

**TECHNO-ECONOMIC ANALYSIS OF OFFSHORE WIND ENERGY
POTENTIAL IN LAMU, COASTAL KENYA**

CHIAW BENARD OWINO

**A THESIS SUBMITTED TO SCHOOL OF ENGINEERING AND TECHNOLOGY
IN THE DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF
DEGREE OF MASTER OF TECHNOLOGY IN SUSTAINABLE ENERGY
ENGINEERING OF TECHNICAL UNIVERSITY OF MOMBASA**

2025

DECLARATION

This thesis is my original work and has not been presented for a degree award in any other university.

Signature..... Date

Chiaw Benard Owino

MTSE/0021/2020

This thesis has been submitted with our approval as the university supervisors.

Signature.....Date

Dr. Gideon G. Kidegho

Technical University of Mombasa

Signature.....Date

Prof. Michael J. Saulo

Technical University of Mombasa

ACKNOWLEDGEMENTS

I wish to thank:

The Almighty God for the wisdom, knowledge and tender care offered unto me during my learning period.

My parents, siblings, relatives and friends for the immense support they have offered to me during my post-graduate studies. It is because of their full support that I have managed to sail through up to the end of my degree programme.

Dr. Gideon G. Kidegho and Prof. Michael J. Saulo, my supervisors, for the kind of guidance and mentorship they have offered me during this coursework and since the commencement of my research work. He has been for me and shaped me in the required manner.

DEDICATION

I dedicate this thesis to my lovely mum, siblings, relatives and friends as well as the entire fraternity of teaching staff in the Department of Electrical and Electronic Engineering, Technical University of Mombasa; who have been supportive to me in all manners during my cause of study.

TABLE OF CONTENTS

DECLARATION.....	ii
ACKNOWLEDGEMENTS.....	iii
DEDICATION	iv
LIST OF TABLES	x
LIST OF FIGURES	xi
LIST OF PLATES.....	xiii
ABBREVIATIONS.....	xiv
DEFINITION OF TERMS	xvi
ABSTRACT	xix
CHAPTER ONE.....	1
INTRODUCTION.....	1
1.1 Background of Study	1
1.2 Statement of the Problem.....	5
1.3 Objectives.....	6
1.3.1 General Objective	6
1.3.2 Specific Objectives.....	6
1.4 Research Questions.....	7
1.5 Justification.....	7
1.6 Significance of the Study	8
1.7 Scope of Study	8
1.8 Limitation of the Study	8
CHAPER TWO.....	10
LITERATURE REVIEW	10
2.1 Introduction.....	10
2.2 History of Offshore Wind Energy and Wind Farm Development.....	10
2.3 Offshore Wind Market	12

2.3.1 Offshore Wind Energy Market in Europe.....	12
2.3.2 Developers and Investors in Offshore Wind Industries.....	17
2.4 Wind Energy in Africa	19
2.5 Offshore Wind Turbine Technology	20
2.5.1 Evolution of Wind Technology and Turbine Size.....	21
2.5.2 Evolution of Offshore Wind Turbine Technology and Foundation Building	22
2.5.3 Leading Manufacturers of Offshore Wind Turbines	24
2.5.4 Wind Speed Distribution Analysis	26
2.5.5 Wind Power and Energy Analysis.....	28
2.6 Cost Functions for Offshore Wind Energy Production	29
2.6.1 Capital Expenditure (CAPEX) Cost	29
2.6.2. Wind Turbine’s Cost.....	30
2.6.3. The Support System Cost.....	30
2.6.4. Electrical System Cost.....	30
2.6.5. Electrical Layout Cost.....	30
2.6.6. Substation Cost.....	31
2.6.7. Transmission Line Cost	32
2.6.8 Project Development and Management Cost	32
2.6.9 Operational Expenditure (OPEX) Cost.....	32
2.7 Economic Cost Function Analysis	33
2.7.1 The Cash Flow Model.....	33
2.7.2 Simple Payback Period.....	33
2.7.3 Net Present Value	34
2.7.4. Internal Rate of Return	35
2.7.5. Return of Investment	36
2.7.6. Levelized Cost of Energy	36
2.8 Financial Trend in Offshore Wind Technology.....	37
2.9 Wind Energy Modelling and Simulation Tools	38
2.9.1 System Advisor Model	39
2.9.2 Cost of Renewable Energy Spreadsheet Tool	40
2.9.3 Windographer	41

2.9.4 WindPro	41
2.9.5 Renewable Energy Technology Screen.....	41
2.9.6 Renewable Energy Optimization (REopt).....	42
2.9.7 Hybrid Optimization of Multiple Energy Resources (HOMER)	42
2.9.8 Regional Energy Development System (ReEDS)	43
2.9.9 EnergyPLAN	43
2.9.10 KomMod	44
2.10 Techno-economic Analysis of Offshore-Wind Energy Projects - Case Studies	44
2.11 Energy Outlook in Kenyan Situation.....	46
2.11.1 Power Generation Mix in Kenya	46
2.11.2 The Spatial Distribution of Kenya Generation Plants.....	48
2.11.3 Kenya’s Electricity Consumption.....	49
2.11.4 The Energy Use Efficiency in Kenya.....	51
2.11.5 Exclusive Economic Zone in Coastal Kenya	52
2.11.6 The Untapped Offshore Wind Potential in Kenya	53
2.11.7 The Blue Economy - Energy Demand Nexus	54
CHAPER THREE.....	57
METHODOLOGY.....	57
3.1 Introduction.....	57
3.2 Procedure for the Research Process and Activities	57
3.3 Data Collection and Analysis	59
3.3.1 Wind Data Access	59
3.3.2 Load Profile Data Access.....	65
3.4 Wind Resource Adjustment.....	69
3.5 Mathematical Modelling for Vision 2030 Load Parameters.....	71
3.5.1 Adjustments for Power Demand Profile under Vision 2030	71
3.5.2 Determination of Number of Wind Turbines Required under Vision 2030.	71
3.5.3. Determination of Number of Batteries Required under Vision 2030.....	72
3.5.4 Determination of Number of Power Converters Required under Vision 2030	72
3.6 Mathematical Modelling for Vision 2050 Load Parameters.....	73
3.6.1 Adjustment for Power Demand Profile under Vision 2050	73

3.6.2 Determining the Number of Turbines Needed under Vision 2050.....	73
3.6.3 Determination of Number of Batteries Required under Vision 2050.....	73
3.6.4 Determination of Number of Power Converters Required Under Vision 2050	74
3.7 HOMER Simulation.....	74
3.8 Evaluation of Economic Indicators	75
3.8.1 The Payback Period	75
3.8.2 The Net Present Cost	75
3.8.3 Internal Rate of Return	76
3.8.4 Return of Investment.	76
3.8.5. The Levelized Cost of Energy.....	76
CHAPER FOUR	78
RESULTS AND DISCUSIONS	78
4.1 Introduction.....	78
4.2 Optimization Results	78
4.2.1 System Architecture.....	78
4.2.2 System Cost.....	79
4.2.3 Renewable Fraction and Total Fuel	81
4.2.4 V47 Wind Turbine.....	82
4.2.5 1MLI Lithium-Ion Battery Storage.....	83
4.2.6 ABB-PSC Power Converter.....	85
4.3 Sensitivity Analysis Results.....	86
4.3.1 Power Generation Capacities	86
4.3.2 Monthly Electricity Yield	88
4.3.3 Cash Flow by Component under Nominal Conditions	89
4.3.4 Cash Flow by Component under Discounted Conditions	91
4.3.5 Other Sensitivity Results	94
CHAPER FIVE	98
CONCLUSION AND RECOMMENDATION.....	98
5.1 Introduction.....	98
5.2 Conclusion	98

5.3 Recommendations	101
REFERENCES	103
APPENDICES	107
Appendix I Questionnaire	107
Appendix II: Ethical Review Approval.....	113
Appendix III: NACOSTI Research Licence.....	114
Appendix IV: Researcher Registration with the Kenya Met. Department.....	115
Appendix V: Data Access Fee Charged at Kenya Met. Department	116
Appendix VI: During the Visit to the Kenya Met. Department	117
Appendix VII: Research Approval by KPLC.....	118
Appendix VIII: Load Profile Data Access Authorization by KPLC.....	119
Appendix IX: During the Visit to the KPLC Headquarters at Stima Plaza.....	120

LIST OF TABLES

Table 2.1: World Top Largest Offshore Wind Farms.....	10
Table 2.2: Expected New Installations From 2022 - 2026	16
Table 2.3: OWE Market Players as Per the Year 2018	18
Table 2.4: Comparing Performance Capability of Different Simulation Tools for Wind Energy Systems	39
Table 2.5: Kenya's Regional Maximum Power Demand (MW) Trend	50
Table 2.6: Trend In Electricity Sales per KPLC Customer's Category (GWh).....	50
Table 2.7: Kenya's Regional Trend Total Unit Sales (GWh)	51
Table 3.1: Peak Load Profile & Electricity Sales Data for Lamu.....	58
Table 3.2: Economic Indicator Evaluation Criteria	68

LIST OF FIGURES

Figure 1.1: A Typical Wind Turbine	1
Figure 1.2: General Layout of Offshore Wind Farm	2
Figure 2.1: Global Versus EU-28 Offshore Wind Power Capacity, 2010-2018	13
Figure 2.2: New offshore and onshore wind installation in 2021.....	14
Figure 2.3: Offshore Wind Capacity Yearly Addition from 2010 to 2018	15
Figure 2.4: Installed Wind Capacity in Africa’s Selected Countries	19
Figure 2.5: Trend in Installed Wind Capacity in Africa.....	20
Figure 2.6: Increasing scales of offshore wind turbines.....	21
Figure 2.7: Illustration of the main foundation type concepts.....	23
Figure 2.8: Leading Manufacturers of Offshore Wind Turbines from 1995 to 2018.....	25
Figure 2.9: Leading Manufacturers of Offshore Wind Turbines from 1995 to 2018.....	25
Figure 2.10: Flow: Three Years Trend in Kenya’s Generation Mix	47
Figure 2.11: The Spatial Distribution of Power Generating Plants within Kenya	48
Figure 2.12: Electricity Consumption by Various Categories of Electricity Utilizers ..	49
Figure 2.13: Kenya’s Exclusive Economic Zone.....	52
Figure 2.14: Completed and Planned Development Projects for New Lamu Port and Its Environ.....	56
Figure 3.1: Steps Involved In Techno-Economic Analysis of OWE Model.....	59
Figure 3.2: Lamu Wind Rose As Extracted In 2021 By Kenya Met. Department.....	63
Figure 3.3: Monthly Average Wind Data for the Year 2016.....	64
Figure 3.4: Monthly Average Wind Data for the Year 2018 – 2020.....	65
Figure 3.5: Comparison in Lamu Load Demand Projections under Visions 2030 and 2050.....	67
Figure 3.6: Average Monthly Power Demand Profile for Lamu	68
Figure 3.7: Electricity Sales in Lamu County	69
Figure 3.8: HOMER Simulation Model for Lamu VWF	75
Figure 4.1: Projected Lamu OWF System Architecture under Vision 2030	78
Figure 4.2: Projected Lamu OWF System Architecture under Vision 2050	79

Figure 4.3: Projected Lamu OWF System Cost under Vision 2030	80
Figure 4.4: Projected Lamu OWF System Cost under Vision 2050	80
Figure 4.5: Projected Lamu OWF System Renewable Fraction and Total Fuel under Vision 2030	81
Figure 4.6: Projected Lamu OWF System Renewable Fraction and Total Fuel under Vision 2030	82
Figure 4.7: Projected V47 Wind Turbine System under Vision 2030	82
Figure 4.8: Projected V47 Wind Turbine System under Vision 2030	83
Figure 4.9: IMLI Lithium-Ion Battery Storage under Vision 2030.....	84
Figure 4.10: IMLI Lithium-Ion Battery Storage under Vision 2050.....	84
Figure 4.11: ABB-PSC Converter Output System under Vision 2030.....	85
Figure 4.12: ABB-PSC Converter Output System under Vision 2030.....	86
Figure 4.13: Daily Generation for Proposed OWF under Vision 2030	87
Figure 4.14: Daily Generation for Proposed OWF under Vision 2050	87
Figure 4.15: Monthly Electricity Production for Proposed OWF under Vision 2030 ...	88
Figure 4.16: Monthly Electricity Production for Proposed OWF under Vision 2050 ...	89
Figure 4.17: Cash Flow under Nominal Condition for Proposed OWF under Vision OWF 2030	90
Figure 4.18: Cash Flow under Nominal Condition for Proposed OWF under Vision 2050.....	91
Figure 4.19: Cash Flow by Component for Discounted Condition under Vision 2030	92
Figure 4.20: Cash Flow by Component for Discounted Condition under Vision 2030	93
Figure 4.21: Annual Energy Output for Lamu OWFs under Visions 2030 and 2050 ...	94
Figure 4.22: Total Annual Operating Cost for Lamu OWFs under Visions 2030 and 2050	95
Figure 4.23: Levelized Cost of Energy for Lamu OWFs under Visions 2030 and 2050	95
Figure 4.24: Net Present Value for Lamu OWFs under Visions 2030 and 2050	96
Figure 4.25: Payback Period for OWFs under Visions 2030 and 2050	96
Figure 4.26: Internal Rate of Return for OWFs under Visions 2030 and 2050	97
Figure 4.27: Internal Rate of Return for OWFs under Visions 2030 and 2050	97

LIST OF PLATES

Plate 2.1: Some Technologies Used for Floating Wind Turbines.....	21
Plate 3.1: Mtwapa Meteorological Station.....	60
Plate 3.2: Meteorological Station at Kenya Met. Department.....	61
Plate 3.3: The Battery Box for Anemometer - Aero Vane at Station within Kenya Met Department.....	62

ABBREVIATIONS

AEO	Annual Energy Output
AEEP	Africa-EU Energy Partnership
BNEF	Bloomberg New Energy Finance
CAPEX	Capital Expenditure
CF	Capacity Factor
EPRA	Energy and Petroleum Regulation Authority
ESMAP	Energy Sector Management Assistance Program
EU	European Union
GOK	Government of Kenya
HOMER	Hybrid Optimization for Multiple Energy Renewables
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KMFRI	Kenya Marine and Fisheries Research Institute
KENGEN	Kenya Electricity Generating Company
KPLC	Kenya Power and Lighting Company
LAPSSET	Lamu Port – South Sudan – Ethiopia Transport
LCDA	LAPSSET Corridor Development Authority
LCDP	Least Cost Development Plan
LCOE	Levelized Cost of Energy
NPV	Net Present Value
OPEX	Operational Expenditure
OWE	Offshore Wind Energy
OWF	Offshore Wind Farm
PBP	Payback Period
PDM	Power Density Method
RE	Renewable Energy
ROI	Return of Investment
SPP	Simple Payback Period

SSC	Static Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
VAR	Volt-Ampere Reactive
VWF	Virtual Wind Farm
WPD	Wind Power Density
XLPE	Cross-linked Poly-ethylene

DEFINITION OF TERMS

Bloomberg New Energy Finance	This refers to a strategic research provider that global commodity markets and disruptive technologies that drive the transition to low carbon technology.
Cable ampacity	This refers to the maximum current that a cable can bear at the rated temperature.
Capital Expenditure	This refers to initial amount paid for establishing an item or acquiring goods or services.
Internal Rate of Return	This refers to an estimate of future annual rate of return when external factors are excluded.
Levelized Cost of Energy	This refers to unit cost per kilowatt-hour or per megawatt-hour electrical energy that is equivalent of payment stream that has the same value as the total cost of commissioning and operating an electricity generation plant over its life-cycle.
Net Present Value	This refers to the difference between the present value of total cash inflow and the present value of the cash of total cash outflow over a period of time.

Operational Expenditure	This refers to an ongoing cost used for running a system, product or business.
Offshore Wind Energy	This is energy available in wind that can be converted to electrical energy generated via wind farms located in large water bodies such as sea or ocean.
Offshore Wind Farm	This refers to a group of wind turbines usually located in large water bodies such as sea or ocean.
Payback Period	This is the time required to recover the initial cost of an investment or to reach its break-even point.
Renewable Energy	This is the energy that is derived from natural sources which are replenished at higher rate than they are consumed.
Return on Investment	This refers to the approximate measure of probability of an investment.
Static Series Compensator	This flexible solid-state voltage source inverter coupled with transformer to provide controlled voltage compensation when connected in series with a transmission line.
Static Synchronous Compensator	This refers to a module consisting of high power converters that are capable of generating or absorbing a variable

**Static Volt Ampere Reactive
Compensator**

reactive power to maintain control of specific parameters of a bus.

This refers to group of shunt-connected capacitor and reactor banks with fast control action of thyristor switching to allow regulation of the voltage magnitude.

Volt-Ampere Reactive

This is a unit of measuring reactive power.

Voltage compensator

This is a device that compensates for voltage drops in cable that transmits power to the load over long distances.

Virtual Wind Farm

This is a software based model that is simulated based on the data of a real world wind farm.

Wind Power Density

This refers to the mean annual wind power available per square meter of swept area by wind turbine's blade.

ABSTRACT

Wind power generation has experienced a continuous attention and investment in Kenya. As a country, Kenya borders Indian Ocean that is rich of renewable energy sources such as the offshore wind and tidal waves. In Kenya, the World Bank's funded "Energy Sector Management Assistance Program (ESMAP) has facilitated researches geared to estimate the Offshore Wind Energy (OWE) potentials. These researches have all been potential based. However, for an investment-oriented system, wind energy potential alone is never enough to serve as the only investment parameter. Today, no ocean energy resource system such offshore wind farm has been established to boost the energy requirement and development in Kenyan coastlines. The area of concern in Coastal Kenya is the Lamu. The choice for Lamu as the location of interest for this research work was motivated by expected increase in energy demand for industrialization and shortage of electricity generating plants in Lamu. The expected increase in energy demand is mainly attributed to the proposed development project at Lamu Port and its environs. Lamu Port has three operational berths, which are among the proposed thirty-two. Other consumers include the go downs, hotel industries and other businesses as well as domestic consumers. This research therefore, performed a comprehensive techno-economic feasibility and analysis from offshore wind energy generation system models that geared towards investment forecast in Lamu. To achieve the objectives of this research work, Lamu wind speed and wind direction data were accessed and analyzed during the attachment with Kenya Met. Department. The Lamu load profile data was accessed and analyzed during the attachment with Kenya Power and Lighting Company (KPLC) Limited. Necessary adjustments were made through Mathematical designs. Wind farm models were developed by using application software called Hybrid Optimization for Multiple Energy Renewables (HOMER). Based on the models realized, techno-economic feasibility analysis was achieved. The analysis was made in terms engineering and financial results from the models. Under Vision 2030 projection, the following sets of results were realized: daily peak generation of 50,160 kW, Annual Energy Output (AEO) of 266,204,237 kWh, Net Present Cost (NPC) of \$ 1,088,225.00, Levelised Cost of Energy (LCOE) of \$ 20.47/MWh, Pay Back Period (PBP) of 3.36 years, and Internal Rate Return (IRR) of 6.13% and Return of Investment (ROI) of 77.87%. Under Vision 2050 projection, the following set of results were realized: daily peak generation of 200,640 kW, AEO of 1,064,816,947 kWh, NPV of \$ 285,447.70, LCOE of \$ 5.37/MWh, PBP of 3.19 years, IRR of 4.05% and ROI of 76.95%. From the generation capacity and hence AEO achieved for OWFs under Visions 2030 and 2050 projections, would be capable of meeting the projected Lamu's load demands in both scenarios. The values of LCOE, NPV, IRR and ROI would give positive margins, which are clear indications for profitability from Lamu OWFs projected in both scenarios. The PBP for Lamu OWFs projected in both scenarios would both be achieved before the end of the plant's life-cycle period. From these indicators it would therefore be suitable to pursue Lamu OWF investment projects based on projected models under Visions 2030 and 2050.

Key abbreviations: OWE, OWF, VWF, HOMER, AEO, PBP, IRR, NPV, LCOE, ROI