gears and control box) as shown on Figure 4.2.1, it is either anchored or tethered on the seabed depending on the type of foundation. The tower should be structurally sound so to withstand the dynamic aerodynamic, mechanical loading effects and external impacts.

ii. Foundations

Foundation play an important role of anchoring the tower and offshore platforms so as to elevate turbines and offshore substations respectively above the sea level. Any of the types of foundations are used depending on the weight to be supported, water depth and cost. For water depths of about less than 50m, bottom fixed foundation structures are ideally appropriate whereas floating foundation structures should be used for water depths of above 50m. The various foundation topologies commonly used are illustrated in Figure 4.2.3.

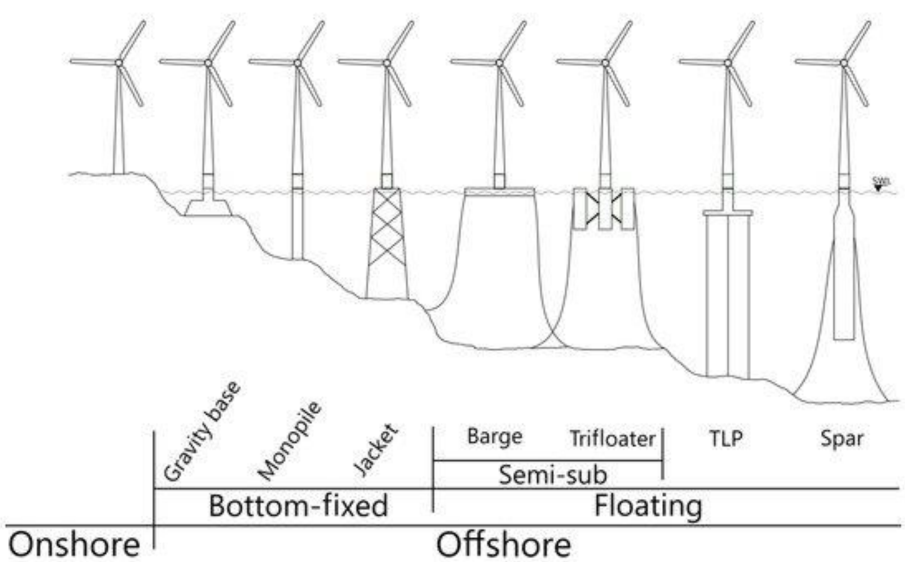


Figure 4.2. 3 An illustration of the main foundation type concepts. A Feedback Control Loop Optimisation Methodology for Floating Offshore Wind Turbines. *Energies* **2019**, *12*, 3490.

Gravity base and monopole topologies are used for water depths of up to 50m deep and can support wind turbines of about 2 MW capacity. Jacket/tripod foundation structures are superior to the former foundation topologies, they can be used offshore in area of up to 50m deep and can safely support turbines of up to 5 MW.

Berge, trifloater, Tension Leg platform (TLP) and spar foundations are all floating structure types. They are used where sea depth exceeds 50m.

iii. Cables

Cables are used to transfer electrical power the turbines to the electrical network via the substation and other intermediate electrical devices as shown in Figure 4.2.4.

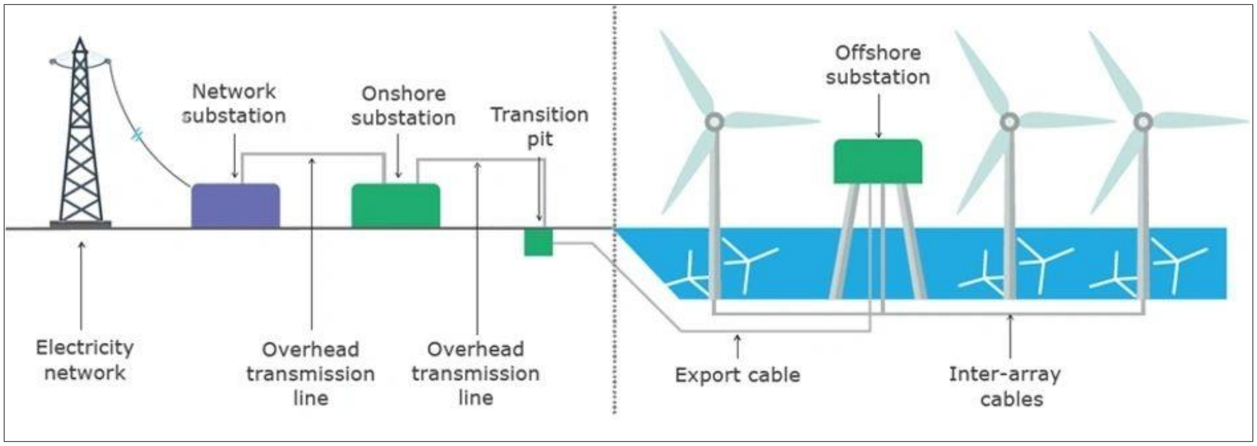


Figure 4.2. 4 An illustration of the turbine – cable – substation connection in a wind farm.

Source: WA Offshore Windfarm Pty Ltd. 2021.

Inter Array

These are single length subsea cables used to connect one turbine to another hence forming an electrical circuit that eventually terminates at the offshore substation as shown in Figure 9.

Export cables

Export cables are akin to inter array cables except that they are of a higher voltage rating, they are used to link the turbine circuit to the transmission network via an off/onshore substation electrical configuration adopted.

iv. Substations

This is where all the power generated by all the turbines is collected. The substation transformers then step up the voltage of the power voltage into a high transmission voltage such as 132KV before the power can be exported to the grid. The step is necessary so as to reduce power transmission losses. Substations can either be located on/offshore and are made up of switchgear equipment for isolating the circuit.

v. Onshore Electrical

This refers to the transitional equipment for coupling the offshore export system with the existing national transmission network. It also includes equipment for synchronizing power characteristics to ensure that the exported power meets the grid's power quality requirements.

4.2.3 Optimization of Wind Farm Design

An offshore wind farm is an assemblage of individual wind at sea interlinked using array cables and then connected to the power transmission system using an export cable(s). The turbines can be installed adjacent to each other equidistantly in a straight line, in a grid pattern or randomly clustered together as shown in Figure 4.2.5.

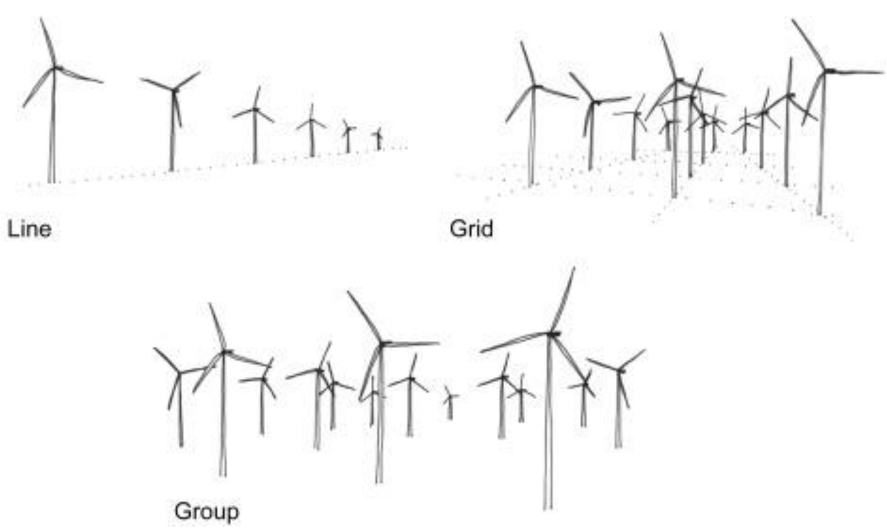


Figure 4.2. 5 Wind farm installation topologies.

Source: Chapter 23 - wind turbines and landscape. In T. M. Letcher (Ed.), *Wind energy engineering* (pp. 493-515).

Wake losses

The wake effect phenomenon arises as a result of reduced speed of the prevailing wind as it blows downstream through a series of turbines such that the subsequent turbines experiences a lower speed than the preceding one relative to the prevailing wind.
A key aspect of wind farm layout is inter-turbine distance; this is because wake losses arise if the wind turbines get closely clustered. The minimum distance between turbines for this study was assumed to be at minimum four times the turbine rotor diameter as shown in Figure 4.2.6.

The minimum distance between turbines should be typically at least 4 to 7 times the turbine rotor diameter and in the region of 4 to 5 times across the wind. The preferred specifications are usually stated in the provided Wind Farm Site Decision document during auction. Optimization can also be efficiently achieved using advanced software such as DNV's Wind Farmer and DTU's WindPro.

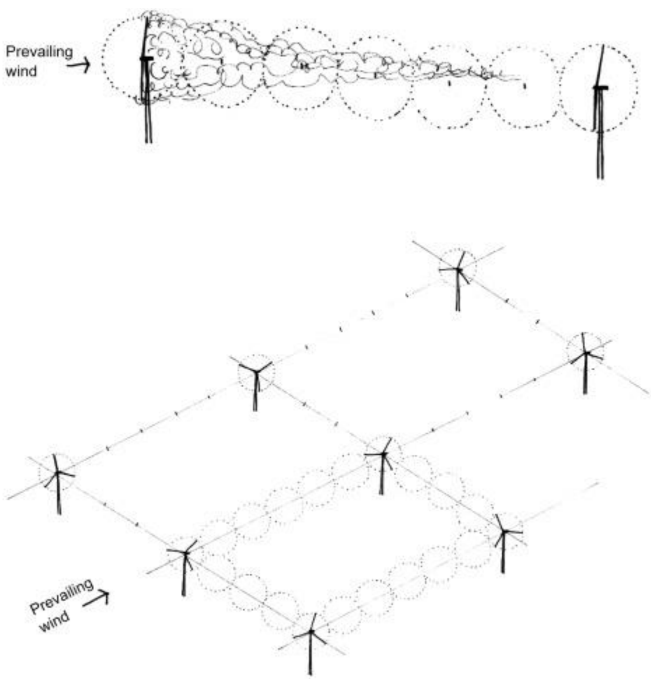


Figure 4.2. 6 Wake effect illustration.

Source: Adapted from Chapter 23 - wind turbines and landscape. In T. M. Letcher (Ed.), *Wind energy engineering* (pp. 493-515).

CHAPTER 5 – CASE STUDY: OFFSHORE WIND POTENTIAL IN KENYA

5.0 Kenya's EEZ explained.

Kenya is a country located in Eastern Africa with a coastline bordering the Indian ocean. It has an EEZ extending 200nm into the sea covering a total area of about 142,00 km^2 located within a Minimum Latitude of 4° 54' 1.2" S (-4.9003°), Minimum Longitude of 39° 13' 16.7" E (39.2213°), Maximum Latitude of 1° 39' 14.7" S (-1.6541°) and a Maximum Longitude of 44° 19' 46.5" E (44.3296°) according to marine regions (2021). The total ocean area amounts to about 245,000 km^2 which is more than 42% of her land mass area therefore making the EEZ a significant part of Kenya's territory as shown in Figure 5.0.1.

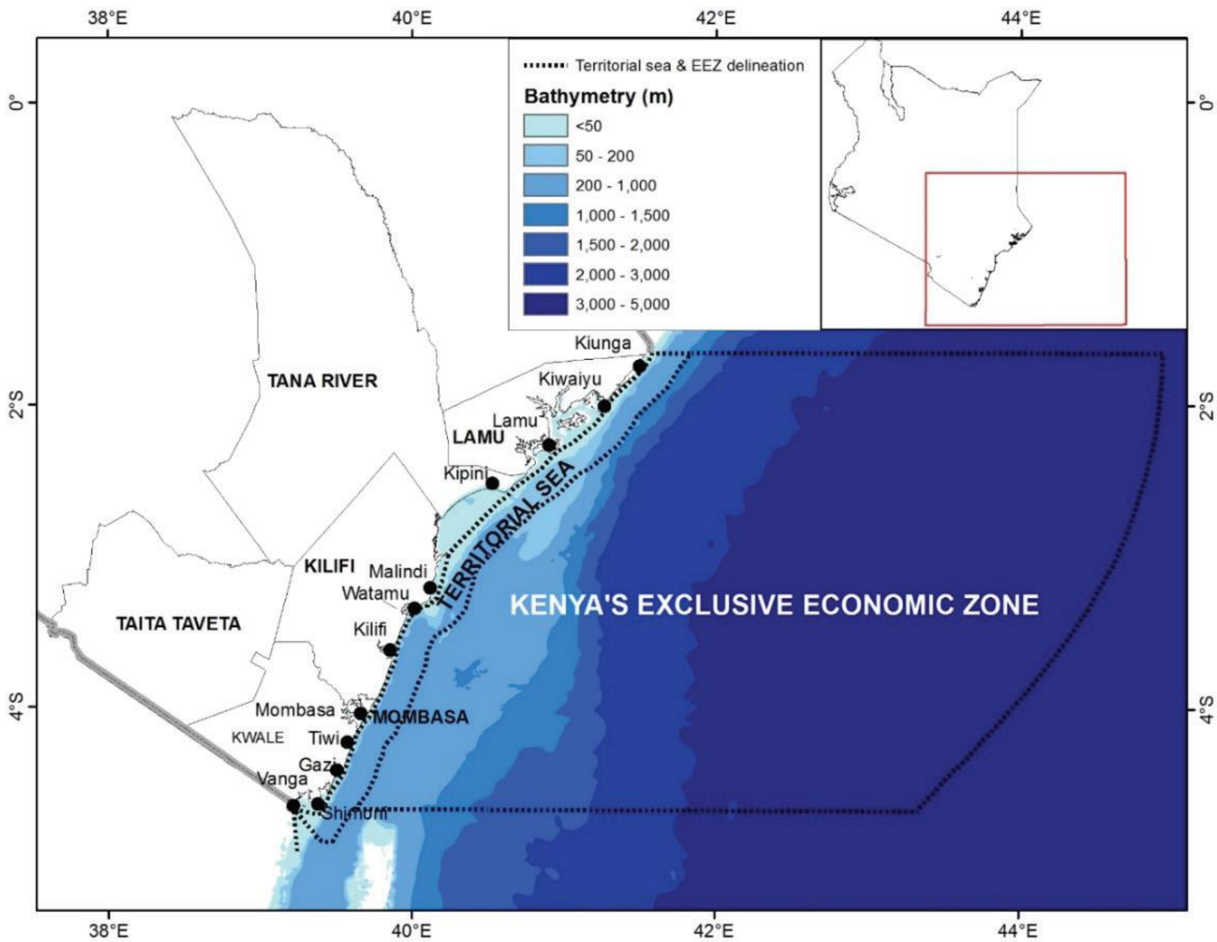


Figure 5.0. 1 Kenya's EEZ according to the Presidential Proclamation Legal Notice No. 82.

Source: Marine Research towards Food Security and Economic Development in Kenya by Kenya Marine and Fisheries Research Institute, 2018, p.10.

5.1 Kenya's energy sector outlook

5.1.1 Power Generation Mix

According to the Energy sector overview and 2020 outlook report by EPRA, Kenya's installed capacity as at the end of year was 2,819 MW with a peak demand of 1.912 MW. This translated into about 86.8% from renewable energy sources with Geothermal accounting for 45% of the total energy mix. Thermal energy sources contributed 11.3% of the total generation in 2019 (EPRA, 2020). According to the Kenya Power and Lighting Company (KPLC) – the state's power utility company annual financial report, 2Geothermal and Hydro combined contribute the largest share of the energy mix while Wind and Solar show an upward trend as shown in Figure 5.1.1 (KPLC, 2020).

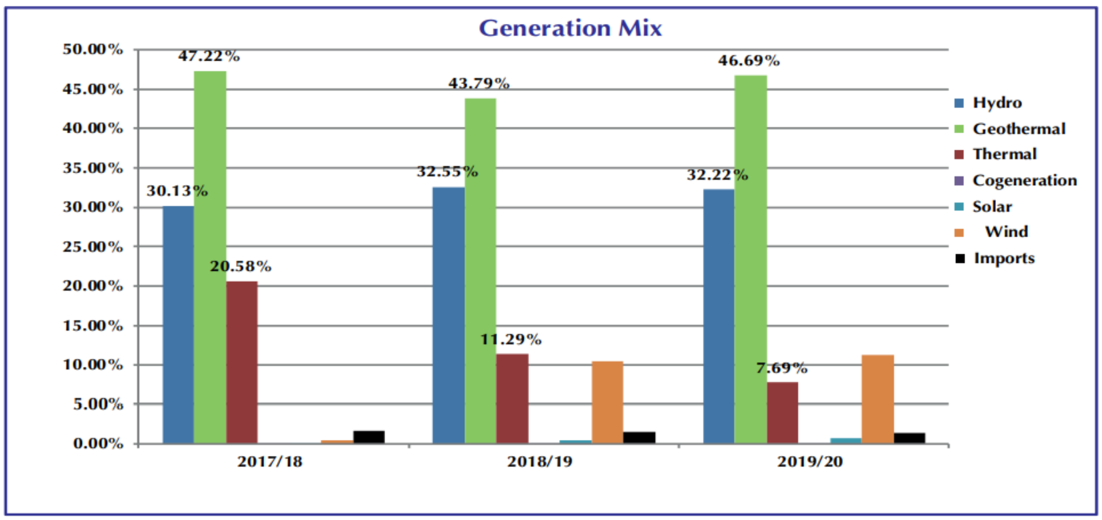


Figure 5.1. 1 Kenya's Power Generation mix.

Source: Kenya Power Annual Report and Financial Statements for the year ended 30th June, 2020.

2019's installed capacity of 2,819 MW represents a 5.7% rise compared to the year 2018 due to the commissioning of The Lake Turkana Wind Power project (LTWP). LTWP is the biggest wind power project in Africa with an installed capacity of 310 MW consisting of 365 turbines each with a capacity of 850KW. Additionally, the 50MW Garissa solar power plant and the 150 MW - Olkaria Geothermal power plant also contributed to the increased capacity in the same period.

5.1.2 The spatial distribution of Kenya's Generating Plants.

Most of the country's the high economic activities are conducted in and around Nairobi which is Kenya's capital city. Nairobi located in the central part of Kenya. The geographical distribution of these major power generating plant is mainly around the central region of the country as shown in Figure 5.1.2. This is because most of the country's the high economic activities are conducted near Kenya's capital city, Nairobi whose location is central relative to Kenya's international boundaries. Consequently, this reality has resulted into huge settlement in Nairobi county and its cosmopolitan counties such as Kiambu, Machakos, Nakuru and Kajiado. Effectively, there is a huge demand for power around the central part of the country.

The coastal area is linked to the national grid via a 220KV transmission line spanning a distance of about 500 km.

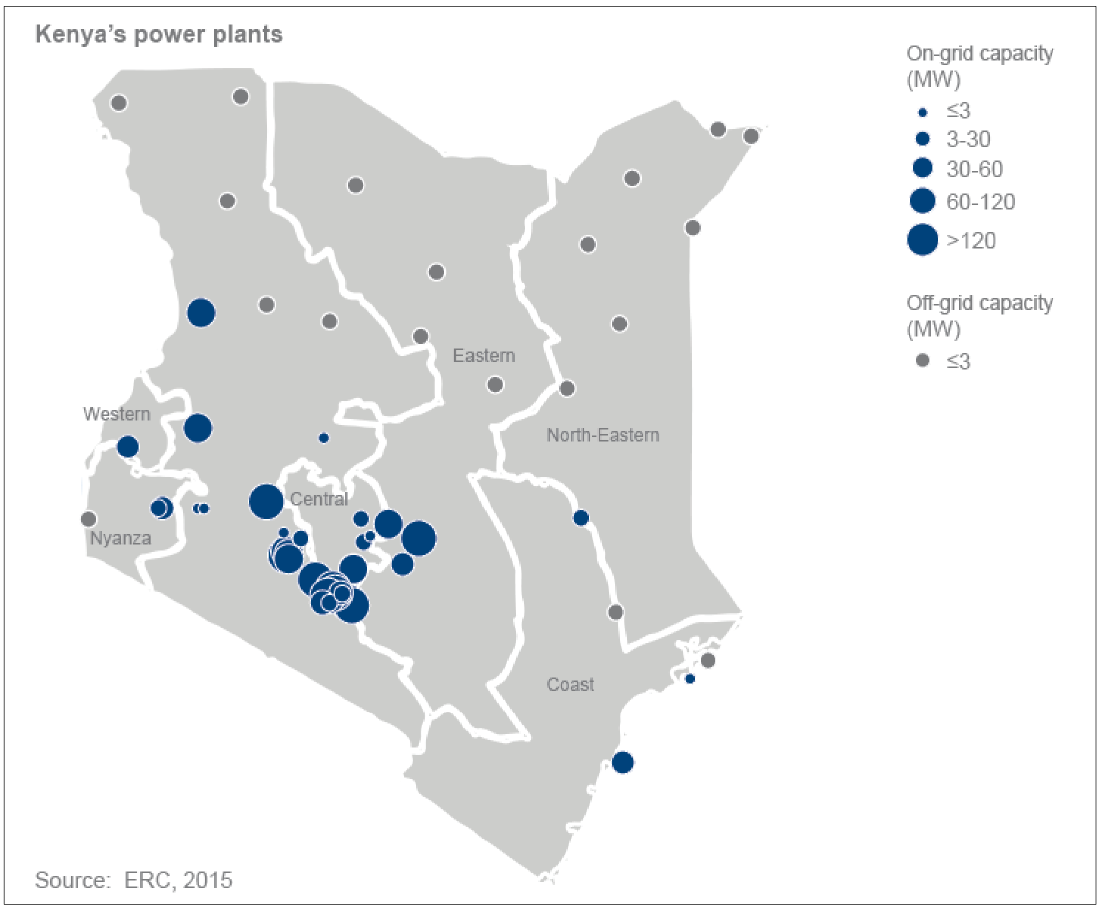


Figure 5.1. 2 The spatial distribution of power generating plants within Kenya. Adapted from The Kenya power sector report, p. 11.

5.1.3 The blue economy – Energy demand nexus

Despite the prevailing slow down due to the COVID-19 pandemic, Kenya has sustained her ambitious development agenda. The LAPSSET project is fast taking shape, port operations have since commenced at the first three berths out of the planned thirty-two berths (LAPSSET, 2021). The Port of Mombasa is fast expanding in capacity with the ongoing construction of more berths expected to increase the port's throughput by around 450,000 TEU per annum, the recently completed standard gage railway linking Mombasa to the capital city – Nairobi is planned for electrification in the near future and the planned development of The Dongo Kundu Special Economic zone that is poised to be a major transshipment hub is in the pipeline. The construction of a fishing port – Shimoni Port is about to take off. Consequently, Industrial development is expected pace up given that companies shall seek to position their operations near the port city.

These developments are expected to result in a surge in the demand for electricity in the coastal region. This necessitates the need for a reconsideration of the historical concentration of the power generation activities at the central and northern parts of the country that are averagely 600 km away from the coast. Kenya's coastal region has largely been preferred for the development of thermal Power plants by KenGen, the state's main power producer and other Independent Power Producers (IPPs) such as IBERA Africa and WARTSILA given the proximity to port facilities hence leveraging on the advantage of minimized transportation cost of diesel oil used for generation purposes. Diesel powered plants averagely account for more than 13% of the energy consumed as at the end of 2019 (EPRA, 2020).

The Levelized Cost of Energy (LCOE) of diesel thermal power plants is significantly higher thus contributing to the high per unit price of electricity in Kenya. In February 2021, EPRA set Fuel Cost Charge on electricity at a 14-month high of 0.0261 $/Kw/h (Business Daily, 2021). According to EPRA's strategic plan status information, energy losses have also been on the rise and now stand at 22.2% against an allowable loss factor of 14.9% (EPRA 2021). As a mitigation measure against the significant power transmission costs and associated energy losses there is a need to focus on investing in renewable energy alternatives such as solar, offshore wind and wave energy that are available within the coast region so as to match the expected exponential demand for power in the near future.

In order to accelerate achievement of the set energy objectives, The 2006 Energy Act was revoked upon enactment of the new Energy Act 2019, this new law addressed the coherence of the inter-institutional framework of the energy sector and expanded the roles of The Energy Petroleum Regulatory Authority (EPRA) which are: oversee procurement of energy continuously appraise the state of Kenya's energy security, formulate and update energy tariff and also avail bankable renewable energy resource data for utilization by potential investors (EPRA, 2021).

The installed capacity of 2,819 MW against a population of more than 50 million translates to a relatively lower per capita unit of electricity as compared to developed economies. Kenya plans to ramp up her installed electricity capacity to 10,000 MW by 2030 in order to keep up with the projected increase in electricity demand and also so as to achieve universal access to electricity by connecting the remaining 30% of the country's population.

5.1.4 Baseline data - Based on energy utility sales.

Kenya Power, Kenya's sole utility power company made a sale of 1,464 GWh units of electricity in the coastal region for the year ended June 2020 hence making the coastal part of the country a significant load center ranking third in the country as shown in Figure 5.1.4.1.

Table 5.1.4. 1 Total electricity unit sales by region in Gwh.

REGION	2015/16	2016/17	2017/18	2018/19	2019/20
Nairobi North	1,187	1,301	1,204	1,219	1,209
Nairobi South	1,696	1,759	1,728	1,719	1,733
Nairobi West	808	853	898	958	960
Coast	1,338	1,389	1,435	1,477	1,464
Central Rift	569	596	650	689	680
North Rift	280	269	303	288	302
South Nyanza	48	86	88	104	123
West Kenya	320	313	361	376	376
Mt Kenya	413	431	437	456	439
North Eastern	671	704	776	862	869
KPLC Sales	7,330	7,701	7,881	8,147	8,154
R.E.P. Schemes	537	549	554	595	602
Export Sales	45	22	23	27	18
TOTAL	**7,912**	**8,272**	**8,459**	**8,769**	**8,773**
%INCREASE P.A.	**3.4%**	**4.5%**	**2.3%**	**3.7%**	**0.05%**

Extracted from "Kenya Power Annual Report and Financial Statements for the year ended 30TH June 2020".

CHAPTER 6 – CASE STUDY: OFFSHORE WIND FARM PROTOTYPE DESIGN.

6.0 Key Technical Assessment considerations

This encompasses the technical analysis of Kenya's: Offshore Wind characteristics, Water depth (bathymetric characteristics), Marine Protected Areas, Ship traffic density and availability of transmission infrastructure.

i. Kenya's Offshore Wind resource

This study uses Wind Atlas version GWA 3.1 as the primary data source for Wind speed data at a height of 100 m resolution. This data is based on 10 years of mesoscale time-series model simulations covering at 3 km resolution, and microscale model calculations at a 250 m grid spacing. Validation of the data extracted was performed using data from measurement campaigns in Pakistan, Papua New Guinea, Vietnam, and Zambia (Wind Atlas, 2021).

The offshore wind data available on wind Atlas is up 200 km from the baseline. The data presented in Figure 4.2.8 was downloaded from Global Wind Atlas with a coverage of 30km offshore at a 250m resolution in tiff format, using QGIS's clipping tool the offshore area was selected, analyzed and visualized applying a pseudocode symbol option to illustrate the wind speeds at the various coordinates.

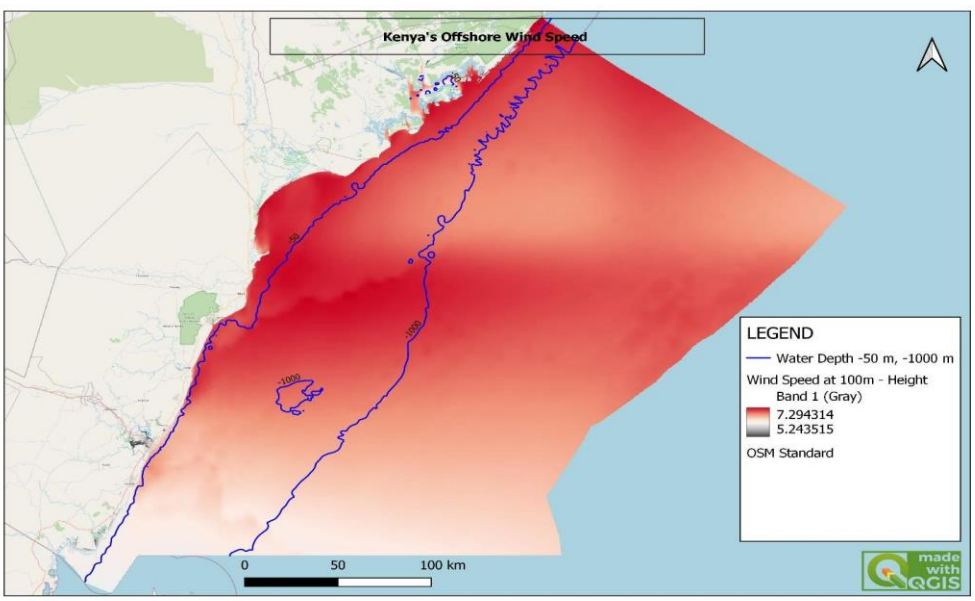


Figure 4.2. 7 Kenya's Offshore Wind Speed Source. (Author, 2021).

The Global Wind Atlas's mesoscale and microscale modelling can cause uncertainties in calculations which can be attributable to representativeness of the large scale forcing and sampling, model grid size, description of the surface characteristics and departures from the reference wind profile

These wind data should therefore be validated by carrying out actual wind measurement data acquired using an on-site LIDAR wind deployed offshore on a fixed platform for at least one year in the post-feasibility period.

Wind speed patterns above show that higher average wind speeds are experienced in areas close to the shores within water depths of less or equal to 50m.

The wind speed data in Figure 4.2.9 is further analyzed as presented in Figure 4.2.9. It is evident that the frequency of wind speed is more than 50 for wind speeds between 6.8 m/s and 7.2 m/s. This implies that the select area average wind speeds are significant enough to warrant further assessment.

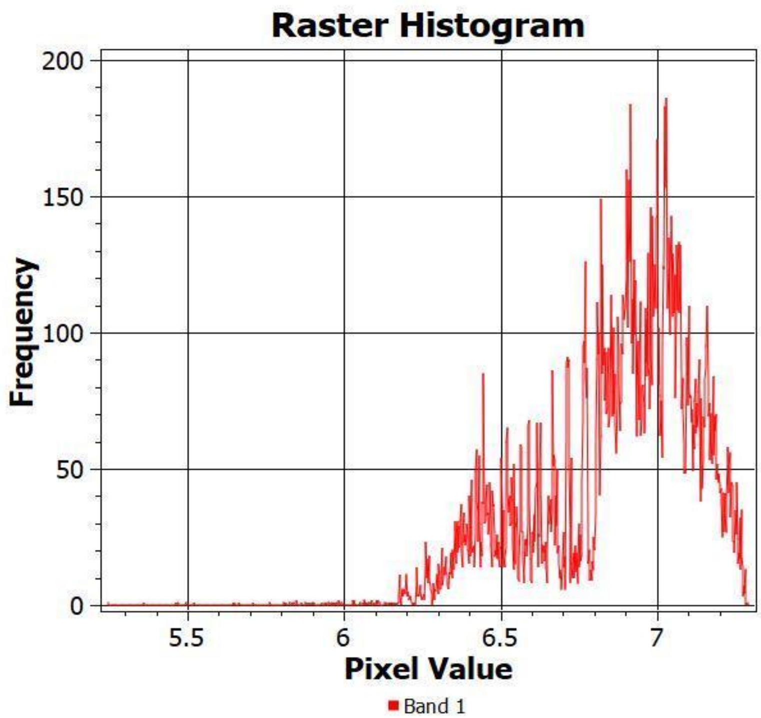


Figure 4.2. 8 A graph of Frequency against Average Wind Speed (Pixel Value)

(Author, 2021).

ii. Bathymetric conditions of Kenya's EEZ

Water depth is a key consideration when establishing the most optimal site for OWE development. Water depth dictates the type of foundation to be employed which in turn significantly affects the cost of the project. Water depth study was conducted by analyzing data acquired from the General Bathymetric Chart of the Oceans (GEBCO), this freely accessible bathymetry data resource was developed through Nippon Foundation-GEBCO Seabed 2030 Project. "GEBCO Grid is a continuous, global terrain model for ocean and land with a spatial resolution of 15 arc seconds" (GEBCO, 2021).

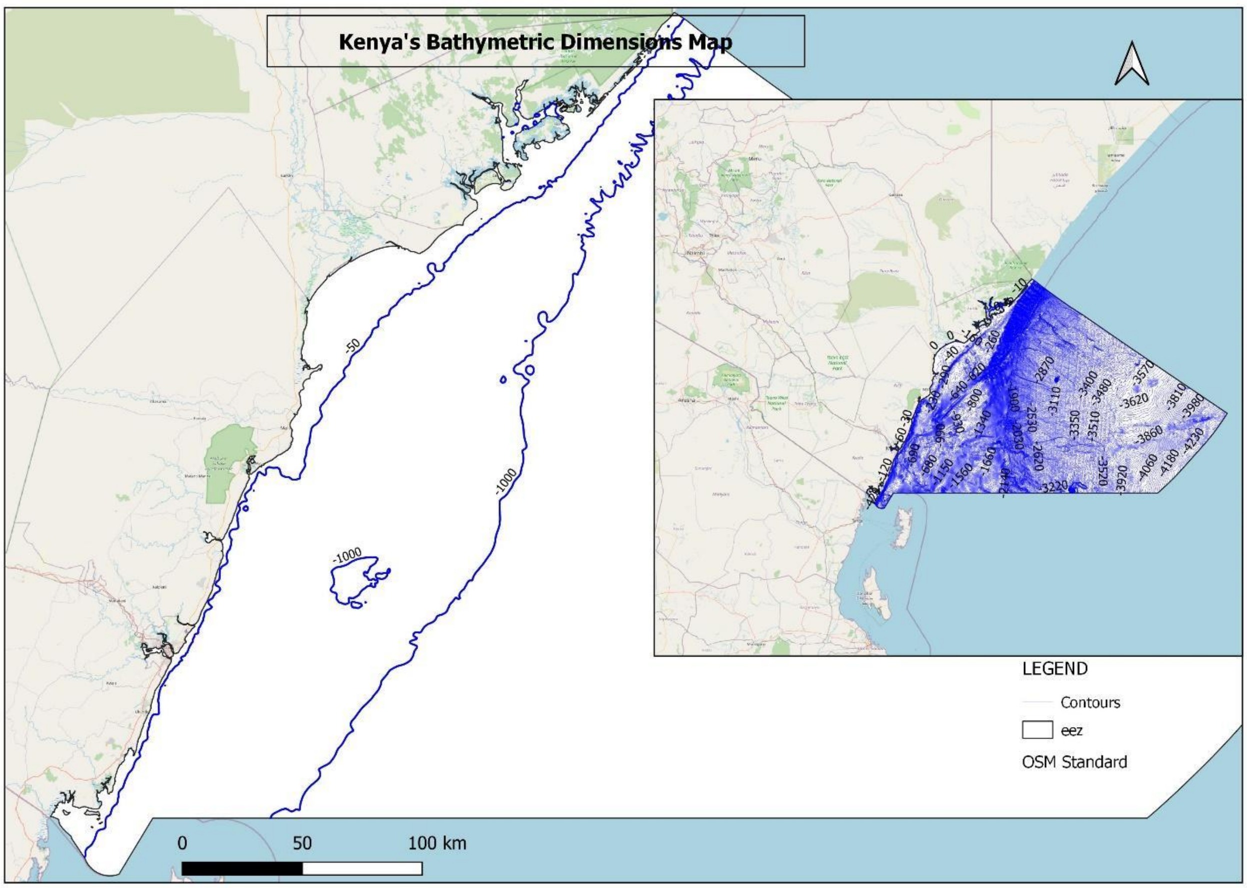


Figure 4.2. 9 Kenya's offshore Bathymetric profile.

(Author, 2021).

Figure 4.2.10 illustrates the water depth profile, data from GEBCO was extracted in raster format (.tiff), since GEBCO is only downloadable in extends beyond the exact area covered by the EEZ it was clipped using an EZZ shape file as the masking layer obtained from Flanders Marine Institute (2019). The visualization of the data is further enhanced by using the contours tool with the interval set as 10m. The results are as shown on the cropped map to the right on Figure 4.2.10.

Since shallow water offshore wind turbines with a fixed foundation type can be implemented up to water depths of about 50m while going by recent studies floating offshore wind turbine structures can be implemented up to water depths of about 1000m, the contours on the map to the right were filtered thus producing a map with only two contours representing the average boundaries of water depths at 50m and 100m. It is evident that Kenya has a narrow shallow offshore area compared to the water depth range of between 1,000m and the maximum of about 4,230m.

This is attributable to Kenya's narrow continental shelf. This consequently means that fixed foundation OWE projects sites will fall not so far offshore. This information shall be incorporated in the subsequent analysis that involves considering the average wind speeds experienced, mapping and hiving off marine protected areas.

iii. Marine Protected Areas in Kenya

OWE projects have numerous environmental effects during construction and the operation phase. Construction involves intensive pile driving operations, dredging, frequent transportation, construction of offshore platforms and mooring to the seabed. This results in changes of oceanographic processes such as fragmentation of habitats, changes in benthic and pelagic habitats and entanglement of animals in mooring systems. Electromagnetic field from connecting undersea cables from the various turbines and for evacuating power offshore is another pollution component in the post construction phase (OSPAR Commission, 2008). Design of OWE and their location relative to sensitive marine zones are important factors in minimizing impact.

In order to ensure that environmental impact due to OWE is minimized this study considered the gazette Marine Protected Areas (MPAs) within Kenya's EEZ as illustrated in **Figure 4.2.11.** The objective is to buffer the areas from consideration as potential sites for OWE development. The data was obtained from an online repository of The World Database of Protected Areas UNEP-WCMC (2021).

Kenya has six main MPAs: Mombasa, Malindi, Kiunga, Kisite and Diani-Chale. The MPA covers 857 km^2 of the marine and coastal area against a total marine coastal area of 112,400 km^2 which translates to 0.76%.

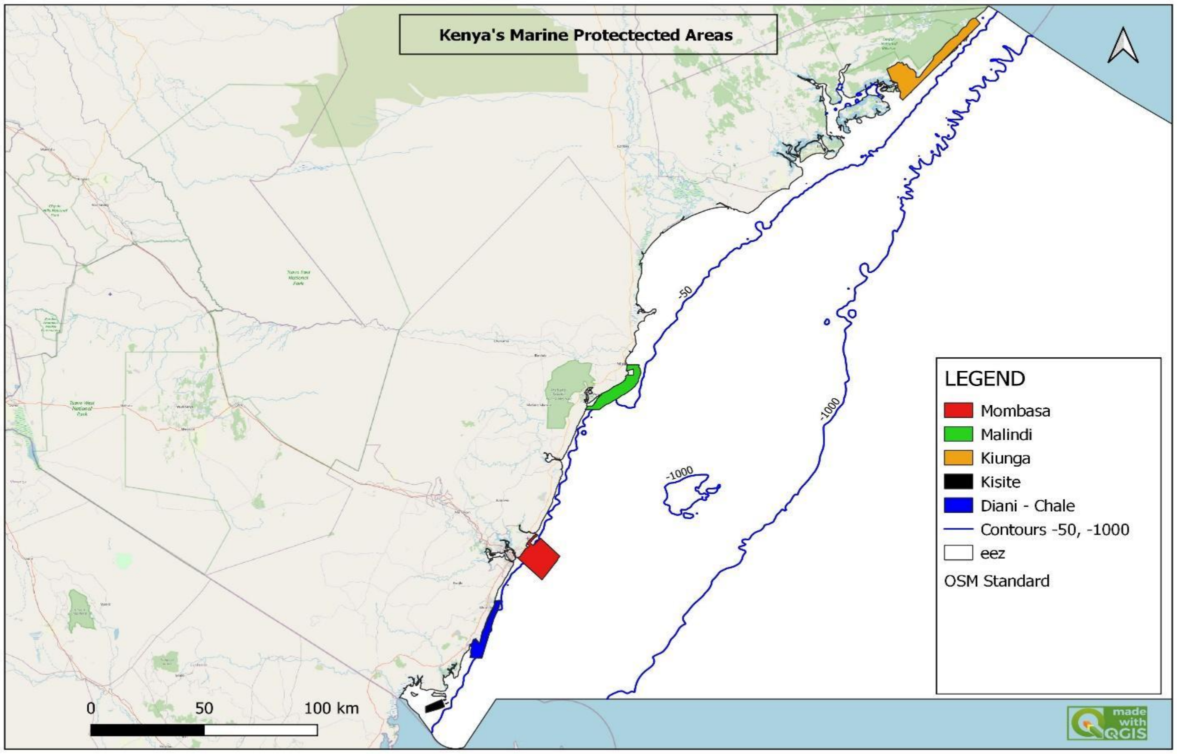


Figure 4.2. 10 Kenya's Marine Protected areas.

Generated on QGIS based on data from UNEP-WCMC. (Author, 2021).

Other key environmental survey activities such as Benthic environmental surveys, ornithological studies (study of birds), marine mammals, onshore environmental effects and human impact assessments should also be conducted during the feasibility studies (BVG, 2019)

iv. Kenya's Shipping Traffic Density

Marine transport continues to emerge as a key economic factor for developing countries such as Kenya. Kenya is a key gateway to East and Central Africa, the port of Mombasa serves the regions landlocked countries such as Uganda, Rwanda, Burundi, Ethiopia and South Sudan. The port provides direct connectivity to over 80 ports worldwide. The cumulative expansion activities at the port of Mombasa contributes to the increased ship traffic along Kenya's EEZ. Recent developments such as the launching of the new Lamu Port towards the northern side of Kenya's shoreline will result into more increased shipping traffic (Kenya Ports Authority, 2021).

In order to reduce maritime conflict in proposing sites for OWE development it is important to consider the distribution of ship traffic, navigation patterns and established shipping routes. The objective is to ensure that proposed shipping routes would not opaque shipping activities. This study adapts publicly available Global Shipping Traffic Density data available on The World Bank website. The data set represents a combination of hourly AIS positions received six types of vessels for the period between 2015 and 2020, the objective was to enable integration into of this data into World Bank's OWE program. The data was developed through a partnership with IMF as part of IMF's World Seaborne Trade Monitoring System (The World Bank, 2021).

The data is extractable from The World Bank's catalogue as a raster image. Using QGIS it is visualized and resampled as shown in Figure 4.2.12. It is evident that shipping traffic density is concentrated towards the southern part of the EEZ since most of the ship traffic starts and terminates at the Port of Mombasa. Traffic density patterns further shows that ships navigate to and from the south eastern cape and straight off the coast towards the Eastern part of the Indian ocean.

Another key consideration that will redefine the shipping routes is the recently launched Lamu Port and the planned port projects such as Shimoni port. It will be necessary to factor in any foreseeable trends that are likely to affect the siting decision of OWE projects.

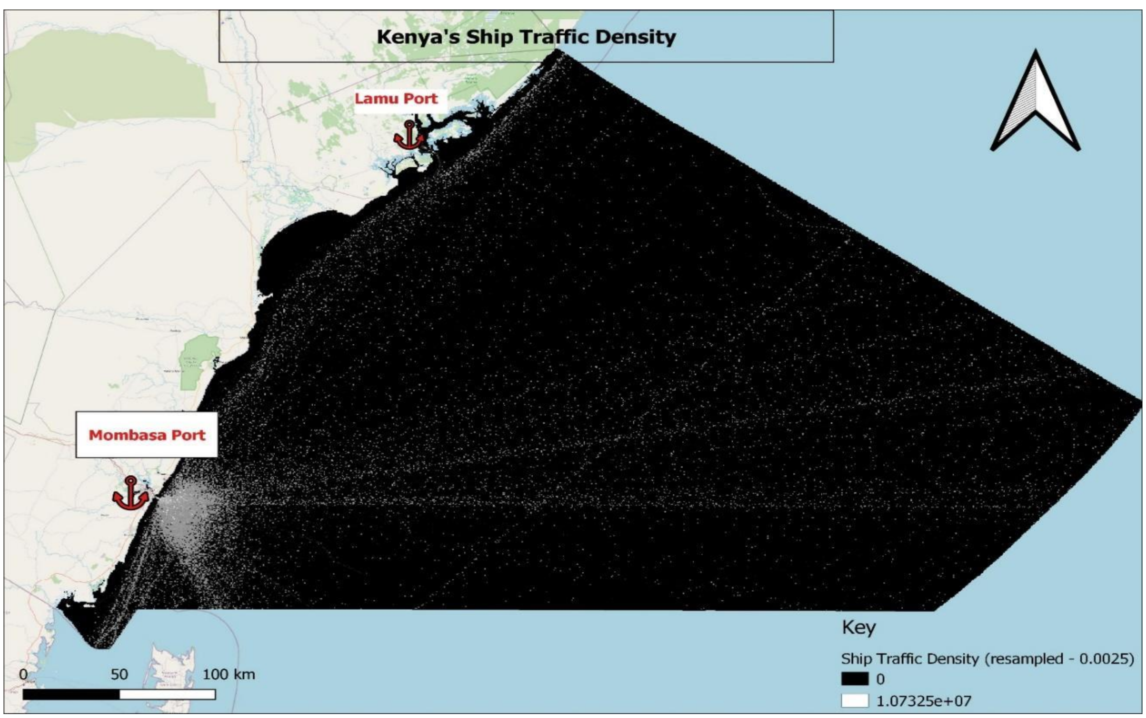


Figure 4.2. 11 Kenya's Shipping Traffic Density.

(Author, 2021)

Also shown in Figure 4.2.12 are the two major ports: Mombasa and Lamu Ports. Their location relative to the proposed site for development is important since implementation of OWE projects comes with a lot of transport and logistics requirements.

v. Kenya's Coastal Zone Power Transmission Network

Kenya through KETRACO, a state corporation charged with the mandate to plan, design, construct and operate a high voltage transmission grid continues to fast-track the development of transmission infrastructure along the coastal region. This was driven by the growing demand for power in the North coast towns, the ongoing construction of the Lamu port and expanding interest by energy investors in the region. In January 2021, the corporation commissioned a 320km, 220Kv Rabai - Malindi – Garsen 220Kv and Garsen – Lamu transmission line with substations at Malindi, Garsen, Lamu and Rabai (KETRACO, 2021).

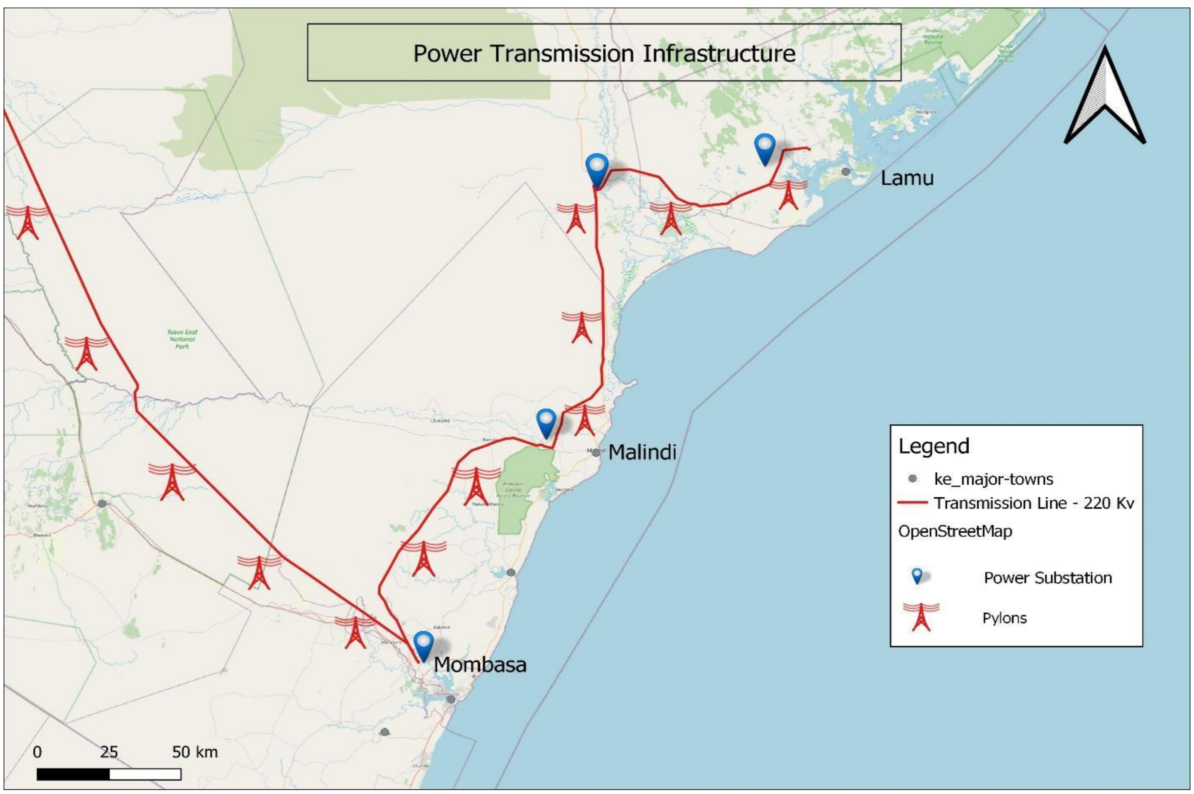


Figure 4.2. 12. Power Transmission infrastructure along Kenya's coast.

(Author, 2021).

The power transmission infrastructure network and substations at Rabai (-3.9332069, 39.5604906), Malindi (- 3.209425, 39.979290), Garsen (-2.3245417, 40.1070615) and Lamu (-2.201215, 40.782007) are as represented in Figure 4.2.13 using GIS data obtained from World Bank's Energy Data (2021).

Since the aim is to have the power generated offshore injected to the grid, it is critical to consider the distance between the proposed site and the nearest transmission substation so as to minimize power transmission losses.

Selection of suitable site for Offshore Wind Development in Kenya

6.1.1 Spatial Analysis

Having loaded and symbolized the various constraints into QGIS as illustrated in the preceding subheadings spatial analysis follows. For the purposes of this study, all the data sets shall be converted into raster format at a resolution of 0.0025 pixels and subsequently analyzed, this process is referred to as **resampling**. Although it is possible either to increase or decrease the resolution of a raster it is best practice to only decrease the resolution such that all the data sets have their resolution set to match the minimum resolution set for either data sets before carrying out any transformation.

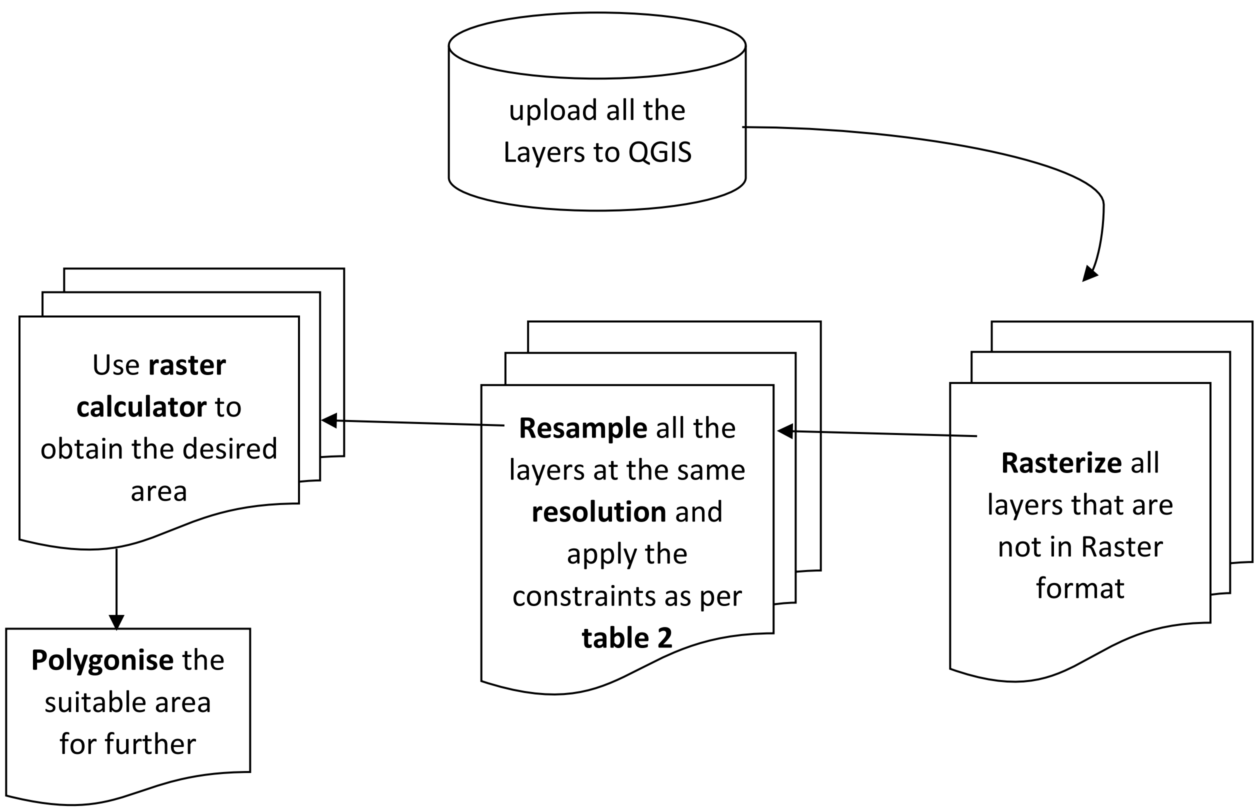


Figure 6.1 1 Spatial analysis process.

(Author, 2021).

In QGIS the GDAL translate tool is used to resample all the data sets: Bathymetry, Wind Speed and Ship Traffic Density. The spatial analysis process executed is as illustrated in Figure 6.1.1.

The principle criteria for selecting a suitable location for the development of a wind farm is that the potential zone should sumultaneously experience adequate wind, be of the desired bathymetric conditions depending on whether the intention is to either develop a bottom-fixed wind farm or a floating one. Additionally, the distance to show is crtical for purposes of ensuring economical power dispatch.

Using the raster calculator function in QGIS the offshore wind data layer is further analyzed processed so as to create a new raster layer representing areas with wind speeds of at least 7 m/s as shown in Figure 6.1.2

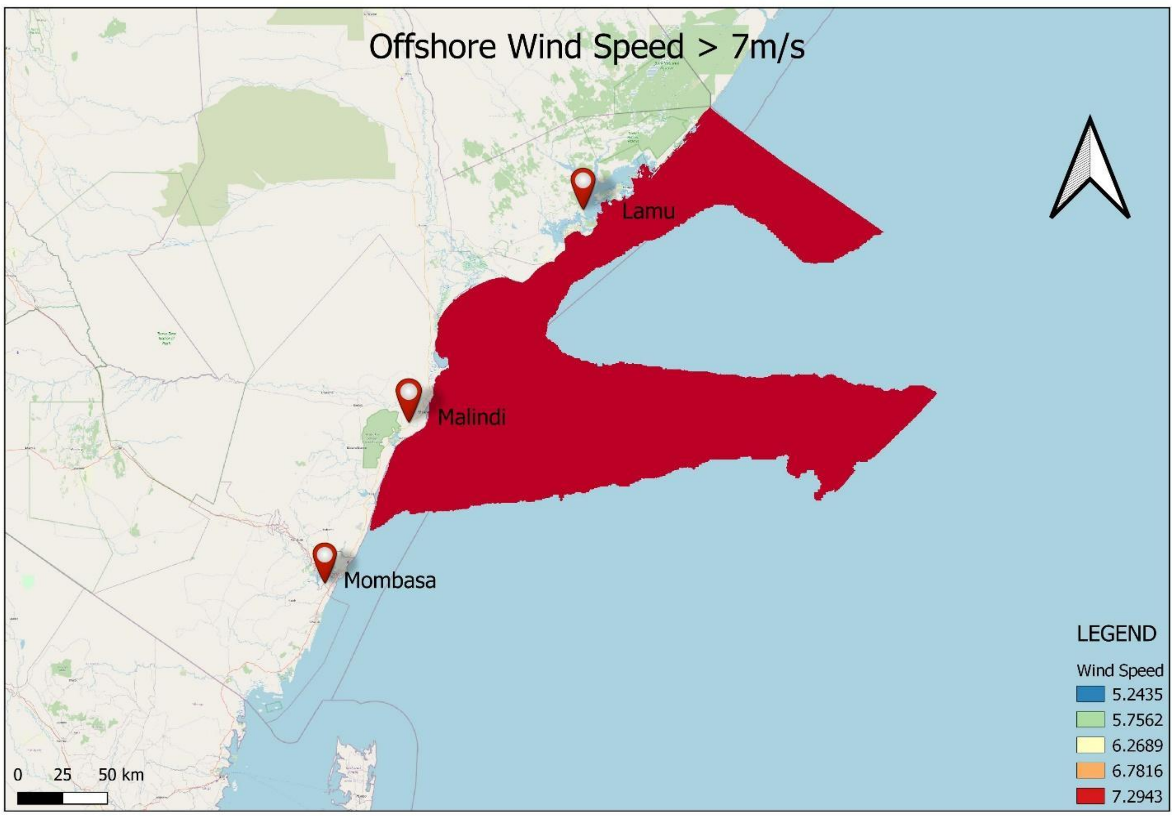


Figure 6.1 2 A map showing areas with Kenya's mean offshore wind speeds of > 7 m/s. Created using QGIS (Author, 2021).

Additionally, the bathymetry raster layer was processed by applying the raster calculator algorithmic functions so as to create a new raster layer that represents the area that has water depths of less than 50 m but excludes all the marine protected areas as shown in Figure 6.1.3.

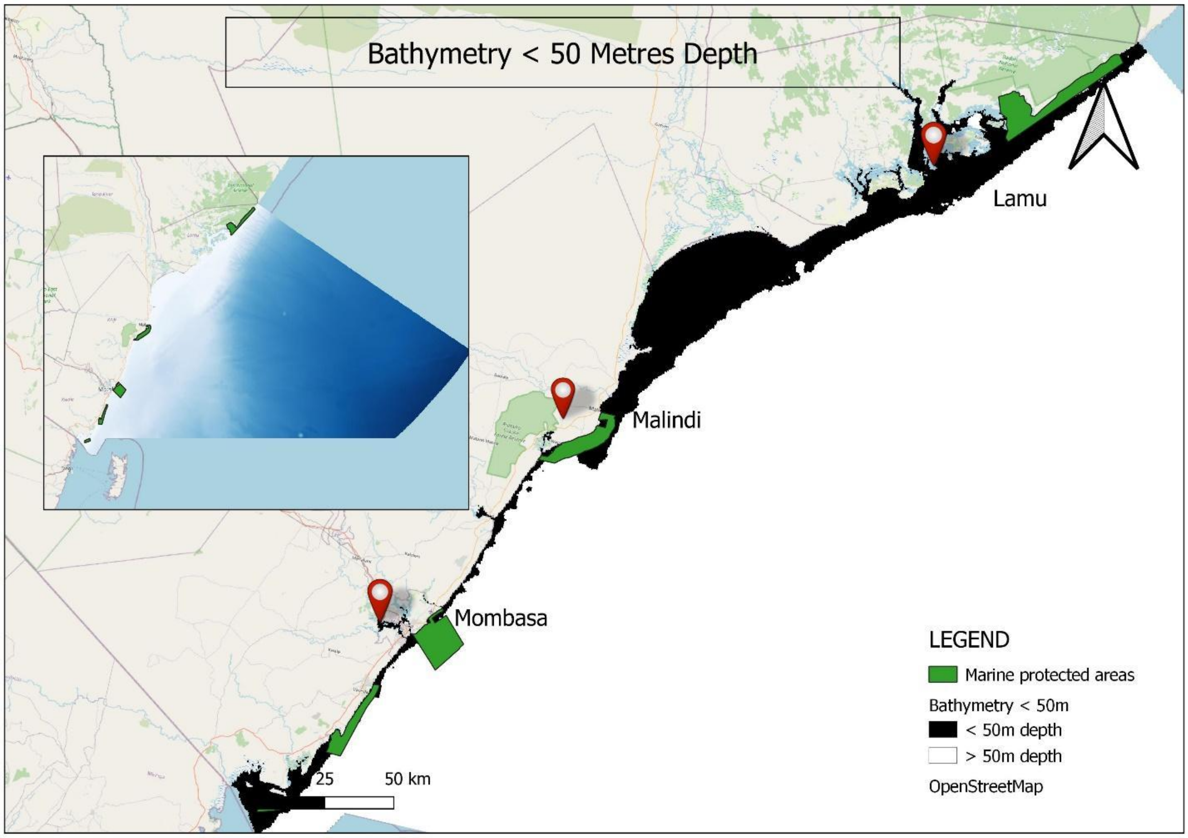


Figure 6.1 3 A GIS map showing bathymetry below 50 m and marine protected areas extent.Source:

(Author, 2021).

Both raster bands above were processed into a single raster band whose extent defines the suitable zone that meets the criteria (at least mean wind speed of 7m/s, water depth of less than 50 m and lies outside the marine protected zone).

The raster band was subsequently converted into a polygon defining the extent of the area suitable for the development of an Offshore Wind Farm as shown in Figure 6.1.4.

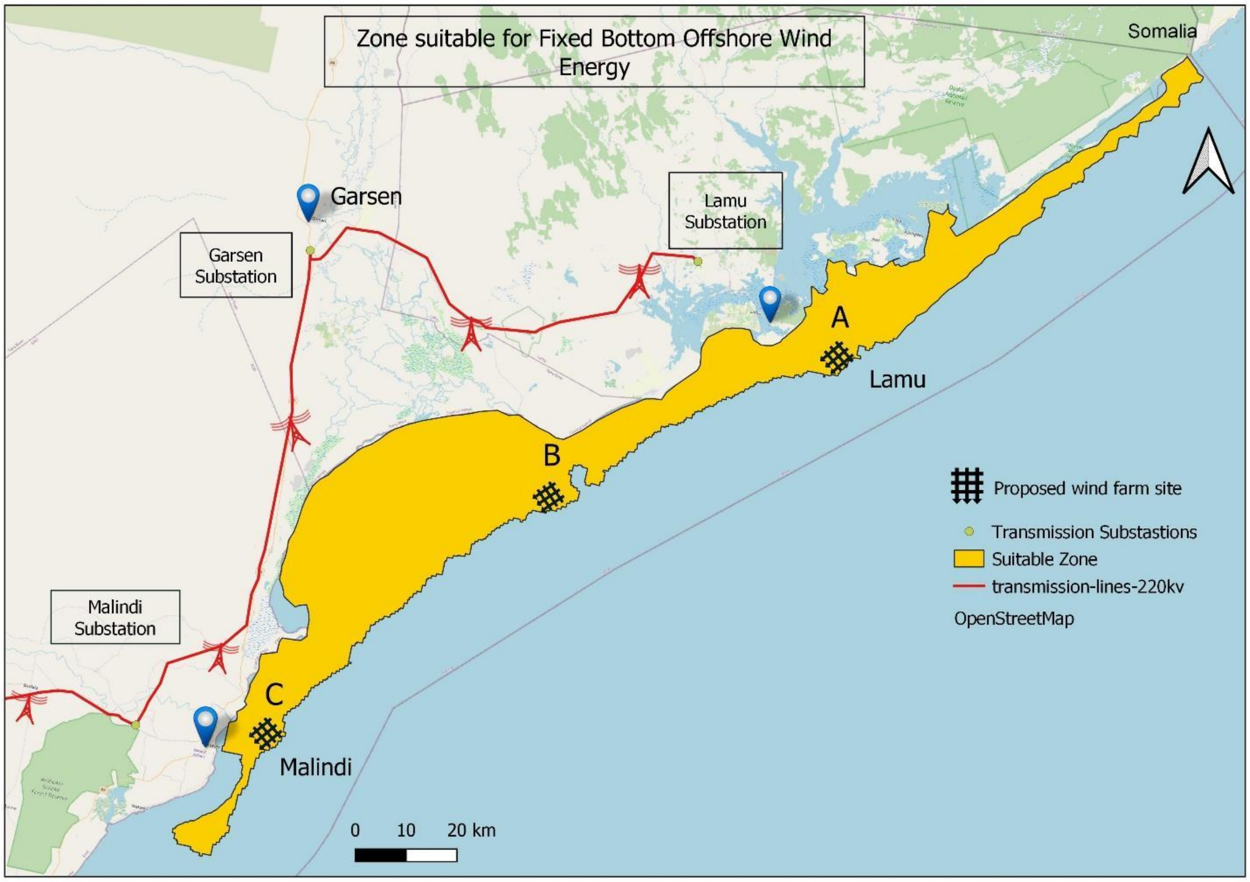


Figure 6.1 4 A map showing the suitable zone identified for offshore wind development. Generated by way of spatial analysis using QGIS.

(Author, 2021)

The suitable zone lies in the north coast side of Kenya's EEZ off the coastal counties of Kilifi (at Malindi), Tana River and Lamu. There exist three transmission substations located onshore. In order to select the most optimal site for an offshore wind farm three farms are proposed namely: A, B and C.

The magnitude for each constraint is as indicated in Table 3.2.1. It is evident that the Malindi offshore area is closer to the region's transmission substation as opposed to the are off Tana which is served by the Garsen substation. The three sites have the same water depth but seabed geotechnical studies should be carried out so as to ascertain which of the areas are suitable for a cheaper turbine foundation option. The wind speeds are relatively the same however the data should be validated through installation measurement stations on site such as LIDARs. The Lamu offshore region is expected to experience increased shipping traffic given that Kenya recently launched the Lamu Port. On the flipside, this will improve the ranking of Lamu offshore since the port is critical in the construction of offshore wind turbines since this will reduce the cost and ease transport and logistics operations. In conclusion, the Malindi offshore region ranks as the most favorable area for shallow water OWE development.

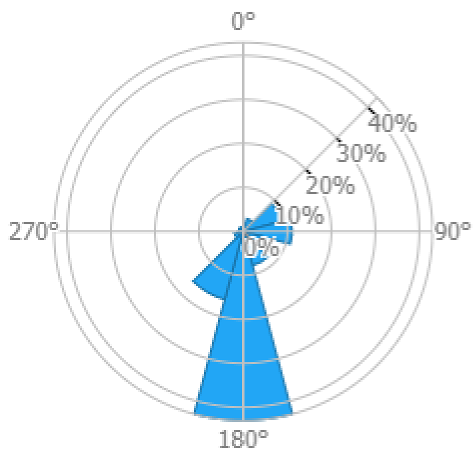
Table 6.1.1. 1Ranking of Proposed OWE sites

Proposed Site Name	**Centre Coordinates**	**Constraints**					**Comments**	**Ranking**
		Mean Wind Speed (m/s)	**Water Depth (Foundation type)**	**Distance to nearest substation**	**Global Marine Traffic**	**Others**		
A - Malindi	3°09'40.7"S 40°12'57.6"E (-3.1613, 40.2160)	7.25	40.2	> 28 km to Malindi substation	Very Low	Area has recreational beaches and rich in tourism	Proposed site is the nearest to transmission substation	1
B - Tana	2°38'39.8"S 40°38'07.8"E (-2.6444, 40.6355)	6.88	40.6	>70 km to Garsen substation	Very Low	Should be reviewed	Is located furthest from substation	3
C - Lamu	2°19'32.2"S 41°03'01.1"E (-2.3256, 41.0503)	7.01	41	> 35 km to Lamu substation	Medium	Security concerns due to proximity to Somalia	Requires further studies beyond the scope of this study	2

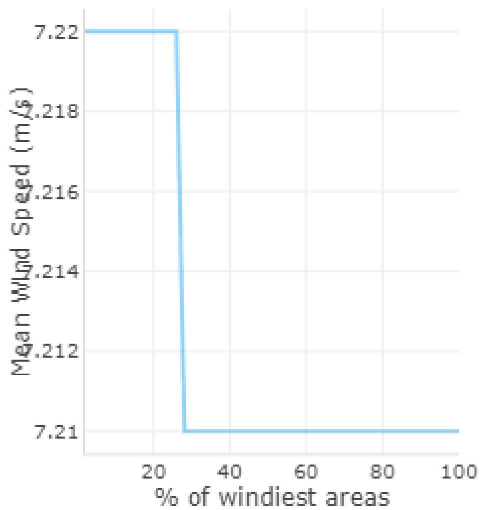
(Author, 2021).

6.1.2 Wind Farm Layout

The 180^0 sector has the highest frequency of occurrence of the mean wind speeds as illustrated in Figure 6.1.5. This corresponds to the Southern Direction of the Kenyan coast. It can therefore be concluded that the exploitable offshore wind resource travels from the southern part towards the Northern coast side. This should however be validated by carrying out onsite wind measurement.



(a)



(b).

Figure 6.1. 5 Frequency Wind Rose (a) and Mean Wind Speed graph (b).

Adapted from Global Wind Atlas (Author, 2021).

Arrangement of turbines on site

The turbines are installed at a distance of at least 4 to 6 times the diameter of the blade. A Vestas 10 MW, V164-10.0 offshore wind turbine was selected. It has a cut-in and cut-out wind speed of 3 m/s and 25m/s which is within the speed range of the selected Malindi site. It is also a class S turbine with a 164m rotor diameter (Vestas, 2021). The capacity factor of 50% was selected.

The turbines should therefore be installed at a distance of 656 m (4*164). The 10 turbines will therefore cover a total area of about 1,721,344m^2 (656*4*656) = 172 Hectares.

The arrangement of the wind turbines is as shown in Figure 6.1.6.

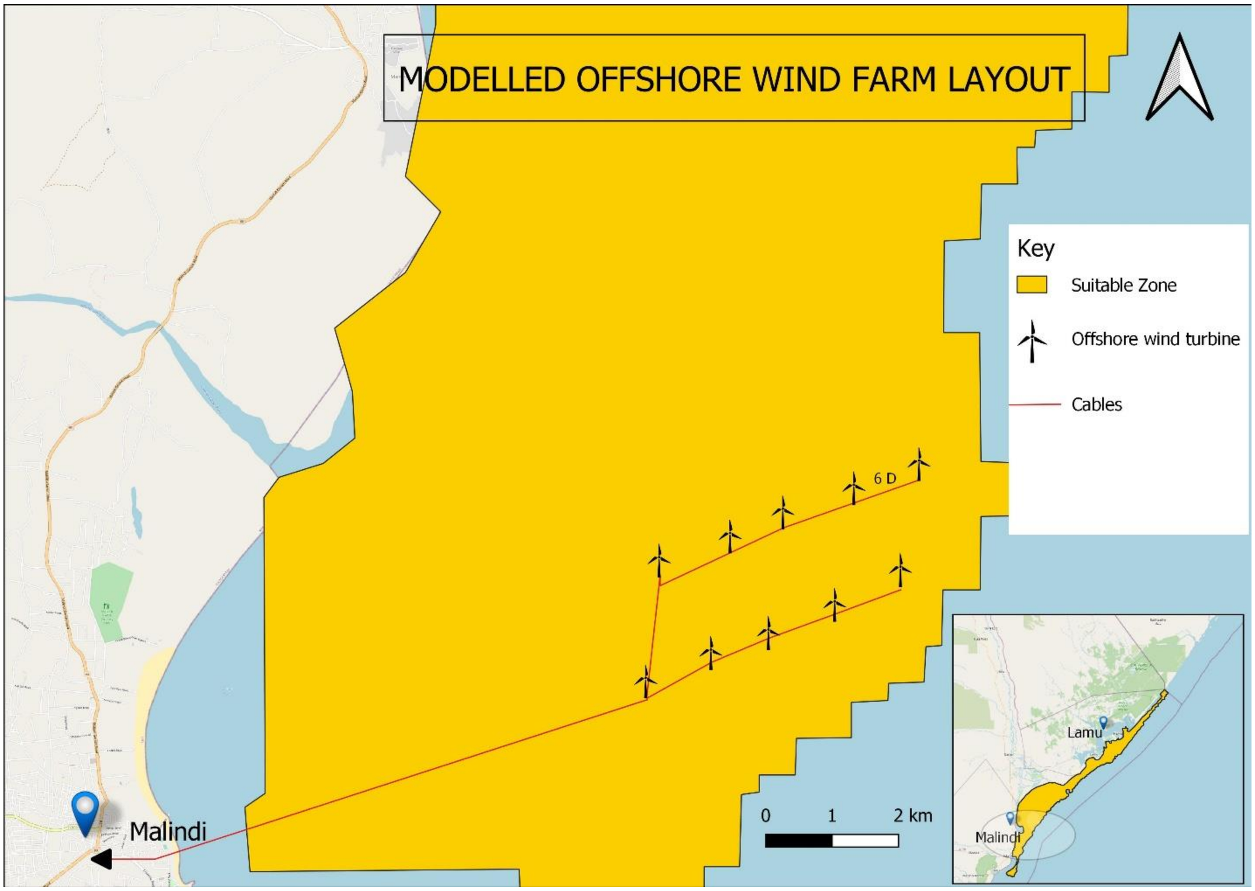


Figure 6.1 6 Map showing the wind farm model at the select Malindi location.

(Author, 2021).

CHAPTER 7 – ANALYSIS & DISCUSSIONS

7.0 Energy Yield

In order to establish the energy generated by each turbine at the select site of Malindi the energy yield formulation outlined in the methodology was applied. The values of the parameters for the select site will be first obtained, the Global wind atlas resource provides this variable in the format of a generalized wind climate file (GWC), the file contains the frequency values for each wind sector and the corresponding wind speed probability (frequency distribution) for each sector in the form of A and k Weibull parameters at the various wind heights 10m, 50m, 100m, 150m and 200m as shown in index II.

An extract of the GWC file (which is available under Index II) for **A** and **k** values at 100m reference height above ground level for the Malindi site (3°09'40.7"S 40°12'57.6"E) is as tabulated in Table 7.0.1.

Table 7.0. 1 An extract of GWC file for the Malindi site.

Sector	**Sector Probability**	**A**	**k**
0^0	1.05%	3.87	1.857
30^0	3.35%	4.82	2.369
60^0	8.83%	6.3	2.4
90^0	11.18%	7.06	3.088
120^0	4.93%	5.38	2.775
150^0	7.6%	6.12	2.596
180^0	43.52%	9.61	3.354
210^0	15.23%	9.2	3.814
240^0	2.47%	5.32	2.334
270^0	0.855%	2.84	1.615
300^0	0.6%	2.92	1.678
330^0	0.44%	3.5	1.92

The execution of the energy yield for each turbine will be done using a python program. The flow chart in Figure 7.0.1. illustrates the working principle of the yearly energy yield from the selected Malindi Site.

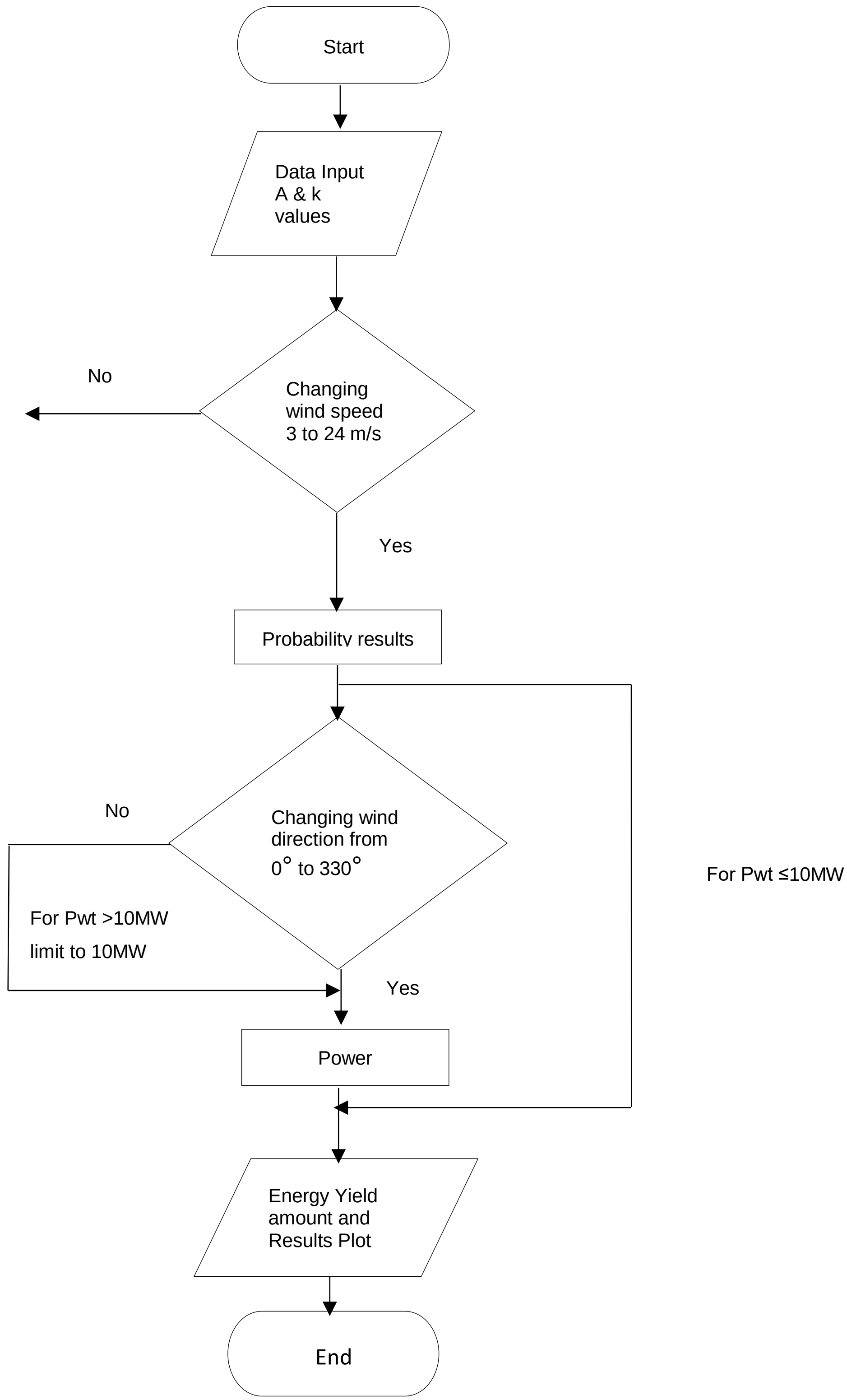


Figure 7.0. 1 A flowchart illustrating the python program in Appendix III.

(Author, 2021).

The results obtained upon execution of the python program illustrated are as shown in Figure 7.0.2. It is evident that the farms annual energy yield amounts to **292.675 GWh**.

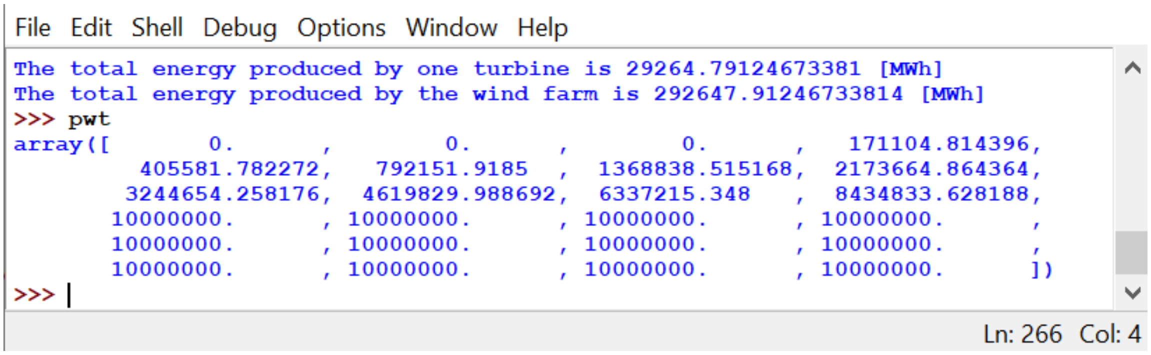


Figure 7.0. 2 An excerpt of the results obtained upon execution of the python program.

(Author, 2021).

Shows a plot of the average probability of each wind speed occurring. The wind speeds of between 2 and 7m/s have higher probabilities of occurrence.

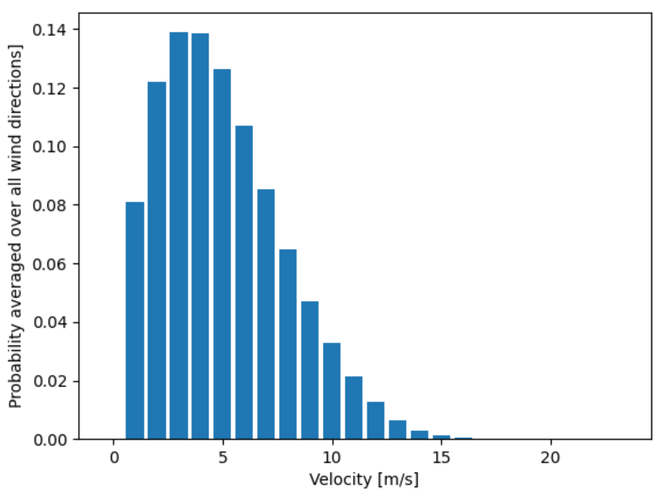


Figure 7.0. 3 A plot of average probability versus speed produced using the python program.

(Author, 2021).

7.1 Financial assessment of the Proposed Malindi Offshore Wind Farm.

An OWE project has three main cost elements namely: CAPEX, OPEX and DEPEX. CAPEX is incurred during the first phase of development that involves: Design, production of turbines and balance of plant and also installation and grid connection. Operation and maintenance cost incurred in the post-construction phase is referred to as the OPEX. DEPEX is incurred at the end of the useful life of the plant, this involves dismantling of the offshore infrastructure, disposal or forwarding for recycling and site restoration activities.

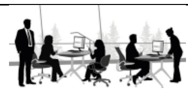
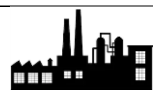
	Phase I	Phase II	Phase III	Phase IV	Phase V
					
Description	Design and Development	Turbine production and Balance of Plant	Installation & Grid connection	Operation & maintenance	Decommissioning
CAPEX					
OPEX					
DEPEX					

Figure 7.1. 1 Gantt chart showing development roadmap of a typical offshore wind farm.

An extract of “Socio-economic impact study of offshore wind”, by QBIS, 2020, P. 17.

Availability of accurate information regarding the cost of commissioned projects is almost nonexistent given the competitive procurement auctions and confidentiality issues which make information less available in the public domain. The variations in the policy, regulatory requirements and cost of capital have the effect of causing significant variances of the costs across the various OWE markets.

Despite these limitations there exist published information obtained through research carried out by reviewing energy trading activities and privileged access available to organizations such as IRENA, WindEurope, BVGA, DNV, NREL and also through derived research activities such as QBIS’s Social-economic impact study of offshore wind on Denmark sectors (QBIS,2020).

Estimated CAPEX, OPEX and DEPEX: based on case studies

European countries such as UK and Denmark have emerged as world leaders in OWE development and have exhibited mature cutting edge technological advancements as a result of extensive research activities and cumulative knowledge. The USA and Asian economies such as China, Japan and The Republic of Korea have also emerged strongly in the recent past having largely developed the support mechanisms and policies that have resulted in a great number of projects due for commencement. In order to establish likely cost of development of offshore wind at Kenya's Malindi this research only reviewed available published information on OWE cost trends in OWE markets of Europe, USA and Asia.

The choice of the three markets was based on the need to gain a diverse insight based on offshore wind regimes that are diverse geographically, economically and policy wise.

i. CAPEX and OPEX

IRENA, (2020) report states that weighted-average total installed cost for offshore wind as of 2020 rapidly fell to **3,185 $/kW** as compared the period preceding 2015 when it stood at about $ **5,000 $/kW** notwithstanding the fact that projects moved further offshore into deeper waters. Denmark recorded a comparatively competitive weighted-average cost of **2,963 $/kW** against $ Europe's average which amounted to **3,384 $/kW**.

China on the other hand led the Asian pack by recording the lowest weighted-average total cost of **2,968 $/Kw** ahead of Japan and Republic of Korea while the Asia's average was recorded as **3,001 $/Kw** which was largely impressive compared to Europe. This was largely influenced by China's heavy deployment in 2020 and its associated lower labor and commodity costs and also near –shore offshore sites.

USA made a delayed entry into the OWE market compared to her peers in the EU. Commissioned in 2016, Block Island Wind farm with a capacity of 30MW was USA's first offshore wind farm to be built off the coast of Rhode Island. The Federal Government through U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM) and The National Renewable Energy Lab (NREL) continue to develop enabling mechanisms and facilitating OWE development. According to the 2020 revised Offshore Wind Energy International Comparative Analysis report by International Energy Agency (IEA) that focused on select sites in the various countries globally, USA's 456 MW offshore wind farm made up of 60 turbines with a 6 MW rating each was found to have a CAPEX amounting to **3,518 €/kW** and a total OPEX of **61 €/Kw** (IEA,2020).

Operation and Maintenance costs (O&M) are largely riddled with uncertainties due limited operational experience, nondisclosure practices and variances in approaches taken after the lapse of warranty period. According to IRENA (2020), further analysis of projects commissioned within the last 5 years shows that projects located in mature European Markets and China near-shore projects recorded lower O&M costs of **0.017 $/kWh** compared to less-established energy markets such as South Korea whose O&M supply chains are yet to fully develop which recorded a higher value of **0.030 $/kWh** (IRENA, 2020).

ii. DEPEX

On July, 2020 QBIS published a report on the Socio-economic impact of offshore wind in Denmark based on information obtained from previous studies by BVG associates and leading market players such as: Vattenfall, Orsted, Siemens Gamesa and Semco. The study was based on a model plant assumed to be of 1,000MW capacity, made of 10 MW turbines installed 60 km offshore at 30m of depth. DEPEX was assessed to be **0.392 million €/MW** (QBIS, 2020).

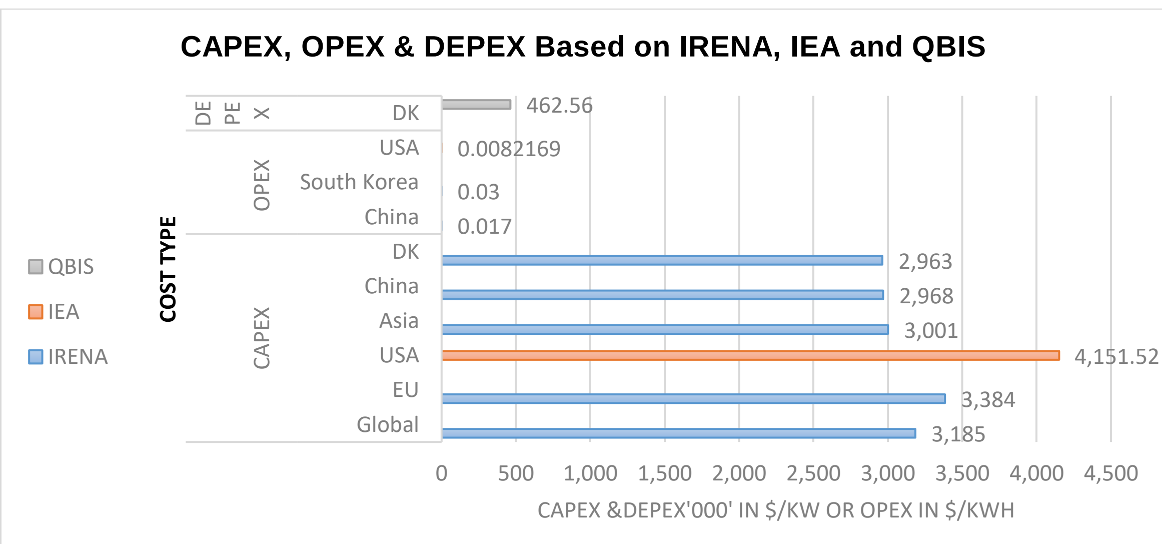


Figure 7.1. 2 Summary of the findings of the Financial Assessment based on case studies. Source: (Author, 2021).

7.2 LCOE Analysis

LCOE is a measure used to assess whether a certain project is worth investing in and how it compares with alternative ventures. The following formulation was applied;

$$\text{LCOE} = \frac{\text{Total CAPEX(\$)} + \text{Total OPEX (\$/Year)}}{\text{Net Annual Energy Production(MW/Year)}} \quad \text{............................(Equation 5)}$$

The CAPEX, OPEX and DEPEX variables were based on the findings of the case studies under 4.5 which were summarized in Figure 7.2.1.

Consequently, the highest published CAPEX, OPEX and DEPEX based on the case studies above were applied on assumption that the most probable costs of offshore wind development in Kenya would be higher than those recorded in 2020 by existing mature markets that are by far competitive.

USA recorded the highest CAPEX as per published estimates = 4,151.52 $/kW

South Korea also posted a comparatively higher OPEX = 0.03 $/kWh

DEPEX based on QBIS socio-economic assessment study in Denmark was adopted = 462.56$ /kW

Other relevant assumptions include:

i. Annual degradation of 0.50%
ii. An annual OPEX escalator rate of 3%.
iii. An Offshore wind turbine Capacity Factor of 50% was selected.
iv. The net annual energy production for the 100 MW offshore wind farm made up of 10 offshore wind turbines rated 10 MW each as computed using the python program is; **292,647.91 MWh/ Year**
v. The project's useful life was assumed to be 25 years since this is the typical design life foe wind turbines.

The computation was carried out on MS Excel as shown in Figure 7.2.1.

Levelized Cost of Energy (LCOE) Model		
Malindi offshore Wind Farm		
System Inputs		**Input Description**
System Size (kW)	100000	*(Please insert the aggregate system size for a site)*
1st-Year Production (kWh)	292 647 912,50	*(Please insert the aggregate forecasted system production at a site*
Annual Degradation	0,50%	*(Please insert the expected system yearly performance degradation)*
Direct Purchase Inputs		
Initial Cost ($/KW)	$ 3 185	*(Please insert total system cost per Watt. If not available, use the formula: Cost ($/KW) = (Total-system-cost/Total-system-size-in-Kwatts)*
Initial Rebate/Incentive	$ -	*(Please insert the total value of rebates/incentives received within the first year)*
O&M Cost ($/kW)	87,7944	*(Please insert the per kW O&M cost. If not available, use the formula: O&M Cost ($/kW) = (1st-year-O&M-Cost/Total-system-size-in-kW)*
O&M Escalator (%)	3%	*(Please insert the expected yearly escalation)*
DEPEX - Cost of Decommissioning	462,56	$/kW
LCOE Outputs*	Price per production, the longer the project, the cost will be lower	
Direct Purchase		
25 Year	0,0993	(initial cost+ o&m cost)/25 years production
Feed in Tarrif	0,11	$/kWh
Exchange rate	1,18	€/$

LCOE Calculator

Year	Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)
0	-	$ 318 500 000	
1	292 647 913		$ 8 779 437
2	291 184 673		$ 9 042 820
3	289 728 750		$ 9 314 105
4	288 280 106		$ 9 593 528
5	286 838 705		$ 9 881 334
6	285 404 512		$ 10 177 774
7	283 977 489		$ 10 483 107
8	282 557 602		$ 10 797 601
9	281 144 814		$ 11 121 529
10	279 739 090		$ 11 455 174
11	278 340 394		$ 11 798 830
12	276 948 692		$ 12 152 795
13	275 563 949		$ 12 517 378
14	274 186 129		$ 12 892 900
15	272 815 198		$ 13 279 687
16	271 451 122		$ 13 678 077
17	270 093 867		$ 14 088 420
18	268 743 397		$ 14 511 072
19	267 399 680		$ 14 946 404
20	266 062 682		$ 15 394 797
21	264 732 369		$ 15 856 640
22	263 408 707		$ 16 332 340
23	262 091 663		$ 16 822 310
24	260 781 205		$ 17 326 979
25	259 477 299	$ 46 256 000	$ 17 846 789
Total	**6 893 600 007,1581**	**$ 364 756 000**	**$ 320 091 827,8519**

Figure 7.2. 1 LCOE analysis using an LCOE calculator.

Adapted from Analytical assessment of port energy efficiency and management: a case study of the Kenya Ports Authority (Kidere, 2017).

Results from the above analysis show that the estimated LCOE for the Malindi Offshore wind farm is **0.0993** $/kWh. This estimated value is within the range of the reported LCOE of newly commissioned OWE projects. IRENA (2020) in its recent published report on Renewable Power Generation Costs in 2020 disclosed that "the global weighted-average LCOE of newly commissioned projects declined from USD 0.162/kWh in 2010 to USD 0.084/kWh in 2020, a reduction of 48% in 10 years" (p.14).

This is evidence that the available wind resources in Kenya's offshore can be competitively exploited

Sensitivity analysis

In order to gain an understanding of which are the most influential factors of the LCOE, a sensitivity analysis was performed. Total units produced in the first year, the annual degradation rate, operation and maintenance cost, the O&M escalator and the CAPEX were defined as assumption variables in a simulation aimed at forecasting the LCOE in over 5,000 trials.

The summary results of the simulation shown in Figure 7.2.2 indicated that the LCOE is likely to vary from a minimum of **0.0851** $/kWh and a maximum of **0.1224** $/kWh with a mean of **0.1008** $/kWh.

Statistic	Forecast values
Trials	5 000
Base Case	0,0993
Mean	0,1008
Median	0,1004
Mode	---
Standard Deviation	0,0062
Variance	0,0000
Skewness	0,2688
Kurtosis	2,82
Coeff. of Variation	0,0612
Minimum	0,0851
Maximum	0,1224
Mean Std. Error	0,0001

Figure 7.2. 2 Summary of Sensitivity Analysis results.

Additionally, the certainty that the maximum amount of the LCOE will be 0.0955 was predicted to have a probability of 59.62% as shown in **Figure 7.2.3**.

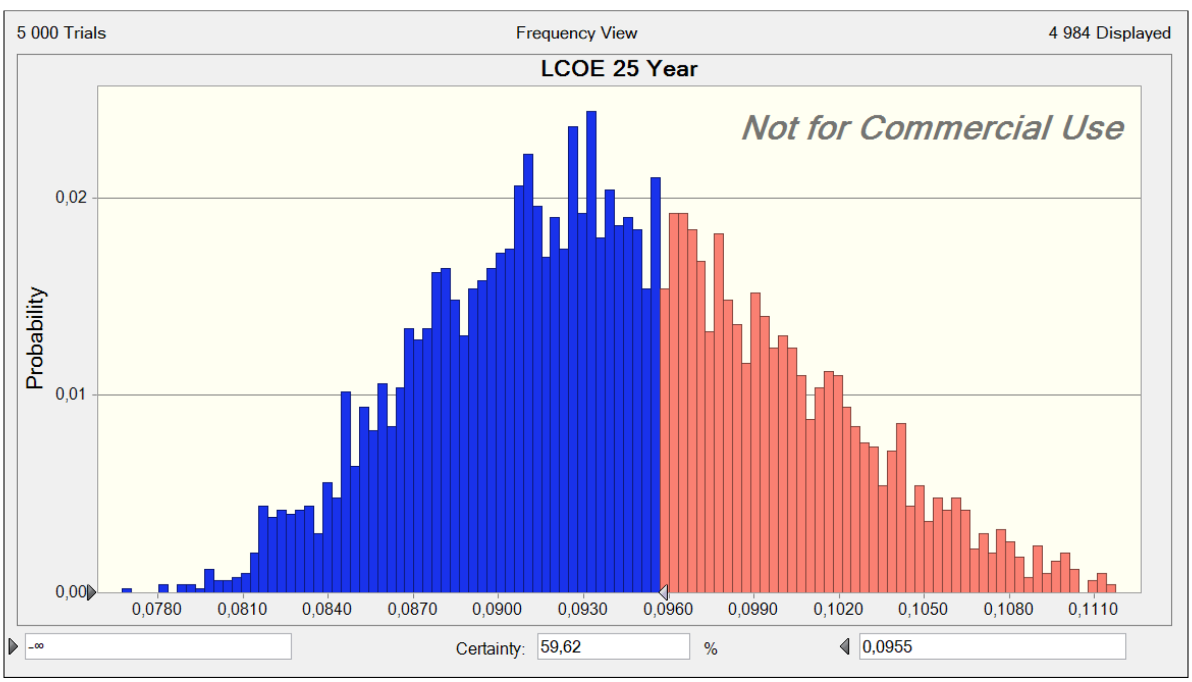


Figure 7.2. 3 The LCOE Frequecy curve (Maximum).

Further analysis shows that the probability that the minimum amount of the LCOE will be 0.0935 cents is 52.23% as shown in Figure 7.2.4.

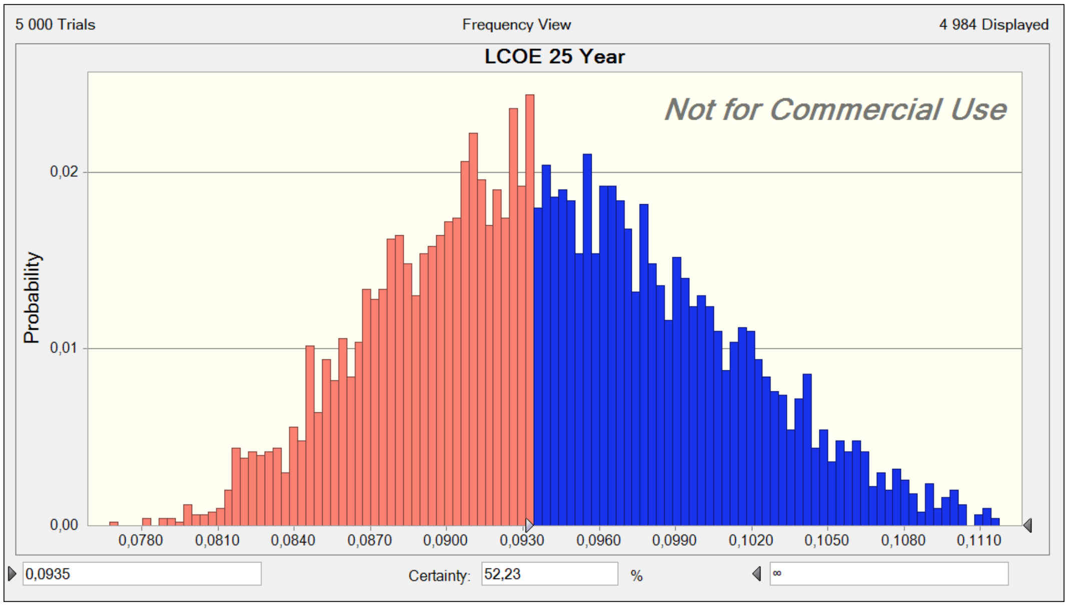


Figure 7.2. 4 The LCOE Frequecy curve (Minimum).

As shown in Figure 7.2.5 a unit increase in O&M escalator is likely to lead to an increase in LCOE by 53.3%. Similarly, a decrease in production in the 1st year will result in an increase in the LCOE by 38.1% while the Direct Purchase Cost increase is projected to result in an increase in LCOE by 8.4%.

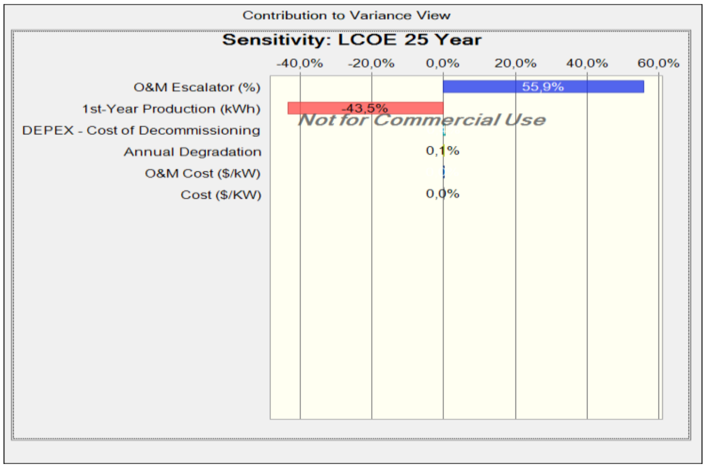


Figure 7.2. 5 Contribution to LCOE variance by each variable.

7.3 Comparison with Kenya's Feed in Tariff

The Feed-in-Tariff system (FiT) is still in use in Kenya. The country introduced the FiT system in 2008 covering Wind, Biomass and Small Hydro. It was further reviewed in 2010 to include: solar, biogas and Geothermal as a way of enabling investment activities by Independent Power Producers (IPPs) and accelerating energy generation from renewable energy sources so as to bridge the huge energy deficit (Ministry of Energy Feed-In-Tariffs Policy, 2012).

Table 7.3. 1 The Feed in Tarrif for renewable projects > 10 MW of installed capacity.

The FiT values for renewable projects above 10 MW of installed capacity

	Installed capacity (MW)	Standard FiT (US $/ kWh)	Percentage Escalable portion of the Tariff	Min. capacity (MW)	Max. capacity (MW)	Max. Cumulative capacity (MW)
Wind	10·1-50	0·11	12%	10·1	50	500
Geothermal	35-70	0·088	20% for first 12 years and 15% after	35	70	500
Hydro	10·1-20	0·0825	8%	10·1	20	200
Biomass	10·1-40	0·10	15%	10·1	40	200
Solar (Grid)	10·1-40	0·12	12%	10·1	40	100

Adapted from The Ministry of energy Feed-in-Tariff policy (2012).

This study shall therefore adapt the values of FiT as indicated in the subsisting policy as shown in Table 7.3.1. Kenya's FiT for wind starts at **0.11 $/ kWh,** a value higher than the computed LCOE rate of **0.0993 $/kWh** for the modelled wind farm in this study.

This therefore makes a strong business case for offshore development in Kenya since the investor is able to recover all the costs of the project before factoring in any Government subsidy benefits that may be made available.

7.4 Social and environmental cost savings analysis

The cost of environmental damages in the form of human health impact and crops were based on the findings of a study carried out by AEA Technology Environment on behalf of the EU in 2005. The study sort to quantify the damages per ton emission of PM2.5, NH3, SO2, NOx and VOCs[5] from each EU25 Member State (excluding Cyprus) and surrounding seas AEA Technology Environment (2005). The results of the investigation are as tabulated in Table 7.4.4. The scope of this study showing the focus areas is as documented in appendix IV.

Table 7.4. 1 Average Environmental damages per ton of pollutant

PM mortality O_3 mortality Health core? Health sensitivity? Crops O_3/health metric	VOLY median VOLY median Included Not included Included SOMO 35	VSL median VOLY median Included Not included Included SOMO 35	VOLY mean VOLY mean Included Included Included SOMO 0	VSL mean VOLY mean Included Included Included SOMO 0
EU25 (excluding Cyprus) averages				
NH_3	€11,000	€16,000	€21,000	€31,000
NOx	€4,400	€6,600	€8,200	€12,000
$PM_{2.5}$	€26,000	€40,000	€51,000	€75,000
SO_2	€5,600	€8,700	€11,000	€16,000
VOCs	€950	€1,400	€2,100	€2,800
Seas averages				
NH_3	n/a	n/a	n/a	n/a
NOx	€ 2,500	€ 3,800	€ 4,700	€ 6,900
$PM_{2.5}$	€ 13,000	€ 19,000	€ 25,000	€ 36,000
SO_2	€ 3,700	€ 5,700	€ 7,300	€ 11,000
VOCs	€ 780	€ 1,100	€ 1,730	€ 2,300

AEA Technology Environment. (2005).

The value for the CO_2 in this study was based on a report by German Environment Agency (UBA) which indicated that the price of carbon going by the EU emissions Trading System (ETS) ranges between 160 **€/tonne** to 375 **€/tonne** (UBA,2016).

Life Cycle Analysis of offshore wind farm show that this technology also contributes to GHG emissions as shown in Table 7.4.1. The variance between expected emission from offshore

[5] Check List of abbreviations for full meaning of acronyms

wind and a typical fossil fuel power generating plant represents the portion referred to as the social and environmental cost savings.

Modelled Offshore Wind Farm Emissions

Wind technology's emissions factors were adopted from the reference provided in Table 7.4.1.

Table 7.4. 2 Life-cycle emission factors for different energy sources (g/kWh).

Energy source	CO_{2e}	SOx	NOx	PM
Non-renewable				
Coal	1,000	7.000	3.400	9.800
Natural gas	490	0.320	0.570	0.130
Renewable				
Biomass and waste	31	0.370	0.650	0.030
Geothermal	120	0.000	0.000	0.000
Large hydroelectric	240	0.370	0.650	0.030
Small hydroelectric	11	0.027	0.074	0.005
Solar	50	0.370	0.180	0.000
Wind	14	0.032	0.048	0.004
Nuclear	20	0.032	0.070	0.007

(Kim et al., 2012)

The emissions from the modelled offshore wind farm were computed as follows

Emissions = Annual Energy Yield (kWh) x Life-cycle Emission Factor (g/kWh) ….. (Equation 6)

The results showing the emissions resulting from offshore wind are as Tabulated in Table 7.4.5.

Estimated emissions from a typical fossil fuel power plant

The Kipevu III which is the largest diesel plant in East Africa, it is located in Mombasa – Kenya (KenGen, 2021). It is a typical thermal plant such which runs on heavy fuel oil (HFO). In order to quantify the emissions that would occur as a result of using an HFO fired Diesel plant as opposed to an Offshore Wind Farm, the HFO emission factors shown in Table 7.4.2. were applied.

Table 7.4. 3 Emission conversion factors of HFO

	CO_2 (g/kWh)	**NO_x** (g/kWh)	**SO_2** (g/kWh)	**PM** (g/kWh)
Heavy Fuel Oil - 2.7% Sulphur fuel	690 to 720 (Cooper, 2004).	12.47	12.30	0.80

(Entec, 2005, p.13)

Applying equation 7.4.1 as per the values in Tables 7.4.2 the following results were obtained;

Table 7.4. 4 Estimated emissions from an HFO plant

	CO_2	NO_x	SO_2	$PM_{2.5}$
Emission values **(tons)**	206,316.78	3,649.32	3,599.57	234.12

(Author, 2021)

The cost of mitigating against the environmental effects of the emissions were obtained by applying the following formulation;

Cost of Emissions = Energy yield (kWh) * EF * Average Environmental damages per ton of pollutant ………………………………………………. (Equation 7.1)

Where by: EF – Emission Factor (g/kWh)

Table 7.4. 5 Net social cost savings from Offshore Wind

	HFO - Emission values (tons) **X**	Offshore wind Emission values **Y**	Net emissions savings **= X - Y**	Environmental cost in **€/tonne**	Cost of environmental impact (**€**)
CO_2	206,316.78	4,097.07	202,219.71	160 (UBA,2016)	32,355,153.21
NO_x	3,649.32	9.36	3,639.95	12,000	43,679,456.83
SO_2	3,599.57	14.05	3,585.52	16,000	57,368,355.58
PM	234.12	1.17	232.95	75,000	17,471,080.38
				Total	**150,874,045.99**

(Author, 2021)

This amounts to about 40% (€150,874,045.99 /$ 318,500,000) of the initial cost.

7.5 SWOT Analysis

Offshore wind energy has a lower carbon footprint compared to other renewable sources such as Solar PV. On the flipside this renewable resource has a number of shortcomings. A comprehensive analysis of both the two extremes is as documented in Table 7.5.1.

Table 7.5. 1 SWOT Analysis

Strengths	**W**eaknesses
• Mitigates against the use of fossil fuel which is responsible for causing air emissions. • Helps eliminate noise pollution and reduces visual impact since wind farms are located away from settlements. • Improved health benefits due to reduced respiratory dieses caused by using fossil fuel. • Has higher capacity factor. • Enables use of larger turbines hence more energy per unit cost of installation.	• Installation of Offshore Wind farms is capital intensive. • Wind farms are believed to alter weather conditions because of the change of air flow direction by the rotating blades. • Change of biodiversity behaviour due to intensive construction activities such as such pile driving. • High voltage subsea array and export cables pose a danger to humans, sea mammals and other marine habitats. • Higher energy demand based on Life cycle assessment.
Opportunities	**T**hreats
• Ongoing push for the removal of fuel subsidy for fossil fuel likely to increase the LCOE of fossil fuel above that of offshore wind. • Technological advancements in offshore wind likely to reduce development costs. • Expanding knowledge and skills through research.	• In long run there is possibility of loss of biodiversity due to the increased activities offshore • There exist economical risks of investing in offshore wind because of the long payback period. • The high voltage subsea cables pose a threat to habitats

(Author, 2021).

CHAPTER 8 – CONCLUSION AND RECOMMENDATIONS

Having analysed Kenya's offshore wind resource, bathymetric characteristics, existing Power Transmission Infrastructure, ship traffic density and marine protected areas. Thereafter modelled an offshore wind farm, calculated the expected energy yield of the project, estimated the initial, operation and decommissioning cost, computed the LCOE and further analysed its sensitivity and estimated the social cost savings the following conclusion and recommendations were reached at:

8.1 Conclusion

Offshore wind deployment is projected to grow exponentially in the coming years given the ambitious initiatives such as Europe's goal of achieving carbon neutrality by 2050, Asia's initiative to reduce dependence on coal and USA's clean energy policies that have been reignited by among other things the re-entry into the Paris agreement. On the other hand, as of today, offshore wind technology is yet to be implemented by any single country in Africa despite the favorable offshore wind resources that exists going by the findings of the studies cited in this study. The intensification of climate change mitigation initiatives that aims at accelerating the decarbonization of the energy sector are set to invigorate the uptake of renewable energy options such as offshore wind.

This study sort to assess the technical and financial viability of offshore wind energy development in Kenya. Additionally, the research quantified the social cost savings as a result of reduced emission due to offshore wind technology.

Analysis of the offshore wind data obtained from The Global Wind Atlas and the bathymetry data from GEBCO shows that a significant portion of Kenya's North Coast offshore regions that lie within the administrative boundaries of the County Governments of Kilifi, Tana River and Lamu experience exploitable wind resources of above 7m/s. Equally the same zone has a wider continental shelf hence a significant portion offshore with water depths of less than 50m which renders the zone suitable for bottom-fixed offshore wind development. Additionally, the North Coast region has both 132 KV and 220 KV Power Transmission Infrastructure networks with adequate capacity to dispatch power from any future power generating plants. The marine protected areas were found to be clearly demarcated thereby reducing the risk of conflict between offshore wind development with marine conservation efforts.

The modelled Offshore wind farm of 100MW was estimated to generate about 292.675 GWh of energy annually at a cost of $ 318,500,000, this amounts to an LCOE of 0.0993 $/kWh as shown in the analysis in Figure 7.2.1. The generated energy is sufficient to meet the coastal region's last published electricity demand of 1,464 GWh as reported by Kenya's power utility company KPLC as shown in Table 5.1.4.

Though the LCOE results show that there is a marginal business case given that it is slightly lower than the currently prevailing FiT rate of 0.11 $/kWh set by Kenya. This margin can be significantly improved if the government incentivizes investment in offshore wind in the future. The LCOE is seen to be highly sensitive to the operation and maintenance cost escalator by a factor of 55.9%. This means that the LCOE is likely to reduce significantly if the maintenance cost does not change significantly in the subsequent years relative to year 1. Equally, the energy yields as at year 1 which is the energy generated when the installation is still new and devoid of any degradation has a positive correlation with the LCOE by 44.5% hence more efficient wind turbines of the that would keep the CAPEX constant can significantly lower the LCOE.

Based on the SWOT analysis results, it is evident that offshore wind technology has a number of advantages. Despite the fact that it is capital intensive, has negative marine environmental effects and requires specialized expertise and equipment, offshore wind has a lower carbon footprint compared to other renewable energy sources such as Solar PV. Moreover, the modelled offshore wind farm was estimated to result in social cost savings amounting to $176,913,397.59 which would therefore further reduce the LCOE of the project. This Green Premium is worth considering given that societal costs have far reaching disastrous effects in the long run.

In summary, offshore wind development in Kenya presents a positive outlook. The technical conditions critical to the development of offshore wind such as wind characteristics are largely favorable but require onsite validation. Equally, the financial performance of offshore wind investment is fairly promising. The social cost saving potential was found to be an equivalent of 40% of the initial cost there by enhancing the ranking of the modelled project. To overcome the constraints identified in the course of this study the recommendations in the subsequent section are worth being considered.

8.2 Recommendations

Based on the findings of this study that were subject to the prevailing circumstances in Kenya and going by a review of the global trends in offshore wind that highlight the progressive policy frameworks of economies such Denmark that has angled itself as a leader in offshore wind technology, the researcher considers the following recommendations critical to the success of offshore wind technology in Kenya:

I. Kenya should commence a more **comprehensive offshore feasibility study** that shall take into consideration all necessary factors such the review of port capabilities and geotechnical studies This study shall help form the basis for identifying suitable locations for the installation of offshore wind data collecting equipment such as LiDAR, this site specific bankable offshore wind data is critical to potential investors since it helps reduce the time taken to make site decisions.

II. The development of Kenya's **Marine spatial plan (MSP)**should be fast-tracked so as to enable sustainable development of offshore wind in Kenya. An MSP will help reduce conflict with other marine services and guarantee sustainable development of Kenya's Blue Economy.

III. Kenya should adopt an offshore wind energy policy and legal framework that should provide a clear legal framework will guide the assessment, survey, permitting and auction processes. Additionally, the creation of **a National Wind Energy Agency** to more effectively help manage the wind development process akin to the Geothermal Development Agency (GDC) that has been instrumental in unlocking Kenya's geothermal energy potential. As of today, more than 50% of Kenya's energy mix is sourced from geothermal powered plants. A case in point is India's successes under the stewardship of The National Institute of Wind Energy (NIWE) which helped birth India's planned Offshore wind development dubbed '0 GW to 5 GW'.

IV. **Feed-In-Tariff** Kenya is yet to establish an energy auction framework, the FiT policy was last revised almost a decade ago in 2012 despite the technological advancements and subsidy programs that have resulted in reduced cost of generating electricity from renewables. Transitioning into the energy auction system in the near future similar to countries in the region such as South Africa, Ethiopia, Zambia and Uganda. However, there is no certainty as to when this shall commence.

V. The Kenyan Government should consider **allocating adequate financial resources** for the purposes of initiating and sustaining **research activities** in offshore wind energy so as to help leverage on the opportunities that are tied to enhanced cost effectiveness through research.

VI. **Technical capacity building** should be another focus area that Kenya should take up. Given the heavy deployment of onshore wind technology such as The Lake Turkana Wind Power Energy Project – the largest wind farm in Africa, there is need for a skills transfer scheme to help domesticate the wealth of knowledge and expertise that foreign developers possess. This strategic initiative will enable the country to build on her human capital that shall be capable of taking part in future offshore wind farm development activities in and outside the country.

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APPENDIX I

DOWNLOADED GWC FILE FOR THE SELECTED MALINDI OFFSHORE WIND SITE.

gwa3_gwc_69vr8fji - Notepad

File Edit Format View Help

```
Global Wind Atlas 3.0 (WRF 3-km)<coordinates>40.222,-3.167,0.0</coordinates>
5 5 12
   0.000    0.030    0.100    0.400    1.500
    10.0     50.0    100.0    150.0    200.0
    1.05     3.35     8.83    11.18     4.93     7.60    43.52    15.23     2.47     0.80     0.60     0.44
    2.95     3.72     4.87     5.49     4.18     4.74     7.49     7.18     4.11     2.14     2.21     2.67
   1.549    1.975    1.998    2.572    2.314    2.162    2.791    3.182    1.951    1.354    1.404    1.604
    3.52     4.42     5.78     6.49     4.95     5.62     8.84     8.47     4.88     2.57     2.65     3.19
   1.693    2.154    2.182    2.811    2.521    2.357    3.045    3.471    2.127    1.475    1.529    1.748
    3.87     4.82     6.30     7.06     5.38     6.12     9.61     9.20     5.32     2.84     2.92     3.50
   1.857    2.369    2.400    3.088    2.775    2.596    3.354    3.814    2.334    1.615    1.678    1.920
    3.89     4.84     6.45     7.16     5.43     6.17     9.77     9.17     4.16     1.66     2.24     3.18
   1.795    2.260    2.377    3.029    2.725    2.572    3.385    3.615    1.541    0.912    1.248    1.678
    3.71     4.84     6.64     7.25     5.40     6.16     9.85     9.37     2.60     2.93     1.85     3.32
   1.670    2.170    2.357    2.994    2.682    2.510    3.400    3.654    1.205    1.506    0.986    1.873
    0.58     2.24     6.86    12.28     5.85     5.66    30.55    31.22     2.65     0.81     0.70     0.59
    1.95     2.36     2.99     3.78     3.09     2.92     5.00     5.13     2.72     1.45     1.49     1.67
   1.158    1.545    1.385    2.107    1.842    1.850    2.119    2.838    1.533    1.170    1.127    1.221
    2.85     3.35     4.29     5.29     4.34     4.10     6.99     7.12     3.87     2.11     2.18     2.42
   1.400    1.889    1.682    2.580    2.248    2.268    2.592    3.471    1.869    1.416    1.365    1.482
    3.49     4.02     5.18     6.27     5.17     4.88     8.30     8.42     4.64     2.58     2.68     2.95
   1.732    2.342    2.084    3.205    2.783    2.811    3.221    4.295    2.311    1.748    1.686    1.834
    4.04     4.28     5.51     6.83     5.56     5.20     8.92     9.01     3.81     1.43     2.21     2.78
   2.100    2.436    2.236    3.436    2.998    3.014    3.361    4.666    1.807    1.064    1.225    1.670
    3.84     4.45     5.94     7.33     5.84     5.46     9.36     9.69     2.97     2.02     2.62     3.19
   1.705    2.314    2.213    3.482    2.959    2.947    3.377    4.740    1.709    1.420    1.232    1.998
    0.61     2.26     6.45    12.69     5.85     5.66    28.46    30.89     5.07     0.81     0.70     0.54
    1.65     2.09     2.52     3.37     2.71     2.56     4.21     4.67     3.14     1.29     1.32     1.49
   1.240    1.592    1.545    2.131    1.904    1.920    2.326    2.670    2.275    1.213    1.162    1.271
    2.49     3.08     3.73     4.92     3.97     3.74     6.13     6.77     4.58     1.95     2.00     2.24
   1.471    1.900    1.842    2.549    2.275    2.299    2.787    3.201    2.709    1.436    1.377    1.506
    3.05     3.71     4.50     5.87     4.75     4.48     7.31     8.06     5.46     2.39     2.46     2.74
   1.775    2.295    2.225    3.080    2.744    2.779    3.369    3.865    3.244    1.729    1.654    1.814
    3.24     3.96     4.86     6.34     5.10     4.78     7.86     8.64     5.92     1.33     2.03     2.55
   1.834    2.385    2.381    3.322    2.971    2.982    3.666    4.162    3.139    1.061    1.213    1.619
    3.30     4.10     5.22     6.80     5.34     5.01     8.33     9.10     6.75     1.84     2.44     2.81
   1.725    2.229    2.338    3.322    2.908    2.920    3.643    4.104    2.986    1.389    1.236    1.764
    0.78     2.25     6.45    12.68     5.86     5.67    28.47    30.87     4.65     0.97     0.81     0.55
    1.33     1.66     2.00     2.66     2.14     2.02     3.32     3.67     2.56     1.24     1.00     1.15
   1.287    1.670    1.607    2.221    1.986    1.998    2.424    2.779    2.580    1.529    1.123    1.432
    2.18     2.69     3.24     4.26     3.44     3.25     5.30     5.85     4.09     2.02     1.66     1.88
   1.498    1.947    1.881    2.600    2.322    2.338    2.842    3.260    3.006    1.787    1.307    1.670
    2.70     3.29     3.97     5.17     4.18     3.95     6.43     7.08     4.96     2.48     2.08     2.32
   1.760    2.295    2.213    3.064    2.729    2.756    3.350    3.834    3.518    2.100    1.529    1.963
    2.90     3.52     4.31     5.62     4.52     4.23     6.94     7.62     5.33     1.36     1.62     2.00
   1.830    2.357    2.346    3.283    2.928    2.939    3.604    4.088    3.256    1.268    1.057    1.607
    2.93     3.65     4.63     6.03     4.74     4.44     7.36     8.04     5.98     0.91     2.51     2.11
   1.705    2.213    2.311    3.275    2.877    2.877    3.580    4.049    2.955    1.045    1.459    1.545
    0.64     1.76     5.91    12.84     6.06     5.53    28.57    31.18     5.17     0.97     0.81     0.56
    1.03     1.16     1.40     1.77     1.41     1.37     2.21     2.43     1.65     0.84     0.68     0.85
   1.604    1.768    1.779    2.299    2.006    2.150    2.525    2.900    2.459    1.592    1.178    1.932
    2.04     2.29     2.75     3.45     2.77     2.67     4.31     4.74     3.21     1.66     1.38     1.67
   1.846    2.041    2.053    2.654    2.314    2.479    2.916    3.346    2.826    1.834    1.346    2.229
```

APPENDIX II

PYTHON PROGRAM SCRIPT FOR CALCULATING ENERGY YIELD OF THE MODELLED WIND FARM

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```
# Wind Energy Yield Calculation for the proposed Malindi Offshore Wind Farm #
import numpy as np
import matplotlib.pyplot as plt
import array as array

SecProb = [1.05, 3.35, 8.83, 11.18, 4.93, 7.60, 43.52, 15.23, 2.47, 0.80, 0.60, 0.44] # Frequency of occurrence of wind for each sector
pi = 3.14159

# Technical specification of the turbine - Vestas 10 MW - V164-10.0 offshore wind turbine with a rotor diameter of 164m and  a cut-in and cut-out wind speed of 3 and 25m/s respectively

r = 82              # Turbine rotor radius [m]
Area = r**2*pi      # Area of rotor [m2]
cp= 0.50            # Capacity factor
rho = 1.2           # Density [kg/m3]
Maxrating = 10000000 # Wattage of turbine [w]
N = 10

# Initialize matrix of zeros

Energy = np.zeros((len(SecProb), 24))

t = np.zeros((24))

speed = np.zeros((len(SecProb), 24))

pwt = np.zeros((24))

p = np.zeros((len(SecProb), 24))

for f in range(len(SecProb)): # (for e in ρ)/ loop function to operate frequency of occurence per wind sector

    for i in range (3,24): # loop function to calculate energy between 1 and 21 m/s

        v = i

        A = [3.87, 4.82, 6.30, 7.06, 5.38, 6.12, 9.61, 9.20, 5.32, 2.84, 2.92, 3.50] # A-factor for weibull distribution
        k = [1.857, 2.369, 2.400, 3.088, 2.775, 2.596, 3.354, 3.814, 2.334, 1.615, 1.678, 1.920] # k-factor for Weibull distribution

        speed[f,i] = i
        p[f, i]= (k[f]/A[f])*(v/A[f])**(k[f]-1)*np.exp(-(v/A[f])**k[f])

        print (p[f,i])

        pwt[i] = 1/2*Area*cp*rho*v**3  # [W]

        if (pwt[i]>10000000):
            pwt[i]=10000000

        print (pwt[i])

        t[i]= p[f, i]*24*365 # [h]


        Energy[f,i] = pwt[i] * t[i] * SecProb[f]/100 #[Wh]

        print (Energy[f,i])

AverageSpeed=np.mean(p, axis=0)

TotalEnergy = np.sum(Energy)# Energy per sector at 100% probability

TotalEnergyWindFarm=TotalEnergy*N

print ('The total energy produced by one turbine is', TotalEnergy/1000000, '[MWh]')

print ('The total energy produced by the wind farm is', TotalEnergyWindFarm/1000000, '[MWh]')

plt.bar (speed[0,:], AverageSpeed)
plt.xlabel('Velocity [m/s]')
plt.ylabel ('Probability averaged over all wind directions]')
plt.show ()
```

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APPENDIX III

SUMMARY OF THE CAPEX, OPEX AND DEPEX BASED ON PUBLISHED DATA BY IRENA, IEA AND QBIS

Source	**(IRENA, 2020)**						**(IEA, 2020)**	**(QBIS, 2020)**
Market	Global average	DK	EU	China	Asia	South Korea	USA (exchange rate $1=€ 1.18)	Denmark – Socio-economic study
CAPEX	3,185 $/kW	2,963 $/kW	3,384$ /kW	2,968 $/Kw	3,001 $/Kw		3,518 €/Kw ≈ 4,151.52 $/Kw	
OPEX				0.017 $/kWh		0.030 $/kWh	61 €/Kw ≈ 0.0082169 $/kWh	
DEPEX								0.392million €/MW ≈ 462.56 $/kW

APPENDIX IV

TABLE SHOWING THE IMPACTS QUANTIFIED FOR PURPOSES OF ASSESSING THE SOCIAL COST OF EMMISSIONS

Burden	**Effect**
Human exposure to $PM_{2.5}$	Chronic effects on: Mortality Adults over 30 years Infants Morbidity Bronchitis Acute effects on: Morbidity Respiratory hospital admissions Cardiac hospital admissions Consultations with primary care physicians Restricted activity days Use of respiratory medication Symptom days
Human exposure to ozone	Acute effects on: Mortality Morbidity Respiratory hospital admissions Minor restricted activity days Use of respiratory medication Symptom days
Exposure of crops to ozone	Yield loss for: barley, cotton, fruit, grape, hops, millet, maize, oats, olive, potato, pulses, rapeseed, rice, rye, seed cotton, soybean, sugarbeet, sunflower seed, tobacco, wheat